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GROUNDWATER RESOURCES OF THE WORLD AND THEIR USE

Editors

Igor S. Zektser
Lorne G. Everett

IHP-VI, Series on Groundwater No. 6

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PREFACE

The International Hydrological Programme (IHP) is as an evolving programme, ready to adapt to the needs of an ever changing society. In order to respond promptly and with appropriate actions, the programme is implemented in six year phases, so as to identify new emerging problems, alert decision makers, raise public awareness and provide the necessary resources.

Today, integrated water resources management poses not only scientific, but also technical, socio-economic, cultural and ethical challenges. IHP is a multidisciplinary programme at the forefront of research and development; and to this end is a prominent agent in meeting the United Nations Millennium Goals.

Since the seventies IHP has focused in particular on hydrogeology and studies related to groundwater resources.

The intention of this monograph is to contribute to a better understanding of the crucial role played by groundwater resources in the support of both the ecosystems and mankind.

This volume does not claim to offer the full picture as far as world groundwater resources are concerned; indeed our knowledge of the world and its most important aquifer systems is far from complete. As such, in years to come, some of the information contained in this monograph will require updating and this through results of new studies and activities initiated and carried out by UNESCO.

All those who have contributed to this monograph have done so on a voluntary basis and are fully committed to continuing the development of existing knowledge in the field of groundwater resources.

Alice Aureli
Responsible for activities in Groundwater Resources
Secretariat of the International Hydrological Programme

FOREWORD

This monograph represents many years of groundwater data accumulation by a large number of noted hydrogeologists located throughout the world. The project began under the direction of the Russian Academy of Sciences during the time of the USSR. In that context, a substantial part of the descriptive material on hydrogeologic phenomena relies on former USSR examples. By far however, the majority of the material in the book is derived from major continental studies and specific country investigations within those continents. As the English Editor, several points need to be made relative to the document. First, the book represents a multi cultural approach to groundwater resources and their use. As a result, many of the fundamental concepts in hydrogeology are interpreted slightly differently in other countries. In fact, there are a number of hydrogeologic phenomena introduced that for the most part have not been presented internationally. Since various cultures review the science of hydrogeology with their own nuances, a substantial effort was made to provide classic references in the science of hydrogeology. Attempts were not made to show that one country's approach to a problem was better than another countries cultural approach to the same problem. The focus of the monograph was to present data and scientific principals, which are relevant to groundwater use in each of the countries.

This monograph represents a major undertaking by hydrologists and hydrogeologists around the world. Although the fundamental groundwater resource data may change slowly over time, the groundwater use data is rapidly changing. Consulting hydrogeologists, engineers, chemists, geologists, biologists, health officials, and government environmental administrators will find this baseline document of substantial value. It is fully anticipated that this book will serve as the first addition of a series on groundwater resources of the world and their use. This series will be updated with second and third editions as new information is developed in countries throughout the world.

Lorne G. Everett, Ph.D., D.Sc.
Chancellor, Lakehead University

Editor-in-chief

Igor Z. Zektser received his doctorate in 1975 in hydrogeology science from All Union Research Institute for Hydrogeology and Engineering Geology in the former Soviet Union. For the past 30 years, he has been head of the Laboratory of Hydrogeology in the Water Problems Institute of the Russian Academy of Sciences.

For his contributions to hydrogeological sciences Dr. Zektser was awarded the Russian State Prize and other special prizes of the Russian Academy of Sciences.

Dr. Zektser's fields of specialization include: quantitative assessment of groundwater resources; evaluation of the contribution of groundwater to total water resources and water balance; assessment of the interrelation between ground and surface water and groundwater discharge into rivers, lakes, and seas; study of the main regularities of groundwater formation and distribution in various natural as well as disturbed conditions; and assessment of human impact on groundwater and groundwater vulnerability. He has published 10 monographs and more than 200 papers. Under his guidance as full professor, ten postgraduate candidates earned their doctoral degrees.

Dr. Zektser was one of the original authors of the *Groundwater Flow Map of Central and Eastern Europe* as well as the *World Hydrogeological Map,* and his research has international recognition. He also served as expert and scientific leader for several projects of the International Hydrological Program, UNESCO, on groundwater resources assessment.

Dr. Zektser was one of the editors-in-chief of *The World Map of Hydrogeological Conditions and Groundwater Flow,* scale 1:10 000 000,published by UNESCO in 1999. Dr. Zektser is president of the Russian National Committee of the International Association of Hydrological Sciences, a member of the Russian Academy of Natural Sciences and Russian Ecological Academy, the New York Academy of Sciences, and the American Institute of Hydrology.

In 1991, Dr. Zektser was invited by the Environmental Protection Agency (EPA) to the Vadose Zone Monitoring Laboratory in the Institute for Crustal Studies at the University of California in Santa Barbara to serve as a visiting research professor. From 1997 to 1998, he worked as a Fullbright Scholar at the same laboratory at UCSB.

In 2000, Igor S. Zektser published in the United States of America the monograph *Groundwater and the Environment, Application for the Global Community,* English editor Dr. Lorne Everett, which is very widely distributed and used in many countries.

English editor

Dr. Lorne G. Everett is the Chancellor of Lakehead University in Thunder Bay, Ontario, Canada. He is also the Director (Level VII) of the Vadose Zone Monitoring Laboratory at the University of California at Santa Barbara and Chief Scientist and Sr. VP for Stone & Webster, Inc. The University of California describes full professor Level VII as 'reserved for scholars of great distinction'. He has a Ph.D. in Hydrology from the University of Arizona in Tucson and is a member of the Russian Academy of Natural Sciences. In 1996, he received a Doctor of Science Degree (Honoris Causa) from Lakehead University in Canada for Distinguished Achievement in Hydrology. In 1997, he received the Ivan A. Johnston Award for Outstanding Contributions to hydrogeology. In 1998 he received the 'Award of Merit' the highest award given by the American International Society for Testing and Materials. In 1999, he received the Kapitsa Gold Medal – the highest award given by the Russian Academy for original contributions to science. In 2000, he received the Medal of Excellence from the US Navy. In 2001 he received the 'C. V. Theis Award' from the American Institute of Hydrology.

Dr. Everett is an internationally recognized expert who has conducted extensive research on subsurface characterization and remediation. Dr. Everett has received numerous awards, published over 170 technical papers, holds several patents, developed 11 national ASTM Vadose Zone monitoring standards, and authored 13 books including: *Vadose Zone Monitoring for Hazardous Waste Sites,* and *Subsurface Migration of Hazardous Waste*. His book entitled *Handbook of Vadose Zone Characterization and Monitoring* is a 'Best Seller'. His book entitled *Groundwater Monitoring* was endorsed by EPA as establishing 'the state-of-the-art used by industry today' and is recommended by the World Health Organization for all developing countries.

Dr. Everett is editor of the Ann Arbor Press book series entitled *Professional Groundwater and Hazardous Waste Science Series*. He is co-editor of the Journal for Environmental Restoration Professionals entitled *Remediation Management,* and co-editor of the *World Groundwater Map* published by UNESCO. Dr. Everett is the English Editor for the book written by noted hydrogeologist Dr. Igor Zektser entitled *Groundwater and the Environment – Applications for the Global Community*.

Dr. Everett has made presentations before the US Congress on different occasions and participates on Blue Ribbon Peer Review panels for the US DOE installations. Dr. Everett is a member of the UC/LLNL Petroleum Hydrocarbon Panel, the DOE/EPA VOC Expert Committee, the Interagency DNAPL Consortium Science Advisory Board, and a Scientific Advisor to the United States Navy's National Hydrocarbon Test Site Program. Dr Everett is a member of the DOE S & T Roadmap Executive Panel and the DOE Long Term Stewardship Board of Directors.

Dr. Everett is an expert witness with an established track record in over 30 court cases involving over US$2 billion.

Acknowledgments

As Editor-in-chief of the monograph first of all I whish to express my profound gratitude to all of the authors and editors for their contributions and collaborations.

The preparation of the monograph is a contribution to the International Hydrological Program in UNESCO and is an example of the joint efforts of scientists from different countries in carrying out important international scientific projects.

In the names of all of the authors and editors I would like to thank the Division of Water Sciences, International Hydrological Program, UNESCO, The Water Problems Institute, Russian Academy of Sciences, Institute for Crustal Studies, University of California at Santa Barbara, and Stone & Webster, Inc., a Shaw Group Company, for their support and help in preparation of this monograph.

A special thanks to Dr. Alice Aureli, for her constant help during the several years to prepare the monograph. Her help made it possible for this book to appear. I also am pleased to thank O. Karimova, T. Krashina and J. Beniak for their help in its preparation.

While preparing this book for publishing much work was undertaken by its English editor, well-known American scientist Dr. Lorne Everett, to whom I express my sincere and great gratitude.

Igor Z. Zektser

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1 Introduction

In recent decades it has become evident in many countries of the world that groundwater is one of the most important natural resources. As a source of water supply groundwater has a number of essential advantages when compared with surface water: as a rule it is of higher quality, better protected from possible pollution including infection, less subject to seasonal and perennial fluctuations, and much more uniformly spread over large regions than surface water. Very often groundwater is available in places where there is no surface water. Putting groundwater well fields into operation can be gradual in response to growing water demand while hydrotechnical facilities for surface water use often require considerable one time investments.

These advantages coupled with reduced groundwater vulnerability to pollution particularly have resulted in wide groundwater use for water supply. Groundwater is the only source of water supply for some countries in the world (Denmark, Malta, Saudi Arabia, etc.). It is the most important part of total water resources in the other countries. Groundwater in Tunisia is 95% of the countries total water resources, in Belgium it is 83%, in the Netherlands, Germany and Morocco it is 75%. In most European countries (Austria, Belgium, Denmark, Hungary, Romania and Switzerland) groundwater use exceeds 70% of the total water consumption.

In countries with arid and semiarid climate groundwater is widely used for irrigation. About one-third of the landmass is irrigated by groundwater. Out of the total irrigated land in the United States of America, 45% is irrigated by groundwater, 58% in Iran, 67% in Algeria, and in Libya irrigated farming is wholly based on quality groundwater.

The function of high quality groundwater is particularly important in domestic use and drinking water supply. According to the European Economic Commission data, groundwater is the main source of municipal domestic and drinking water supply in most European countries. Water supply of such European cities as Budapest, Copenhagen, Hamburg, Munich, Rome and Vienna is completely or almost completely based on groundwater, and for Amsterdam, Brussels and other cities it provides for more than half of the total water demand. There is strict water legislation in some countries (Bulgaria, Hungary, Russia, etc.) according to which fresh groundwater must be mainly used for domestic and drinking water supply. It is possible to use fresh groundwater for other purposes (industry, irrigation) only under the availability of considerable groundwater reserves sufficient for meeting the available and perspective demand in drinking water and by special permission of nature-protecting institutions.

When studying groundwater and determining the perspectives of its practical use for different purposes, it is necessary to consider that it is not only an important mineral resource (in recent years geologists often call groundwater the 'number one mineral resource') but a component of the total water resources and water balance and is one of the main components of the environment.

Groundwater renewability as part of the total water cycle is the principle difference from other mineral resources. According to calculations on a global model Water GAP-2 (Doll, 2002), an average perennial amount of groundwater recharge is about 14,000 km^3/year for land or, in other words, about 36% of the river runoff is formed by groundwater.

Groundwater is closely interrelated with other components of the environment. Any changes in atmospheric precipitation inevitably cause changes in the groundwater regime, resources and quality. And vice versa, changes in groundwater cause changes in the environment.

Thus, intensive groundwater exploitation by concentrated water well systems can result in a decrease in surface water discharge, land surface subsidence, and vegetation oppression due to groundwater withdrawal. Groundwater pumping can 'entrap' mineralized groundwater not suitable for drinking in deep aquifers, and can draw in saline seawater in coastal areas. All these circumstances should be considered when planning groundwater use.

Various human activities can result in significant changes in conditions of groundwater resource formation, causing its depletion and pollution. Groundwater pollution in most cases is a direct result of environment pollution. Groundwater is polluted mainly by sulphates, chlorides, nitrogen compounds (nitrates, ammonia, ammonium), petroleum products, phenols, iron compounds, and heavy metals (copper, zinc, lead, cadmium, mercury).

Oil pollution is very dangerous and, unfortunately, has caused wide spread pollution of the environment on the whole. Oil fields development in Southern California has resulted in pumping saline brines into aquifers. Intensive use of pesticides and other fertilizes has caused an increase in arsenic content in groundwater.

At present the notion of ecologically pure groundwater should be essentially corrected. Groundwater pollution is a serious danger that limits its practical use, primarily for domestic use and drinking water supply.

Determining the limits of admissible groundwater withdrawal is a significant problem. These limits are determined by two opposite tendencies: on one side, a wish to develop as much groundwater of good quality as possible, and on the other – to exclude depletion, i.e. 'overexploitation' of the aquifer and the negative impact of considerable water withdrawal on the other environment components.

In support of the International Hydrological Program, UNESCO, has sponsored a project aimed at preparing an International Monograph, *Groundwater Resources of the World and Their Use*. Leading experts of many countries participated in this work: Australia, Brazil, China, Czech Republic, France, India, Japan, Syria, New Zealand, Russia, Spain, United States of America and others. Present-day concepts on groundwater resources are present in the Monograph. Modern methods for regional assessment, including groundwater vulnerability to pollution, are characterized. Groundwater discharge in the water and salt balance of the World Oceans is discussed. Social and economic aspects of groundwater use and the current state of groundwater resources and their use in different countries and continents are provided.

The authors of the Monograph are:

Preface – A. Aureli (UNESCO); Introduction: I. Zektser (Russia); 2.1, 4.2: B. Borevsky and L. Yazvin (Russia); 2.2: B. Borevsky and L. Yazvin (Russia), J. Margat (France); 2.3: J. Margat (France) and E. Custodio (Spain); 2.4, 2.5: E. Custodio (Spain); 2.6.1.1: Elpiner (Russia); 3.1, 3.3, 4.2, 6.1 and 6.2: R. Dzhamalov and I. Zektser (Russia); 3.2: V. Kovalevsky (Russia); 3.4: J. Khouri (ACSAD/Syria); 3.5: E. Custodio (Spain) and L. Yazvin (Russia); 4.3, 4.4: J. Vrba (Czech Republic); 5.1: I. Diordiev, R. Dzhamalov, I. Zektser and L. Yazvin (Russia), J. Margat (France); 5.2: K. Jinno and K. Momii (Japan), W. Zhaoxin, J. Chuanmao (China), B. Borevsky and L. Yazvin (Russia), D. Limaye (India); 5.3: W. Alley and J. Miller (United States of America); 5.4: A. Rebouças and A. Mente (Brazil); 5.5: J. Khouri (Acsad/Syria); 5.6: G. Jacobson (Australia), J. Lytham and E. Michael (Papua New Guinea), L. Brown (New Zealand); 6.3: H. Loaiciga (United States of America), I. Zektser (Russia); 6.4.1 to 6.4.6: L. Yazvin and I. Zektser (Russia), R. Llamas (Spain) ; 7.1: G. Vartanyan (Russia); 7.2, 7.3: V. Kononov and A. Shpak (Russia); 8: J. Margat (France); Conclusion: L. Everett (United States of America), I. Zektser (Russia).

Editing and preparing the monograph for publication has been carried out by the International Editing Board including I. Zektser (Editor-in-chief, Russia), L. G. Everett (English editor, United States of America), A. Aureli (UNESCO), R. Dzhamalov (Russia), J. Khouri (ACSAD/Syria), J. Margat (France).

The authors comprehend that it is impossible to consider the whole complex of interrelated problems connected with groundwater resources and their use in a book of only one volume. Thus some aspects of the issues are given in a general form and in several cases only schematically. This disadvantage was significantly compensated for by the authors and editors by providing very extensive references. The book editors have decided that many old classic references and a wide distribution of current references should be included in the book. The logic of this decision is based on the fact that many countries around the world have an emerging water resources program and as such there is substantial value in the ability to identify classic references in hydrogeology. Further, many of the developmental papers in the science of hydrogeology are identified. These references are given because of the need for emerging counties to be able to look at how classic positions have evolved over time and how other developed countries have approached similar problems. Often, financial and cultural attitudes have effected the evolution of the science of hydrogeology and since many countries with diverse cultural backgrounds evaluate water differently, it seemed reasonable to include many of the hydrogeology references, which have moved the science forward in other countries.

The authors and editors welcome comments and remarks, that should be sent to the Division of Water Sciences, UNESCO, 1, rue Miollis, 75732 Paris Cedex 15.

2 Groundwater as a source of public water supply and irrigation

2.1 Main concepts of groundwater use

Intensive groundwater exploitation, its considerable withdrawal under mineral deposits mining and different drainage measures, human activities impact on its quality and resources put in the agenda the problem of groundwater rational use, the main task being to work out scientific bases and technique of its resources management.

When proving groundwater rational use, its principle differences from other natural resources should be taken into account.

Groundwater, as a natural resource and an element of the environment, used in human activities, is of a dual character (Borevsky et al., 1989). On one hand, it is a moving resource in the earth depths and abstracted out of it, on the other, it is a part or total water resource of the earth.

As a *mineral resource,* groundwater is a part of the depths and its safe yield is caused by geologic-hydrogeologic conditions of the territory. As a part of *water resources,* groundwater is directly connected with surface water and atmosphere. Due to this, groundwater safe yield depends not only on geologic-hydrogeologic but also on physical-geographical and human-induced factors, connected with changes of water consumption and resulting in changes of groundwater recharge conditions, its quality and abstraction. The fact, that groundwater is a part of total water resources is the most important in estimating perspectives of fresh groundwater use. In spite of the fact that ground and surface water are separate components of total water cycle in the globe, they are, at the same time, closely connected. Therefore, when solving problems of groundwater use, this interconnection should be considered and tasks will be the following (Yazvin and Konoplyantsev, 1984):

1. Proving the expediency of complex ground and surface water exploitation;
2. Assessing the impact of surface water runoff changes on groundwater storage and conditions of its exploitation;
3. Assessing the changes of surface water runoff under groundwater withdrawal;
4. Proving the use of surface water as a source of groundwater artificial recharge or the use of groundwater in regulating surface water runoff.

Dual character of groundwater is also caused by some peculiarities that make it basically different from other mineral and non-metallic resources; they are as follows (Borevsky et al., 1989):

1. Complete and partial renewability of groundwater, due to its constant or periodic recharge, resulting from its close contact with surface and atmospheric water;
2. Close connection of groundwater with the environment and, as a consequence, dependence of its storage volume on climatic, including hydrologic, and human-induced factors and their change in time. Groundwater is the only resource that is being additionally formed in the process of exploitation due to increased recharge of it caused by withdrawal;
3. Possibility of new groundwater storage formation and its volume enlarging under water-management works or special engineering measures for artificial groundwater recharge;
4. Possibility to change groundwater quality during exploitation under the impact of natural and human-induced factors, that can develop both negatively (contamination) and positively (for instance fresh water lenses formation under surface water entrapment);

5. Possible interaction of well fields and water-level declining and drainage facilities, placed in different parts of one and the same well field, dependence of the abstracted water volume on the scheme of placing capture works and water-enclosing rocks filtration properties, causing the yield of water-withdrawing wells.

Groundwater peculiarities mentioned above, differentiating them from other mineral deposits make it necessary to define some notions, characterizing: a) water amount in the aquifer; b) water amount inflowing the aquifer at a certain period in natural conditions, under water management measures and due to exploitation (total groundwater recharge); c) water amount, that can be abstracted by the well fields.

In other words, when addressing perspectives of mineral resources use, only one notion is needed: 'mineral reserve', characterizing its total weight or volume in the depths, but for groundwater this notion is not enough to characterize its rational exploitation. Besides, when assessing possible groundwater yield, it is necessary to consider, that its exploitation can cause a change of other components in the environment. The main negative consequences of groundwater withdrawal are the following: reduction of surface reservoirs and courses water content, a change of landscapes (vegetation oppression or downfall), land surface subsidence, activization of karst-suffosion processes. Necessity to localize or fully prevent these processes can result in an essential change of groundwater abstraction or a change of water wells scheme.

At present, due to foregoing, the following main notions are used in hydrogeological studies when estimating the possibility of groundwater use:

1. Volume (mass) of groundwater in the water-bearing layers that can be abstracted under decreasing the head, layer drainage or water forcing out of rocks. This notion is most often determined by the term 'groundwater storage'.
2. Total groundwater recharge is a volume of groundwater infiltration into the aquifer in natural conditions due to atmospheric precipitation, filtration from surface water reservoirs and streams, from other aquifers and also under water management measures, including artificial groundwater recharge. To characterize this notion, a term 'natural groundwater resources' is used.
3. Additional groundwater recharge, under its exploitation, is defined by the term 'induced resources'.
4. Possible groundwater withdrawal by a well field under given hydrogeological, engineering, economical and nature-protecting limits is often defined by the terms 'groundwater safe yield' or 'exploited resources'.

With the account of genetic character, groundwater safe yield and dynamic resources are usually subdivided into natural (formed in undisturbed by human activities hydrogeological conditions), artificial (formed under human activities) and natural-artificial (formed under the impact of both natural and human induced factors).

Expediency of groundwater use can be determined only on the basis of its safe yield. The following balance relation connects the latter with other types of groundwater resources:

$$Q_{sy} = \alpha_1 Q_n + \alpha_2 (V_s/t) + Q_{ir}$$

where

Q_{sy}: safe yield (m^3/day);
Q_n: natural groundwater resources (m^3/day);
V_s: storage (m^3);
Q_{ir}: induced resources (additional) (m^3/day);
t: estimated time of exploitation;
α_1, α_2: coefficients of natural groundwater resources and storage use.

It is seen from the equation, that the second term of it becomes equal to zero under $t \to \infty$, i.e. under unlimited term of exploitation, and safe yield is formed only due to recharge under natural conditions and its increase during exploitation.

The present ideas of groundwater use in different countries, depending on climatic, hydrogeological, social and economic conditions essentially differ from each other. Nevertheless, some general features, characteristic for many countries should be noted:

a) Fresh groundwater, of corresponding to the standards quality, should be used first for potable and domestic water supply of the population, and also in industry, if potable water is required according to technology (for instance, in food industry). The use of potable groundwater for other purposes is permitted only in areas with considerable fresh groundwater resources under surface water resources deficit.

b) When investigating fresh groundwater for potable and domestic supply, confined groundwater is considered preferable, as it is protected from surface contamination by layers of poorly permeable or impermeable rocks.

c) Groundwater abstraction in any hydrogeological region should not exceed its safe yield. The latter should not be more than dynamic and induced resources (recharge) of the studied aquifer during its exploiting. However, under certain social-economic conditions, groundwater safe yield can be calculated for a fixed term (for instance 25 or 50 years). In this case groundwater use is considered as the use of undercharged resources, allowing depletion of its safe yield during a given period. In this case, it is taken into account, that under groundwater exploitation, in contrast to other mineral resources, additional formulation of groundwater resources can occur. Therefore, if, for instance, oil or iron reserves can be exhausted, it is not the case with groundwater and a man can always get the water that recharges the aquifer. At the same time, the use of groundwater safe yield can help to obtain an essential social and economic effect.

d) Groundwater abstraction should be made in such quantities, that its quality corresponds to the requirements for the whole exploitation period. It is particularly true for well fields, where the influx of mineralized water from deep aquifers or seawater intrusion is possible during exploitation.

e) When determining groundwater safe yield, possible effect of its abstraction on a general ecological situation should be considered as well as on natural environment components (surface runoff, landscapes, etc.).

f) When constructing groundwater well fields, their possible interaction should be taken into account, that is, the effect of groundwater withdrawal at a certain area on the level and yield of well fields at different areas of exploited aquifer.

g) Mining of mineral deposits, oil and gas developing, industrial and municipal construction, agriculture, hydrotechnical construction should be carried out, with the methods that provide minimal impact on groundwater storage and its quality.

In most countries groundwater use and protection are controlled with legislation. In this case, legal control of groundwater use is carried out, as a rule, with special water legislation, however, in some countries, accounting for a dual character of groundwater, this regulation is a function of two legislation branches – water and mineral resources.

According to legislation of many countries, groundwater is a national property and state ownership. Water resources are managed by state administration, including licensing of groundwater pumping, limiting of groundwater withdrawal, accomplishing of groundwater state monitoring and registration, as well as introducing of state water Cadaster, conducting of state groundwater reserves estimation and state ecological study, and also state control for groundwater use and protection.

The following standard requirements are given in legislation acts of different countries:

1. Payment for groundwater use except for special, legislatively provided, cases (a water tax or a tax for the depth use for water pumping);
2. Obligatory use of a license for groundwater pumping and fulfilling standard requirements for the depths use;
3. Obligatory state geological and ecological study for estimating possible volume of groundwater withdrawal.

Besides, the present-day notions on groundwater use, formulated in this chapter are considered in legislation of many countries (priority for fresh groundwater use for potable water supply of the population, obligatory estimation of groundwater storage, considering the impact of its pumping on the ecological conditions, groundwater protection from contamination and depletion under various human activities, etc.).

2.2 Importance of groundwater for water supply

Groundwater is widely used in national economy of many countries for most different purposes: potable water supply of the population and cattle-breeding farms, industrial water supply, irrigation, balneological use (mineral water), as a raw material for extracting valuable components, such as iodine and bromine (industrial water) and for central heating (thermal power water). Fresh groundwater is of particular importance, as in many countries it is the main source of public water supply and its role in domestic and drinking water supply balance is growing every year, that is due to continuing contamination of surface water resources.

Groundwater, as a source of domestic and potable water supply, has some advantages over surface one. It is, as a rule, characterized with a higher quality (availability of components, necessary for human vital activities) and better protection from pollution and evaporation. Groundwater resources, due to availability of regulating capacity, are not subjected to multiannual and seasonal fluctuations. In some northern and arid zones, where surface water flows freeze up or dry up in some periods of a year, groundwater is the only water supply source. In many cases, it is possible to abstract groundwater in the direct vicinity of a consumer. Putting well fields into operation can be made gradually with the increasing growth of consumption, while hydro-technical constructing, for surface water use, needs usually large one-time expenditures. All the circumstances mentioned predetermined a considerable increase of groundwater use for potable and domestic supply of the population, if compared with surface water, particularly, taking into account its better protection from contamination.

The role of groundwater for public water supply in different countries and in different periods changed considerably. On the hole, at the initial stages of developing a centralized municipal water supply, spring or river water was, as a rule, used as a source of water supply (where it was possible). With a growing of water consumption, surface water was used more intensively. However, increasing surface water pollution in the second half of the nineteenth century and serious diseases of population as a result, caused the necessity of reconstructing water supplying systems, that consisted in improving quality of water purifying or in groundwater use, as a source of water supply (including springs, even at a considerable distance from a consumer). Water supplying system of such big city as Paris can be taken as an example: in 1865–1900 springs on the hills slopes at a distance of 80–150 km from the city were used for public water supply and surface water was used only for process water supply. Hamburg is another example: there, after cholera epidemic in the 1890s, surface water supply from the Elba river was replaced by ground-water one. However, in the twenty-first century, under growing consumption and due to ground-water resources limitedness, surface water was mainly got used for water supply of big cities in

many regions. But increasing pollution of the latter, and also unpredicted emergency discharges of contaminants, that become more frequent, put in the agenda a maximum use of protected from pollution groundwater. Now, it is a governing tendency in the strategy of organizing potable-domestic water supply.

At present, groundwater is the main source of domestic-potable water supply in most European countries (*Water Economy Prospects for 1990 and 2000,* 1982). Thus, groundwater portion in a general balance of domestic-potable water supply exceeds 70% in Austria, Armenia, Byelorussia, Belgium, Hungary, Georgia, Denmark, Lithuania, Switzerland and Germany, and amounts from 50 to 70% in Bulgaria, Italy, Portugal, Ukraine and France. Groundwater is a basis for water supplying of rural areas, small and large towns and in some regions cities with population exceeding 1 mln.p.

Groundwater is widely used in municipal water supply in the United States of America (*Survey of operating and financial characteristics,* 1977). Thus, in the 1970s, a portion of groundwater in municipal water supply exceeds 40%. Groundwater is used in 75% of municipal water supplying systems, that provides more than a half of population in the country with potable water.

Groundwater is of great importance in domestic and potable water supply in Australia and some countries of Asia and Africa (China, the Yemen, Saudi Arabia, Tunis, Libya, etc.). Fresh groundwater is also used for industrial and process water supply in many countries. It is justified when potable water is required according to technology (for instance in food industry). However, drinking groundwater use in industrial process, where there are no special high requirements to water quality, particularly, in the areas with deficit of fresh groundwater, is hardly rightful.

In countries with arid and semiarid climate, groundwater is used for irrigation (southern and western areas of the United States of America, Spain, Greece, Iran, India, the Yemen and some other areas of Africa and Asia); a more detailed characteristic of groundwater use will be given in Chapters 5 and 6.

Groundwater exploitation meets approximately one fifth of current world water needs for all uses combined. That proportion varies by country and by sector.

Groundwater contributes most markedly in countries like Saudi Arabia and the Libyan Arab Jamahiriya, where surface-water resources are scarce, but it is by no means unimportant in temperate or tropical regions where it satisfies a sizeable share of diffuse demand: mainly for rural water supply and private irrigation. India alone extracts a world-record-breaking 160 kilometers of groundwater a year for irrigation: i.e. 35 % of the total national requirement.

Groundwater withdrawal in most cases exceeds one fifth, and often one third, of the total water tapped for all purposes (including cooling thermoelectric power stations). The three main sectors using such volumes are: communities (drinking water), self-supplied industry and agriculture. Communities tend to be the main groundwater users in the developed countries of Europe (Russia included). Industry is the prime exploiter in a number of industrialized countries (South Korea, Japan, the Netherlands, Norway and, until 1980, the USSR), and the second biggest in others (Germany, Belgium, France, the United Kingdom, the Czech Republic and the former Yugoslavia). Agriculture tends to be, often by far, the most prolific exploiter and user of groundwater both in the developed world (chiefly for irrigated farming), and nearly every developing country outside the humid intertropical zone: Saudi Arabia and the Libyan Arab Jamahiriya (90%), India (89%), Tunisia (85%), South Africa (84%), Spain (80%), Bangladesh (77%), Argentina (70%), the United States of America (68%), Australia (67%), Mexico (64%), Greece (58%), Italy (57%), China (54%), etc.

Although the importance that each sector places on it as a source of supply may vary, groundwater is rarely neglected and often regarded as crucial, especially for supplying urban and rural communities with drinking water:

- at world level – and in proportions that vary widely from one country to the next – groundwater exploitation covers approximately:
  - 50% of drinking water needs,
  - 20% of the demand for irrigation water,
  - 40% of the needs of self-supplied industry;
- it also plays a key role in the energy sector (cooling), save in the specific case of geothermics (which uses only water unfit for other purposes) or as a cooling source for the heat pumps being introduced in a certain number of countries (mainly for communal – but also private – heating systems);
- in most of the developed world and many developing countries, groundwater is the chief – and sometimes only – drinking-water supply source: 100% in Austria and Denmark, over 90% in Italy, 88% in Hungary; 70 to 80% in Germany, Switzerland and Poland; over 60% in Greece, Belgium and the Netherlands; 56% in France; close to 70% for the European Community as a whole;
- in many industrialized countries, groundwater covers an often outstanding proportion of the needs of self-supplied industry: 71% in Greece, 65% in Denmark, 40% in Japan, 27% in France and India, 26% in Germany and the United States;
- groundwater is also used – to a considerable degree in some cases – to meet irrigation water needs in regions both arid (Libyan Arab Jamahiriya (100%), Saudi Arabia (86%), semi-arid (Argentina (70%), Algeria (56%), Australia (46%), the United States of America and Mexico (38%), India (35%)), and Mediterranean (Spain, France, Greece and Italy (upwards of 26%)). In arid and semi-arid zones, groundwater also tends to be the basic water resource for extensive livestock farming.

Groundwater serves a wide variety of uses; its share of overall water supply, and perceived use value on the part of the economic agents concerned, also differ.

In terms of drinking-water supply, groundwater corresponds to high economic – and social – use value, is regarded as a public and generally paid-for service, and requires intermediary production-distribution agents whose role varies in importance according to the country and local relations between agents both public (municipalities, unions, etc.) and private (delegated managers). On the whole, the frequently overwhelming degree to which groundwater is pumped and used for drinking water serves to boost its value on – and share of – the market.

In the self-supplied industry sector, companies – both private and public – tend to exploit groundwater explicitly for their own use, and do not regard it as a market commodity.

Likewise, the farmers using groundwater for irrigation purposes are, by and large, both exploiters and users; the individuals concerned have only their direct exploitation costs to consider (and are more likely to receive subsidies than tax demands).

Using groundwater for irrigation is therefore usually more economical and effective than using surface water distributed via collective mains systems. As R. Llamas points out with reference to Spain (Llamas et al., 1996): groundwater is used to water 30 to 40% of total irrigated farming output, yet accounts for no more than 20% of irrigation water used as a whole.

So the economic value of groundwater use – which belongs more to the private than the public sector of the water economy – is clearly too great to be gauged solely in terms of volume.

The various practical advantages of groundwater over surface water as a source of supply are nonetheless offset by a number of constraints (summarized in Table 2.2.1).

Occupying aquifer lands in even greater numbers than the exploiters, are other economic agents who, in the course of their activities, have the power to influence the state and quality of groundwater, particularly in shallow aquifers: farmers (treating soil in such a way as to impede infiltration, or using a surfeit of fertilizer and pesticides); industrial plants with hazardous materials (raw or manufactured) to store, waste to manage, and running accident-prone

Table 2.2.1 Advantages and constraints of groundwater as a supply source in comparison to surface water

Availability (space)	Extensive resource, allowing siting of catchworks close to the users and, hence, minimizing adduction costs. Depending on yield capacity, however, a multiplicity of catchworks may be needed to meet strong local demand.
Availability (time)	Regular resource, offering virtually constant yields, greater resistance to climate change and, hence, a more secure source of supply than surface water. Natural storage needs no artificial regulating, making yield easy to adjust to fluctuating demand.
Resource assessment	Concealed resource, demanding relatively complex precision gauging techniques, making appraisal more costly than surface-water resources, but faster.
Natural qualities	Relatively stable, facilitating treatment – of hardness, Fe or Mn content – for specific uses (drinking water, industrial processes, etc.). Salinity tends to increase with aquifer depth and aridity of surface climate.
Vulnerability to pollution	Water in deep aquifers generally sheltered from harm unless threatened by faulty drilling or injection, etc. Water in shallow aquifers more directly at risk of diffuse or sudden pollution: less so than surface water but sustaining more lasting damage (lower impact resistance).
Cost of production	Investment and operating costs lower than surface water, though varying as per local aquifer characteristics (depth, productivity). Operating costs tied to energy price fluctuations (save in case of gravity wells, etc.). Yield potential drops as overall aquifer exploitation rates rise.
Development flexibility	Possible gradually to install facilities better suited to changing demand than surface-water projects: quicker returns, divisible investments.

production processes which threaten to damage the environment; quarry owners and mining companies needing to dewater subsoil and dispose of waste (slag heaps, landfills, etc.); local authorities in charge of sewers (not altogether leakage free) and city dumps; public and private sponsors of urban planning and water projects transforming the state of surface conditions, drainage and the interrelationship between watercourses and groundwater bodies; contractors responsible for altering aquifer structures and distorting subterranean streamflow systems owing to underground urban development work, underground conduits, underground storage, etc.; transporters shifting hazardous materials (with the risk of accidents on own sites or public highways), etc. Once again, these agents largely operate in the private sector.

The spin-off effects of their activities are inevitably going to have an impact (albeit unintentional) when the agents responsible regard efforts needed to prevent or minimize such 'externalities' as non-essential to their economic goals.

Finally, few if any of the agents exploiting or impacting on a body of groundwater are conscious of the fact that they – like riverside residents – belong to a wider community of co-proprietors ('co-inheritors'). Their perception of the resource they are using or influencing at best remains fragmentary, even when they come into conflict with other users. In most cases, as long as they themselves are not suffering the backlash of their activities, they are rarely aware of how they might be affecting other localities, other environments (watercourses) or the long-term future.

These agents' individual strategies do not, as a rule, automatically prioritize groundwater

management – which is not defined at their level – and their activities tend to be driven by concerns of a chiefly microeconomic order.

In short, a body of groundwater is a de facto 'jointly-owned property' lacking both recognition as such and spontaneous rules and regulations. Hence, the exploiting community feels no sense of collective responsibility if its overall exploitation of the groundwater impacts negatively on third parties such as the users of dependent surface water.

These distinguishing features will naturally have a bearing on the guidelines and goals of groundwater management both as a resource and as a part of the natural environment (cf. Chapter 8).

2.3 Economic aspects of groundwater use

Human beings in many regions of the world have been managing to draw much – if not the bulk – of their staple water requirement from subterranean sources since earliest antiquity.

Wherever an accessible and exploitable body of groundwater has been detected, it has been recognized as a means of bringing large numbers of users within reach of more extensive and stable resources than might be possible with surface water – particularly in arid or semi-arid lands where the latter is in scarce or infrequent supply. Groundwater exploitation and use thus have a key role in water economics.

Ways of extracting groundwater, benefits arising from its use and its relative importance to the water economy may vary, but there are several broad socio-economic characteristics common to all groundwater use, which distinguish it from that of surface water. These characteristics condition the potentiality of groundwater as a source of supply.

Three particular aspects warrant attention. First, groundwater is open to exploitation by a great many economic agents – land users in aquifer zones as a rule – many more than on the banks of watercourses. Having the means and right to exploit groundwater offers households, farmers, manufacturers, local authorities and companies in charge of water services an opportunity to benefit from what they often find to be the least costly, most convenient and direct source of supply. Indeed, tapping it calls for few, if any, collective utilities, while surface water, on the other hand, requires diversion, regulation and transportation work beyond the scope of agents acting alone. Groundwater is above all else a vicinity resource.

So users tend to be far more personally involved in its exploitation than those relying on surface water; and intermediary production-distribution agents are relatively less important, save for supplying community drinking water. By and large, groundwater is a 'self-service' resource.

As for extraction-related investment and running costs, these are commonly taken care of by the users themselves or by intermediary distributors who then pass them on to the 'consumer', i.e. chiefly by the private sector. Surface-water control and engineering projects, on the other hand, remain more in the hands of the public sector (the State or district authorities).

Groundwater is the world's most extracted raw material, with withdrawal rates currently up in the region of 600 to 700 billion m^3/year. The breakdown of that figure into percentages used per sector is distinctly different from that of surface-water use:

- drinking water (65%);
- irrigation and livestock (20%);
- industry and mining (15%).

The importance of groundwater exploitation and use needs to be determined through its assessment in relation to:

- total human water use – all sources (i.e. from the point of view of the water economy);

- natural groundwater resources or, more broadly, all regular water resources, of which groundwater forms the best part (i.e. from the point of view of impact on the environment).

From either angle, the relative importance of groundwater exploitation will differ from one region or country to the next. Generally speaking, however, groundwater is much exploited and used in a great many countries, and is crucial to the few for whom it is their chief source of supply (and where the bulk of natural water resources are being tapped, even over-exploited).

Economic problems derived from groundwater exploitation depend on aquifer characteristics, on where the extraction works arc and on the intensity of exploitation relative to recharge. Many of them derive from groundwater level drawdown and imply that the cost of extracting groundwater increases. This is due to greater energy consumption, which may be accompanied in some cases by the cost of substituting the wells for deeper ones, or deepening existing ones, the cost of new electric transport lines, transformers and pumps, and the extra energy losses due to the decreased efficiency of the pump. All these are foreseeable and intemalizable consequences, which should be part of the economic study of properly planned groundwater exploitation. Thus, what are sometimes considered groundwater problems are really mostly problems due to lack of prevision and a consequence of poor knowledge on how an aquifer behaves. It is a serious error to think that the economics of groundwater exploitation can be based on cost calculations based on starting conditions, without considering future changes, which may be quite important in large and thick aquifers. This error is not rare when managers think in surface water terms. Under correct economic planning, this increasing winning cost is really favorable since the water to be extracted is cheaper (less extraction) at the beginning, which favors economic development

Other economic groundwater problems refer to quality deterioration and contamination prevention. Although prevention seems too expensive, in most cases it is worthwhile when the real aquifer opportunity cost is taken into account This is not always easy since there is a series of externalities that are difficult to evaluate, but other alternatives also present externalities that are often unfairly waived to make them more attractive or concealed under subsidies or public deficit Action for aquifer protection may change – often decrease – land and property value, and this may oblige to compensate for singular damages or losses, but not for general limitations or burdens. This includes reducing agrochemicals and manure use, compensating for the loss of agricultural production and in some cases of crop quality. However, in fair play possible benefits should be collected and redistributed. This is not an easy task, needing management skills. Untrained personnel or those who are resistant to change consider this a new groundwater problem.

Some economic groundwater problems refer to management. They involve possible incentives and/or taxes to lower the aquifer system exploitation rate from the value that cancels the net benefit from individual users to that of maximum long-term social net benefit after internalizing the externalities (Young, 1992; Gonzales, 1992). This is also a complex task. Really these actions are more difficult to address than in surface water schemes, but generally this does not justify discarding an alternative since the cost of implementing the necessary organizational instruments is relatively low. Associations of ground-water users may greatly help in attaining these goals, as well as continuous education of water users to change their attitude and increase collective feelings.

Studying, monitoring, protecting and restoring an aquifer system need economic resources. This is clearly so for dams, canals, and treatment and desalination plants, and should be equally clear for an aquifer system that produces benefits to its users. The difference is the result of the larger number of actors, the lack of collective conscience of groundwater exploiters and the inability of some managers to grasp it. However, this can be overcome. Taxation, direct or through other existing fiscal means, or shared expenses, plus economic responsibility for damage and

irresponsible action, and security funds to deal with very delayed effects, are possible sources to cope with management expenses.

2.4 Managerial and administrative problems of groundwater development

Many problems associated to groundwater development are not technical but managerial and administrative ones, including economical and legal ones, and knowledge-, ownership- and regulation-related problems. Some derive from technical circumstances, but others are unrelated and refer to economic, social and cultural circumstances. The management of an aquifer system implies that it is possible to carry out decisions by some kind of management agency. These decisions are directed to modify the extracted flows and volumes, the location of wells and other groundwater winning works, and how they are constructed and operated, considering economical, social, environmental and political goals. There is a wide range of possibilities, from full administrative regulation to doing nothing, to modify the trend.

This management not only refers to sustainable groundwater flow (quantity aspect), but to the preservation of water quality as well. This means decisions on groundwater exploitation and on land use, such as regulations and limitations to the use of agrochemicals, establishing wellhead protection areas or setting the limits of areas in which the aquifer is subjected to specific regulations to protect water quantity and quality. Specific situations appear in coastal aquifers, since the exploitation pattern is a key subject of management. Management objectives include analyzing the positive and negative aspects of each alternative to adopt the right decisions, instead of trying to correct the negative effects – often labeled groundwater problems – once they have been produced. However, unfortunate decisions are often made under poorly informed public opinion pressure and when emotions dominate.

Since aquifer exploitation means groundwater head changes and fluid displacement, as explained before, management rules have to specify whether these changes affect existing groundwater rights and which modifications have to be supported to get full use of aquifer storage capacity after defining environmental goals to be respected. This is difficult to understand for untrained managers and may become a groundwater problem if regulations do not contain provisions or if there is not a general agreement on exploitation rules and cost sharing.

The main groundwater management problem stems from the very large number of actors involved and the very different interests they have. These actors are the persons, enterprises, societies, agencies and public organizations holding groundwater rights and wells, as well as those who are the users of groundwater, people living in the territory who are the possible subject of water taxes, restrictions and conditions of the activities, or who may suffer some water quantity and quality impairment, and the agencies in charge of land management, public works and transport. Complexity is generally much greater for groundwater than for surface water. The public or private character of water ownership has some influence on the way to cope with this complexity, but in real terms probably there is not much difference. This character affects the way in which decisions are to be implemented, but not their foundations.

The problems caused by the large number of actors seem very difficult to solve when there is no experience, when there is no training for using available managerial instruments and when they are dealt with by unprepared personnel. The situation worsens when decisions are taken with arrogance or when they are the result of hectic moves yielding to pressure for solving as fast as possible situations that need a ripping time, training, public education, the rising of confidence between the actors, and the definition of widely consented goals. Often all this leads to consider

groundwater as a too hot and unmanageable issue, a source of conflicts that result in personal loss of prestige, of jobs, or in political troubles. Thus a common reaction is to forget groundwater, leaving it to its own fate and applying only unavoidable policy regulations to apparently comply with what is mandated by law, and to cool down noisy or uncomfortable conflicts raised by the users or by pressure groups. The consequence is fostering large investments for surface water control and interbasin transfers, desalination or treated sewage water reuse, as now happens in Spain. New water managers, often taken from other jobs, who favor exotic and expensive solutions, which are easier to grasp by inexperienced persons lacking a prepared staff or good assessors, currently promote this. Besides, these solutions are politically well marketed and approved by mass media. They are less complex, more docile and more easily subjected to easy-to-enforce centralized decisions. However, often they are not the most appropriate ones from a technical, economic and social point of view, or they imply detracting economic resources from other more needed sectors, or heavy capital borrowing. Under these circumstances conjunctive use is out of consideration since groundwater is neglected or downvalued. This is a new loss of opportunities and of valuable alternatives. Water management decisions should derive from the study of all logical alternatives, weighed with technical, economical, social, environmental and legal considerations, used to support a political decision, but not by pondering on nonexistent or created problems, speculation and opportunism.

Some management agency is needed. It may act by itself, according to the Water Act and its Regulations, may be a consortium of agencies or may act under the agreement of the affected physical and juridical persons (Young, 1992). The country's political system and tradition play an important role in how the management agencies are shaped.

The different interests of the multiple actors can be put together through water districts or associations of water users, under a wide range of forms and control measures. There is a good experience in California, coming from the sixties. In Spain these associations of water users (communities) are included in the Water Act of 1985 as public law entities entitled for water management inside the framework set by the River Basin Water Agency. These organizations are traditional and well established in Spain for surface water, some of them centuries ago, to manage communal and public water works and canals, and to arrange for irrigation shifts and the distribution of available water. For groundwater there are no evident communal water systems – the aquifer is rarely recognized as a common structure – nor the feeling of the need to share available resources, due to the large water storage involved, in spite of the multiple interference effects. To raise the feeling that there is a common aquifer system and recharge, a serious information effort is needed.

The convenience of forming an association of users is unclear at the first stages of exploitation, and when problems appear the actors are often unprepared to understand and recognize that there is a common interest and that yielding some rights and freedom to such an organization produces benefits that exceed the inconveniences. This is a problem of groundwater exploitation, but can be solved through education, good data collection and easy accessibility to users, and the progressive involvement of users in decision-making. This can be anticipated by a responsible Public Water Administration or will come later, after some suffering and losses.

In Spain an association of groundwater users was created in the seventies under the Water Act of 1879. Then groundwater was still a private domain. This was the result of a commonly shared interest in preserving groundwater resources in aquifers dominantly exploited by municipalities and industrial factories. They are more receptive to technical reasoning about the common interest than farmers. The communication between farmers and managers greatly improves if social communicators and agrarian technicians are involved.

Creating new associations of groundwater users appears to be a difficult task in Spain, even if they are now defined in the Water Act of 1985 and administratively needed when an aquifer is

declared overexploited or under risk of salinization. This is presented as a problem for using groundwater. The real problem is that people do not accept something coming from above as mandatory if they do not understand it clearly. Raising a collective conscience, education, trust, information and a share of power needs time and good social communicators. If negative reactions from groundwater users are compounded with the scarce enthusiasm towards these associations from many managers of the Water Authorities the problem becomes practically bogged down, even if groundwater is a public domain. Many managers resist sharing their decision power with outsiders. Things are worsened by the scarcity of studies, patchy monitoring and poor data diffusion means, and the lack of trained personnel to contact, convince, solve problems and educate the groundwater actors. The result is a failure to create associations of users. However, this is only circumstantial and can be solved. The Water Authorities, the universities and other organizations play an important role in advising in supporting, but not in trying to impose what is in the regulations. In fact there is hope for change. Recently a co-ordinating association has been created in Catalonia to reunite efforts, share experience and increase the real management capabilities of existing and future associations of groundwater users in the territory.

It has been said that creating these associations is equivalent to privatization of groundwater management, which is a situation that is fully endorsed by some experts and plainly rejected by others. Really this is not true privatization, but focusing on the problems and benefits of groundwater extractors may easily downgrade general objectives and social goals. Then some external control is always needed and essential, depending on national factors and the ability of the Public Water Administration to play a role that needs skills. Also, the control organization has to be able to supply means for study and specialized monitoring, and to help solving the financial needs.

Other groundwater management problems refer to the availability of technical means for monitoring and studies. They include groundwater level, extraction, recharge and water quality observation, monitoring and control stations and devices, as well as tools to help decision-making, such as calculation methods, from the simple ones up to complex simulation models of the aquifers and the water resources system. If these elements are missing, do not work properly or are insufficient, management errors can be easily made, which add to the perceived aquifer problems.

2.5 Social and cultural problems of groundwater exploitation

Social problems related to groundwater exploitation are mild as compared to what currently happened in large surface water projects, especially at the early stages of construction and exploitation. Since groundwater development follows the pace of regional growth, there is often time to adapt to changes. However, there are cases in which violent reactions appear such as with large groundwater development plans with intensive land use changes from the beginning or when springs and rivers become rapidly dry, due to pumping in the surroundings. Often real or fictitious problems are attributed to the newcomers or to the largest groundwater exploiters. The resulting social unrest makes management more difficult and sometimes there are serious difficulties in co-ordinating efforts. In coastal aquifers well water salinization is a further aspect to be considered. This can cause complaints since it may be a relatively fast process, over a few months or years, even after a delay of decades with respect to the true cause, and if only pan of the exploiters is affected.

Other problems such as groundwater-dependent wetland desiccation, loss of vegetation and

shift of species are not often a serious source of complaints, since changes are slow and may go on unnoticed, especially when other human activities are intense. This does not mean that these are not serious effects or that environmental protection has to be downgraded. This only shows a fact which is progressively reversed as environmental concern, studies and data increase, and as the groundwater role is better understood and the Public Water Administration is responsible for the preservation. This is now included in the Spanish Water Act. Public awareness is important, but some irresponsible managers consider it a groundwater problem. When changes are fast or when local inhabitants and nature preservation organizations are aware of changes and have data to support their claims the reaction can be stiff.

Conflicts like the Tables de Daimiel case are due to unbounded development without a reasonable water plan. In Donana there is the possibility of accommodating urban and agricultural development with reasonable nature preservation, provided all actors agree to compromise, there is fair play and other disturbances are not introduced such as new large developments, with or without water importation from outside. This refers mainly to water quantity aspects. Water quality aspects are still poorly known and they are more difficult to accommodate, but may be dominant in the future.

New problems may appear when groundwater exploitation ceases in some areas. The water table drawdown extraction associated with an intensively exploited aquifer may drain the upper pan of the land, in what were formerly shallow water table areas or even wetlands. If these areas have been later transformed from industrial or agricultural uses into urban sectors, it is not uncommon that basements, cellars, underground parking lots and underground transport ways become inundated or subjected to uplift when the water table goes up. This may produce local unrest, inconveniences and property loss.

Cultural problems are those derived from the traditional use of springs, water mines and wells. Often the water or the site is connected with emotions and tales concerning water quality, properties or benefits from its use. Something linked to local cultures is lost when they become dry due to aquifer exploitation, but it may be often corrected by veiledly introducing water from elsewhere, generally a nearby well. In Barcelona the city network now supplies some of these springs. It is more traumatic when people are not allowed to use the spring or well water because it is contaminated. They try to get the water they consider as having favorable properties, even if it is clearly shown that it is not drinkable.

More important are the problems related to real or assumed groundwater rights based on the continuous use, the fact of living in the territory or being partners of the water winning works. These are also considered groundwater problems. In general the solution is not difficult, but it takes time and some care is needed if lengthy court processes are to be avoided. In some cases quite strong reactions may occur. In the Canary Islands the Regional Government was obliged to call new elections when some right restrictions were introduced into to the Canarian Water Act, a complement of the Spanish one, which takes into account the islands peculiarities.

2.6 Medical problems of groundwater use for drinking water supply

The complex environmental situation that has formed in many developed and developing countries, especially in transitional economy countries, requires the development of a strategy of activity aimed at human health protection in specific hydrological and hydrogeological situation.

The existing international and national water quality standards facilitate the solution of the problems arising in this case. However, economic aspects, associated with the necessity of heavy

capital investments in water protection measures, reconstruction of existing and construction of new water supply systems, improvement of water treatment technologies, selection and use of more safe water sources, make it necessary for local authorities to draw up their own schemes for implementing the targets determined by standards. Substantiation of the relevant decisions requires medical-ecological assessment of the quality of water used in order to establish the role of qualitative and quantitative characteristics of water composition in the deterioration of health of specific population groups. The detection of a specific hazardous pollutant in drinking water with the concentration exceeding the implemented standard is just an indication of its possible influence on the public health. This fact shows that in this situation, the water factor can be among the causes of an elevated incidence of a certain disease. This is a tentative level of indication of cause and effect relationships, however, it determines the direction of necessary studies aimed at more accurate assessment of the water factor effect (Elpiner, 1995).

The focus of this problem is the necessity of the human health risk assessment associated with the environmental quality and, in particular, with the quality of drinking water. The problems arising in this context are due to the lack of reliable data and knowledge necessary for independently assessing the risk factors. The development of the new discipline, ecological epidemiology, is directed towards solving these problems.

Under real conditions there is a necessity to determine the role of each factor and protective (adaptation) human mechanisms in a given ecological situation. Techniques used in modern ecological epidemiology are directed towards these data acquisition. Revealing the differences and similarities of a pathology on a given territory is in the basis of the techniques used in ecological epidemiology. Differences in hypothetical risk factors are also taken into account.

The methods used in ecological-epidemiological studies can be divided into two major groups:

1. Methods of collecting data on the exposure and diseases of individuals;
2. Methods of studying the relationships between the amount of a substance exposed in the environmental sphere under study and the exposure time, on the one hand, and the sick rate at the population level, on the other hand.

Problems with obtaining sufficiently reliable ecological-epidemiological data for vast areas called for the development of methods, which would allow the assessment of public health risk factors by using present-day sanitary-toxicological data as a basis for the establishment of the degree of hazard and the acceptability of different water sources. Thus, two hygienic classifications have been officially adopted in Russia: hazardous substance distribution according to a) classes of hazard and b) character of pollution.

The first one is devided into four classes of hazard:

(a) extremely hazardous; (b) highly hazardous; (c) hazardous; (d) moderately hazardous.

1. Standards for these substances are established in accordance with sanitary-toxicological estimates of their hazard; the Maximum Permissible Concentration (MPC) are of the order of a few hundredth of mg/l and less (e.g., phosphorus, benzo(a)pyrene, some compounds of mercury, tin, and lead);
2. These standards also are established in accordance with sanitary-toxicological estimates of their hazard; the MPC are of the order of hundredths and tenths of mg/l (e.g., thallium, cobalt, tungsten, hydrogen peroxide, some elementorganic, heterocyclic, and halogen-containing substances, the compounds of nitrogen, phosphorus, etc.);
3. In most cases, the relevant standards are based on organoleptic features and the implemented MPC values vary within a wide range from a few mg/l to hundredths mg/l (these are mainly organic substances, e.g., amines and their salts, aliphatic hydrocarbons, and others);

4. The standards are based only on organoleptic features; the MPCs vary within a wide range, though commonly they amount to a few mg/l and several tenths mg/l (europium is an example of inorganic substances in this group; substances of this group can be found in any type of the organic substances under control, e.g., in the group of aliphatic esters and spirits, halogen-substituted thiophosphates, etc.).

Distribution of water bodies in accordance with the character of pollution

Water objects are ranked in accordance with the extent to which the MPCs are exceeded in them (Plitman, 1989). Four degrees of pollution are specified for the substances for which toxicological standards have been established: admissible (concentration close to the MPC), moderate (concentration three times as high as the MPC), high (ten times the MPC), and extremely high (100 times the MPC).

A combination of these two classifications makes it possible to evaluate the degree of discovered level of water source pollution and to see to what extent it may be used for drinking water supply. For example, detection of substances falling under the first and second hazard categories in a water sources with a 'moderate' degree of pollution is likely to produce initial symptoms of intoxication in some part of the population. In case of a high degree of pollution with these substances, the symptoms of intoxication are more pronounced, and pathological effects typical of the discovered substances are at an appropriate stage of development (*On the state …,* 1996). In other cases, the classification is based on the difference between the values of the same health index.

Thus, the methodological basis of the present-day studies into the cause and effect relationships between the population sickness rate and water factor allows productive combining of ecological-epidemiological and experimental-toxicological approaches.

The practical effect of these approaches is illustrated by a wide experience accumulated by Russian and foreign scientists in their studies reviewed in the section dealing with research activity.

Analysis of more than 350 studies of the effect of drinking water quality on the public health published during the last decades reveals a wide range of studies carrying out in many countries. These publications can be divided into three main groups:

1. Studies establishing the presence of hazardous substances in drinking water within a certain area and suggesting the necessity of special-purpose medical/ecological studies;
2. Studies where the fact of water contamination is established and the health risk associated with its consumption is assessed based on the available data on the pathogenic effect of the detected substances (for example, with the help of data that have been used in the substantiation of the standards);
3. Studies applying methods of ecological epidemiology and toxicology to establish the cause and effect relationships between the population sick rate and the peculiarities of drinking water composition.

It is worth mentioning that most publications dealing with the chemical contamination of water belong to the first two groups. As for biological contamination, (either with microbial or parasitogenic nature), in most cases, the relationship between the sick rate and the water factor is established by extensive epidemiological studies.

One should pay attention to the fact that the role of water factor in the spread of infectious diseases primarily reveals itself in the pollution of the first from surface aquifer. Thus, according to the data of Global Consulting for Environmental Health (Moore et al., 1993), most (76%) out of the 34 outbreaks of water-related infections recorded in 1991 and 1992 in 17 states of the United States of America were associated with the use of water from wells for drinking. A total of 17,464 people were affected. In 11 outbreaks, the agent of infection was established, and in 7 cases it was found

to be Lamblia or cryptosporidia, pathogenic protozoan species. One of two other outbreaks was caused by water infection by dysenteric bacteria and the other was due to hepatitis A viruses. It is worth notice that the detection of groundwater infected with cryptosporidia is more and more frequently mentioned in publications.

Water-related outbreaks of intestinal infections associated with the consumption of contaminated groundwater are mentioned in the Russian official sources. However, these are mostly related to either wells or near-shore river infiltration water intakes, immediately depending on the surface water quality. (*On the state …*, 1996).

The most important appears to be the data on relationships between the most widespread and dangerous cancers and consumption of chemically contaminated groundwater. A statistically significant increase in the number of cancer cases in a population group consuming surface water was detected by Kuzma et al. (1977) in Ohio, and Gottlieb et al. (1981) in Louisiana. Similar data were obtained in the studies conducted by Morin et al. (1985) in 473 American cities. The authors note that their results are close to those of earlier works of American, British and Canadian scientists that have dealt with this problem.

However, studies conducted later in United States of America by the National Cancer Institute (Cantor, 1997) show an increased risk of the development of cancer pathology in the population groups consuming groundwater containing elevated concentrations of nitrites, asbestos-containing products, radionuclides, arsenic, and secondary products of water chlorination. At the same time, the authors find no indications to a similar effect of fluorides contained in water. However, Japanese researchers (Tohyama, 1996) established positive correlation between the uterine cancer and the fluoride content of drinking water in 20 areas over the country.

Studies conducted by US researchers in the Argentine confirm the correlation between an increased mortality due to bladder cancer and the presence of inorganic arsenic in drinking water (Hopenhayn-Rich et al., 1996).

The present publications give growing attention to the data on penetration of carcinogens into groundwater due to fuel leakage. American researchers reported about detection of methyl-3-buthyl ether (MTBE) in drinking water. According to Stern et al. (1997), nearly 5% of the US population consume water with high concentrations of this substance (700 to 14,000 ppm).

In the course of their studies of the risk of cancer due to groundwater contamination with MTBE, Dourison and Felter (1997) established that this compound remains toxic when it enters human organism with drinking water. The authors point out that the effect of MTBE on the cancer incidence requires further investigations.

Recent studies of Taiwanese researchers yielded the results that can cause anxiety. In their studies of a possible correlation between the colon cancer and the level of drinking water hardness in municipal water supply systems, they correlated the frequency of deaths of this disease (1,714 cases) with the number of deaths of other diseases (taking into account the hardness of water used by these people) and established a statistically reliable increase in the probability of colon cancer with a decrease in water hardness (Yang and Hung, 1998).

Based on a study conducted in 1997 in 98 cities and towns in Hyogo prefecture, Japanese researchers Sakamoto et al. also came to new conclusions concerning the pathogenic effect of water hardness salts. They established a significant positive correlation between the death rate of cancer of the stomach with the Mg^{2+}/Ca^{2+} ratio in the water of ground sources.

The risk of an increase in the incidence of cancer is associated with detection of carcinogenic organic compounds of anthropogenic origin in subsurface sources. The National Cancer Institute (Allen et al., 1997) draws particular attention to the pesticide contamination of groundwater. The authors suggest a correlation between the increased incidence of breast cancer in Hawaii and the consumption of groundwater containing chemicals such as chlordan, heptachlor, and 1,2-dibrom-3-chloropropane. Studies of Technical University of Denmark (Bro-Rasmussen, 1996) show that a

number of pesticides (DDT, Lindane, dieldrine, and others) can persist in groundwater for a long time. Croatian researchers (Goimerac et al., 1996) detected contamination by the widely used carcinogenic herbicide – atrazine. In a Egyptian region pesticide contamination was detected in groundwater, foodstuffs, soil, on the one hand, and in women's milk, on the other hand (Dogdeim et al. 1996).

Of growing importance in assessing the health risk of groundwater are studies of the effect of a complex of contaminants. Among the recent works in this field we can mark out the study of Young et al. (1995) from the Colorado State University concerning with the improvement of the methods of assessing the health risk of chemical mixtures.

For the past 20 years, experts of some developed countries made attempts to essentially revised the traditional notion of water hardness as an index affecting its organic properties and the suitability for domestic needs. This was called forth by a series of studies aimed at the establishing a correlation between drinking water hardness and the incidence of cardiovascular diseases.

Evidence of the correlation between the coronary disease and the consumption of smooth water (in particular, with Mg deficiency) was obtained also in Finland (Punsar and Karvonen, 1979), Italy (Masironi et al., 1980), Spain (Gimeno-Ortiz et al., 1990), Germany (Sonneborn and Mandelkow, 1981), Russia (Plitman, 1989), the United Kingdom (Lacey and Shaper, 1984), Sweden (Rubenowits et al., 1996), Taiwan (Yang et al., 1996) and the Netherlands (Zielhuis and Haring, 1981).

In assessing the quality of groundwater used for drinking purposes in Russia, the role of anthropogenic pollution also becomes increasingly important.

Aquifers in many regions of the country are characterized by an unusually high content of iron, fluorine, bromine, boron, manganese, strontium and other rated microelements (*On the state…,* 1996). Groundwater pollution with oil products as well as very hazardous substances – dioxins – is found to increase (Lujanchikov, 1996).

In Moscow region groundwater enclosed in carbonaceous rocks has been found to contain an unusually high content (compared with the standard) of stable strontium. With some exceptions, its concentrations in the second and third aquifers from the surface reach 30–40 mg/l (Russia's current state standard of potable water quality sets the maximum permissible concentration of strontium at the level of 7 mg/l).

Researchers now pay special attention to the groundwater quality of recharge-type water intake structures set up on river banks and directly related to both the level and nature of surface water course pollution and the barrier functions of the filtering rocks. For a long time, during a relatively moderate anthropogenic pressure on the surface water bodies, such intakes provided water of a fairly high quality.

Over the last 10 years, information of a different nature has been emerging increasingly. It is associated, above all, with an abrupt increase of anthropogenic pollution of the water bodies.

Toxic substances, that virtually fail to be removed by the existing systems of drinking water treatment, get into surface water courses in large quantities together with inadequately treated (or untreated altogether) sewage of different origin and with the surface runoff from urbanized and agricultural territories.

Over the last decade, a number of comprehensive surveys was carried out in Russia to study the cause-and-effect relationships between somatic (other than infection-induced) disease rate of the population and anthropogenic pollution of drinking water (*On the state …,* 1996; Plitman, 1989; Rachmanin et al., 1996; Semenov et al., 1994, etc.). These studies have made it possible to establish that a higher chronic nephritis and hepatitis sick rate, a higher mortinatality, gestational toxicoses, congenital anomalies of development in children are associated with the use of drinking water polluted with nitrogen-containing and chlororganic compounds (the towns of Kemerovo, Yurga).

Also, a direct relationship has been established between (a) the extremely high disease rate of the digestive and central nervous systems, carcinogenic diseases among the population of certain districts in the Republic of Buryaria and (b) lack of some microelements in drinking water. An in-depth medical survey of the population in Krasnoyarsk Kraj and Amur Oblast has revealed an adverse effect of water deficient in the salts of calcium and magnesium on mineral metabolism and functional state of the central nervous system.

The above mentioned problem about water chlorination by-products having a carcinogenic effect is now topical in Russia.

As applied to the problem of groundwater use for drinking purposes, the emergence of secondary products of water chlorination remains as vital as ever because these are formed as a result of chlorine interaction with natural humic compounds or organic pollution. The former may be discovered in groundwater whose quality is formed under the influence of raised water-logged areas that are likely to occur in recharge-type intakes in connection with river water pollution, especially water polluted with chlorinated organics.

The above-considered data clearly demonstrate the importance of the present-day medicoecological interpretations of hydrochemical data, which have to be taken into account in the assessment of the conditions of drinking water use and in the selection of new groundwater sources.

At the same time, medical ecological studies are expected to provide a reliable basis for the selection of new safe subsurface water sources as well as for the improvement of groundwater protection and water treatment technologies. In other words, they are intended to support efficient water management decisions allowing for human health protection priorities.

3 Modern concepts of groundwater resources of the earth

3.1 The state of knowledge of regional groundwater resources and groundwater discharge investigations

Groundwater runoff (flow, discharge) studies include a major complex of hydrological and hydrogeological problems. The main task herein is the examination of the processes and regularities of groundwater recharge, groundwater flow and interaction with surface water. The problem unites a wide range of issues related to studying the conditions of generation and quantitative assessment of groundwater runoff and resources, its geological activity, it's role in river recharge and the total water balance of regions and sea basins, as well as changes in groundwater resources in the course of human activities, including development of measures for groundwater protection from depletion. The studies of the regularities of the generation and space-time distribution of groundwater runoff and resources are of great importance to water resources research and to the creation of the theory of groundwater management.

Groundwater runoff research began at the end of the last century with predicting river-water availability for navigation during dry periods, when groundwater was considered the only source of river recharge. In the 1920s and 1930s, the groundwater runoff data was used for the solution of some hydrogeological problems and, above all, for estimating natural groundwater resources. In the late 1940s and early 1950s, the first theoretical studies of groundwater-surface water interrelation were carried out. These studies made it possible to elaborate techniques for groundwater assessment with an allowance for groundwater dynamics and a regime for various seasons of the year.

Great contributions to groundwater runoff research has been made by scientists of different countries including: V. G. Glushkov, B.V. Polyakov, F. A. Makarenko, M. I. Lvovich, B. I. Kudelin, C. Theis, W. C. Walton, D. Burdon, J. Margat, G. Castany, J. Toth. In the former USSR, the works of F. A. Makarenko and B. I. Kudelin on groundwater runoff are the leading approaches. These scientists have studied the regime and dynamics of groundwater discharge to rivers depending on the type of hydraulic connection between groundwater and the river. Kudelin has elaborated on the principles of the combined hydrological and hydrogeological methods for the quantitative assessment of groundwater runoff. This method has opened up possibilities for obtaining regional estimates of groundwater resources of large areas and for mapping groundwater runoff.

The present-day methodology for the regional assessment of groundwater runoff allows us to evaluate objectively and economically groundwater runoff and natural resources by analyzing and treating the available hydrological and hydrogeological data without expensive labor-consuming exploration operations. In recent years, the problem of areal mapping of groundwater runoff and resources has been solved both for all the former USSR and its separate regions. This was a valuable addition to existing hydrogeological maps since regional characteristics of the main groundwater runoff parameters were included in the maps.

In 1964–75, various groundwater flow maps of the former USSR on a 1:5 000 000 and 1:2 500 000 scales were compiled for all countries of the former USSR. These maps were the world's first of their kind. They showed the quantitative characteristics of groundwater runoff and natural resources (average annual specific values of groundwater discharge in litre per second per

square kilometer, groundwater runoff precipitation ratios, and ratios of groundwater discharge into rivers relative to total river runoff) and hydrogeological conditions of groundwater recharge.

In subsequent years, more detailed maps of groundwater flow and natural groundwater resources of some large artesian basins were made. These maps showed the principal regional regularities of groundwater generation and distribution under various natural conditions.

In the 1970–80 period, extensive studies on the assessment and mapping of groundwater runoff in the area of Central and Eastern Europe were performed. This project has been realized in keeping with the decision of the National Committees for the IHP of some countries of Europe. The *Groundwater Flow Map of Central and Eastern Europe* on a 1:1 500 000 scale was published in 1983 and the monograph (explanatory notes for the map) *Groundwater Flow of the Area of Central and Eastern Europe* was issued earlier, in 1982. Groundwater discharge values for large regions were obtained, the main features of groundwater runoff and resources generation depending on physiographic, geological and hydrogeological conditions were found, and the space-time distribution of specific groundwater discharge values and ratios were determined.

Without giving the details of the legend on the content of the above maps, which differ appreciably, their common feature is the quantitative characterization of the main aquifers and aquifer systems containing fresh groundwater suitable for public water supply, using average long-term values of groundwater discharge in litres per second per square kilometer, groundwater runoff/precipitation ratios and ratios of groundwater discharge to total river runoff. Some maps show groundwater runoff values in millimeters of a water column for groundwater recharge. Natural conditions and factors governing groundwater generation are also shown on the maps.

Groundwater flow and natural resources maps make it possible, on a quantitative basis, to solve important practical problems of integrated use and protection of water resources over an area. They make it possible to assess: a) groundwater runoff and natural fresh groundwater resources for characterization of water availability in individual regions; b) groundwater discharge to rivers to determine the subsurface component of river runoff (base flow) and to prediction of its possible variation under the effect of groundwater development; c) groundwater recharge values for the regional evaluation of safe yield and making water-resource balances of economic and administrative regions; and d) the amount of groundwater discharge amount as an element of the water balance of the country and its separate regions.

The studies performed have permitted hydrogeologists to find principal regularities of generation and space-time distribution of groundwater runoff and resources under different natural conditions. These regularities are briefly presented in sections 3.3 and 6.2.

Presently, groundwater studies are in developement along the following guidelines.

Regional quantitative assessment of groundwater runoff and resources of large areas

In the former USSR, United States of America, Canada, France and some other countries, successful studies on the improvement of the methodology for the quantitative assessment of natural groundwater resources and groundwater runoff have been carried out and estimates for large regions have been obtained (Kudelin, 1960; Zektser, 1977; Vsevolozhskii, 1983; Zektser, Dzhamalov, 1989; Walton, 1970; Toth, 1972; Glander, 1975; Bodelle and Margat, 1980). Methods of mathematical modelling are widely used in regional quantitative studies of groundwater generation in many countries.

Detailed evaluation and mapping of groundwater runoff of individual artesian basins and regions of economic importance are in progress. Regional assessment of groundwater runoff, revealing the main regularities of groundwater runoff and resources generation, has been made for the majority of large artesian basins in the USSR (*Groundwater Runoff in the Area of the USSR*, 1966; *Groundwater Flow of Area of Central and Eastern Europe*, 1982). Bodelle and Margat (1980) compiled a map of groundwater recharge of France. In their opinion, the average annual recharge

of aquifers, evaluated from the average annual precipitation for the thirty-year period (1946–76), equals groundwater runoff; recharge values of less than 100, 100–200, 200–500 and over 500 mm/yr were distinguished on the groundwater map of France.

Development of principles and methods of evaluation and mapping of groundwater runoff together with hydrogeological surveys on a medium scale is of practical importance. The inclusion of these studies into hydrogeological survies on a 1 : 200 000 scale makes it possible to perform regional quantitative assessment of natural groundwater resources without appreciable expense.

Studying the main regularities of groundwater runoff and resources generation

The results of quantitative estimation of groundwater runoff and resources allow us to pose and solve problems of groundwater generation under different natural conditions on a completely new basis by introducing quantitative data into the analysis. The research, carried out in the former USSR, Bulgaria, France, Spain and some other countries, has found that the principal regional natural laws of groundwater generation and distribution of the main quantitative groundwater discharge characteristics (average annual and minimal discharges in litres per second per square kilometer, groundwater runoff/precipitation and groundwater discharge to river/total river runoff ratios) under different conditions. Studies in recent years found the relationship between groundwater recharge and the natural and climatic zonality. Based on the application of statistical methods and modeling techniques, the effects of such factors as precipitation, evaporation, thickness and composition of the rocks of the vadose zone, erosional dissection of land areas, and water-conducting properties of the main aquifers on groundwater runoff and resources, are being studied. Application of methods of correlation and regression analyses permits examining objectively the influence of natural factors on groundwater generation.

The first studies of this kind showed a close correlation of groundwater runoff with geological and hydrogeological factors. The largest correlation coefficients characterize the relationship between groundwater discharge values and the thickness of the vadose zone or the thickness of overlying rocks. Both of these factors characterize the seepage resistance of rocks at the upper boundary of aquifers and determine recharge conditions. Close co relations between groundwater discharge values and values of transmissivity and hydraulic gradient have been found. The relationship between groundwater runoff, depth of erosional cutting and the density of drainage network, has also been found. All these factors determine the path of groundwater flow and the degree of rock drainage. On the whole, methods of factor analysis are recommended for detailed studies of groundwater runoff and resources generation.

The studies of long-term variability of groundwater runoff as a process of groundwater generation under natural conditions are of great importance. Studying the influence of different natural factors on groundwater runoff and the analysis of its long-term variability allow us to approach prediction of groundwater runoff and resources variation with time and space.

One highly promising direction of research involves studying the mechanism and features of the interrelation of surface and groundwater under different hydrodynamic conditions and the elaboration of direct methods for groundwater runoff assessment, using data from groundwater fluctuations, water balance, field observations and experiments.

Quantitative data on groundwater runoff, characterize natural groundwater resources and is one of the principal components of determining safe yield. Currently, areas with natural groundwater formation are diminishing. The structure of the safe yield of groundwater changes under the effect of large-scale groundwater development, mine drainage, and irrigation. Hydrogeologists face the problem of determining the effect of these factors on the generation of groundwater resources, of developing new techniques and improving existing methods for groundwater discharge and resources evaluation in regions with intensive human impact.

It is appropriate, here, to dwell upon concepts and definitions of terms used in groundwater

runoff research. The authors of this report did not intend to develop a strict system of concepts and definitions in the field of groundwater runoff research. However, they tried to present common and distinctly formatted concepts and definitions of terms which, in their opinion, accurately characterize the process being described.

The concept of groundwater runoff (flow, discharge) is the most general. Groundwater runoff, a component of the hydrological cycle, is understood to be the process of groundwater movement in the zone of complete water saturation of the geologic profile. This process is quantitatively expressed as unit discharge in cubic meters per second, litres per second, or cubic kilometers per year. Groundwater runoff is often considered to be an element of the total water balance of land and a water body, as well as of the groundwater balance of an aquifer or aquifer system.

Two specific groundwater discharge characteristics include areal and linear discharge values. The specific areal groundwater discharge in litres per second per square kilometer is the groundwater flow from a unit area of an aquifer, aquifer system or groundwater basin within which this discharge is generated. The specific linear discharge is expressed in cubic meters per second per kilometer or in litres per second per kilometer. It is discharge per unit width of flow front, e.g. per unit length of a river channel or shore or coastline, where groundwater discharges.

For convenient comparison of values of groundwater discharge with the other components of the total water balance (precipitation and evapotranspiration) and the groundwater balance (recharge and evaporation from the water table), groundwater discharge values may be presented in the form of a water column (in millimeters per year), i.e. the volume of annual groundwater discharge, evenly distributed over the area where this volume is generated.

The values of groundwater discharge, expressed in litres per second per square kilometer or in millimeters of a water column are the principal characteristics, obtained in the regional estimation of groundwater runoff. They are mapped at small or medium scales, which reflects on the non-uniformity of groundwater runoff generation under various natural and artificial conditions.

The groundwater discharge (flow) to rivers or streams from the saturated zone, under the drainage effect of a river system, is called subsurface recharge (feed) of a river or groundwater contribution to river runoff. Specific values of subsurface recharge for a river is the groundwater discharge to a river per square kilometer of drainage area or per linear kilometer of channel length.

Groundwater discharge to a sea or lake is the inflow of groundwater, generated on land, directly to a sea or lake and bypassing the river network. A specific areal groundwater discharge to a sea or lake is the groundwater discharge to a sea or lake per square kilometer of the drainage area of an aquifer. A specific linear groundwater discharge to a sea or lake is the groundwater amount flowing to a water body per kilometer of shoreline.

To define the supply of substances dissolved in groundwater, to rivers, streams, or water bodies, the term 'subsurface discharge of dissolved solids' is used. A specific value of subsurface discharge of dissolved solids is the amount of salts transported to a river or water body by groundwater per square kilometer of drainage area or per kilometer of channel length or shoreline.

Areal and linear groundwater and dissolved solids discharge values allow researchers to compare quantitatively different areas as to their conditions of generation of groundwater and dissolved solids and to find the main regularities of formation and distribution of groundwater and dissolved solids discharge, under different natural conditions.

To assess the contribution of groundwater to the total water balance and total water resources, groundwater runoff/precipitation and groundwater discharge to river/total river runoff ratios are applied. The first ratio is the proportion (commonly expressed in per cent) between the

total groundwater runoff of an area and precipitation falling on this area. The second ratio is the proportion (generally expressed in per cent) between groundwater inflow to a river and the total river runoff (discharge) for the same period.

It should be emphasized that groundwater discharge values, characterizing the natural productivity of aquifers or aquifer systems, are the main indicator of groundwater resources availability in an area. Therefore, it seems advisable to consider the relation between the concept of groundwater runoff (discharge) and natural groundwater resources (recharge). Above all, it is important to select a proper methodology for the evaluation of groundwater resources under various natural conditions (Shestopalov, 1981; Vsevolozhskii et al., 1984; Listengarten, 1984).

Natural groundwater resources are understood to be the total amount of recharge (replenishment) of groundwater under natural conditions as a result of infiltration of precipitation, seepage from rivers and lakes, leakage from overlying and underlying aquifers, and inflow from adjacent areas. This definition has been generally accepted. However, some researchers (e.g. Vsevolozhskii et al., 1984) hold that natural groundwater resources have to include infiltrating irrigation water, seepage losses from channels and reservoirs in addition to natural recharge, i.e. natural groundwater resources represent total replenishment under conditions not disturbed by development. Some other investigators (e.g. Listengarten, 1984) believe that such groundwater resources cannot be called natural since natural conditions are already disturbed by irrigation and canal construction and such groundwater resources characterize the amount of recharge or replenishment of groundwater and represents the principal distinctive feature of groundwater as a renewable useful mineral. A clear distinction, however, needs to be made between a renewable groundwater resource based upon recharge and a non-renewable resource that has been placed in the ground in past geologic time and is not replenished.

The groundwater recharge value minus evaporation is equal to the groundwater discharge value. That is why in many regions, particularly in the humid zone where the value of evaporation from the water table may be ignored, natural groundwater resources are estimated by the groundwater discharge value. However, it should be equally pointed out that groundwater recharge and groundwater discharge (runoff) agreement holds true for average long-term data obtained in the investigation of large territories, e.g. the extension area of an aquifer or aquifer system.

In detailed investigations separate areas, groundwater recharge by infiltration may be found while groundwater discharge may be practically absent. This is the case where evaporation from the water table predominates. On the contrary, groundwater discharge may exist, while groundwater recharge by infiltration is absent. This is the case where thick confining deposits overlie the aquifer and groundwater runoff is of a transitional character. So, it follows that natural groundwater resources may be equated to groundwater discharge (runoff) largely in regional investigations when the evaporation from the water table may be ignored or estimated separately. Based on this assumption, groundwater runoff data are widely used to characterize regional natural groundwater resources.

Studies of the role of groundwater in different geological processes

Groundwater runoff is one of the powerful factors of the redistribution of dissolved solids in the earth's crust; it governs the scale of underground denudation. Groundwater runoff estimates which indicate the quantitative water migration in rocks, are required when studying the processes of heat and mass transfer in the earth's crust. In particular, groundwater runoff data are the basis for evaluating the removal of dissolved solids by groundwater and for estimating the denudation activity of groundwater. The results of the estimation of dissolved solids discharge for individual artesian basins show that the removal of dissolved solids by groundwater runoff is greater than the amount of dissolved solids removed by surface runoff. Under the effect of this

removal, the earth's surface is lowered at a rate of one meter per 120–130 thousand years. This process intensifies appreciably with intensification of groundwater development. Therefore studying the subsurface dissolved solids discharge and its contribution to the total hydrochemical balance of different areas is an important task.

Groundwater runoff data make it possible to quantitatively evaluate groundwater exchange rates and residence time which is of importance in studying water-resources development of regions. The time of one water cycle is estimated to balance regions within which groundwater recharge and discharge are taken into account. The evaluation and mapping of water-exchange rates or residence time for individual balance regions makes it possible to find for large aquifers the general regularities of variation of water-exchange rates which depend on groundwater recharge and discharge conditions and the variability of parameters which determine the amount of groundwater resources.

3.2 Environment and principals of ecological-hydrogeological zoning

In recent years one of the most important problems in hydrogeology is prediction, prevention or minimization of disturbances in natural environments, caused mainly by anthropogenic changes of hydrogeological conditions, including groundwater use. A lot of natural processes occur under active management of water. An opposite effect, caused by anthropogenic impact, will cause changes in the groundwater salt and water balance and can be induced by groundwater level rise and decline. Changes in quality and resources inevitably cause disturbances in the environment, and result not only in complicating human activities but also in considerable loss to national economies. Thus, intensive groundwater pumping, structural drainage and draining amelioration, and decline of ground and confined water levels, affects river runoff interception. It affects navigation, fishing productivity of rivers and water ecosystems on the whole, river water quality, and its ability to dilute the inflowing pollutants. The inflow of aggressive river water into karst aquifers results in karst processes intensification, supported by suffusion (small amounts of leached products) with pumped groundwater.

Groundwater level decline caused by reduction of infiltration recharge and evaporation from its surface, recharge process extension in time, smoothing of seasonal and perennial level fluctuation amplitudes can result in pits and springs drying out, reducing the efficiency of overland ecosystems (parks and forests drying out), changes in vegetation species composition, overdrying of swamps and resulting soil and peat depletion, and the ignition of peat. There is also the possibility of increased seismic activity with water pumping.

Negative consequences in the environment are also connected with groundwater level rise. The reasons for such changes in hydrogeological conditions are the following: irrigation, leakage from channels, water and sewage systems, moisture condensation under buildings, industrial wastes pumping into aquifers, in filtration losses from water reservoirs, ponds, slime reservoirs, street watering and other anthropogenic factors, affecting the increase in groundwater level. Groundwater level rise can also be caused by natural discharge disturbances caused by human activities, connected with barrage construction (embankments, deep foundations and communications), relief planning (filling in gullies), river runoff regulation, etc. All of these situations can appear in area of active groundwater use.

Flooding is the most characteristic disturbance of the natural environment, connected with groundwater level rise. Municipal and agricultural flooding is followed by numerous negative

consequences. The following processes should be singled out: land salinization and swamp creation, decrease in bearing capasity of soils, building deformation and destruction, activization of land, mud flow and subsidence processes, and the interference with the salt, water, temperature and air balance in the soil and root zone. This results in lowering the productivity and harvest of forests and agricultural crops. Excessive water-logging and hydration of soils can disturb their acid and mineral composition, and can result in humus content changes. The effect can cause glaying and meadowing and can decrease heat supply due to heat losses for phase transitions. The effect can interfere with filtration properties and decrease the biological activity of soil micro-organisms. This causes a decrease in soil productivity.

Groundwater table rise in built-up areas causes: cellars to flood, corrosion and aggression of concrete and metal construction, reduced park vegetation, subsidence, soil swelling and shrinkage, a decrease in the strength of engineering-geological soil properties, karst activization, erosion, and a worsening of medical-biological situation. Sewage reservoirs which leak into groundwater not only pollutes, but increases the possibility of illnesses and epidemics. House mold, an increase of malaria, tularemia, leptospirsis, angina, rheumatism, tracheitis, allergy, acute gastric and respiratory diseases are observed in these built-up areas. These diseases mostly affect children.

The third type of hydrogeological disturbance is connected with groundwater quality changes. These changes can be accompanied by water balance changes for instance, as a result of interaction between sea, river and groundwater quality. These changes can exist independently, when groundwater quality is decreasing without essential changes in the groundwater balance of the aquifers. The latter is exemplified by the introduction of toxic chemical fertilizers, acid rains, heat pollution, radionuclides, and hydrocarbons. Groundwater pollution first affects human health. Thus a high content of arsenic in drinking water causes cancer diseases of the skin, mercury causes gastrointestinal, nervous and kidney dysfunction, cadmium causes genetic changes in an organism, lead attacks bone tissues, copper attacks organic tissue, radioactivity causes blood diseases, etc. At the same time, changes in groundwater acidity and free carbon dioxide content can make karst processes active, increase groundwater corrosive activity, intensify subsidence, and decrease soil and ecosystem productivity. Hydrocarbon product leakage can create gas 'caps' in the vadose zone, product lenses on the groundwater surface, and cause odor problems and fires. It goes without saying that prediction and preventive measures against all these negative consequences caused by disturbances of hydrogeological conditions are of great practical value and must be taken into account when planning groundwater use. Prediction methodologies for most of the above-mentioned processes have been evaluated (Kovalevsky, 1996). For some of them (for instance, for flooding or estimation of decreased river runoff due to pumping water, etc.) there are a lot of quantitative models for different types of schematizing natural conditions. Predictions of some other processes can be made only quantitatively or basing on approximate expert quantitative assessments. And finally, using some possible negative processes, primarily of ecological character, one can speak only about a possible trend in developing their changes under disturbed hydrogeological conditions. Nevertheless, such predictions and estimations can help to provide the necessary measures for environment protection and minimization of losses and planning of compensational and alternative solutions.

The above mentioned negative consequences of hydrogeological condition disturbances under different anthropogenic activities can occur both, quickly (for instance, decreased river runoff as a result of water withdrawal, etc.) or slowly after many years (ground surface subsidences, etc.). Therefore, it is important not only to predict these changes but also to systematically assess the ecological-hydrogeological conditions of these areas. The results can be mapped and serve as a basis for regime management, for planning networks and programs of groundwater monitoring connected with the environment, and for working out the recommendations for preventing or decreasing losses caused by these negative consequences. Since these consequences

result from disturbances in hydrogeologic conditions that inevitably affects groundwater balance, land zoning based on the degree of groundwater regime disturbance must serve as a basis for mapping possible consequences in the environment and assessing ecological-hydrogeological conditions of the area. In an area with a natural, slightly and considerably disturbed regime, the areas can be singled out with actual or predicted disturbances of the environment, connected with groundwater. It is important to single out areas with a considerably disturbed groundwater regime with different trends, and within which areas can occur with the above mentioned series of consequences which can cause crisis or even catastrophic states of the environment.

Assessment of slightly disturbed, crisis or catastrophic state of the environment is made by one or a complex of negative processes. Thus, as slightly disturbed, the state can be considered, when some of the above mentioned consequences are only minimal. The territories can be considered slightly disturbed, when negative consequences have not yet occurred, but they can occur due to considerable changes in hydrogeological conditions, that are an element of the environment.

A crisis state of the environment caused by a substantial disturbed groundwater regime can be determined, for instance, by groundwater level rise to critical depths wherein soil salinization or swamping occurs. Other effects include: soil glaying, flooding, an excess of water withdrawal above safe yield or pumping limits, causing their depletion, an excess loss to river runoff as a result of water withdrawal which lowers ecosystem efficiencies and increase in geodynamic processes due to the impact of water pumping.

Catastrophic environmental conditions include; groundwater resources depletion, surface and water ecosystem destruction, lakes drying up, decrease in fish production, land surface subsidence, catastrophic buildings deformations, diseases due to groundwater quality and mildew, desertification, etc.

The character of the processes, which cause crisis and catastrophic conditions, can be mapped using special symbols. Thus, ecological-hydrogeological zoned areas can be identified, basing on the degree and character of groundwater regime disturbances, and the degree and character of environment disturbances caused by corresponding changing hydrogeological condition.

Ecological-hydrogeological maps, depending on the availability and detail of the initial information, can be compiled at different scales ranging from general, regional (200–500,000 and larger). Examples of these map legends are given in Kovalevsky's (1996). Ecological-hydrogeological maps, aimed at groundwater use and protection, should characterize the degree of groundwater susceptibility to pollution (or its vulnerability), depletion, and also environment susceptibility (or its vulnerability) to groundwater exploitation. Depending on the initial information volume, it can be given in one to three independent maps. In addition to objective, concrete or predictive information, it is important in these maps to give an assessment of the acceptability or risk from additional anthropogenic loading on the groundwater and the environment, connected with a further development.

This assessment should consider a complex of factors, which affect the ecological-hydrogeological state and which determine the admissibility for further anthropogenic loading. The assessment should be made in degrees (marks), according to accepted qualitative criteria.

This type of assessment has reference and regulation value and provides for a choice of solution for development or limiting human activities. Similar ecological-hydrogeological maps, will inevitably be among the most important hydrogeological maps.

3.3 Main regularities of fresh groundwater resource generation and distribution

The generation of groundwater flow and groundwater resources occurs under the effect of different natural factors that define conditions and processes of recharge, movement and discharge of groundwater. The effect of some factors (precipitation, evapotranspiration, thickness and composition of the vadose zone that largely determine groundwater recharge conditions) is evident, while the influence of others (endogenic and cosmogenic factors, atmospheric circulation patterns) is not as significant and is more difficult to analyze. The complexity of the effect of various factors on groundwater runoff is explained by the fact that everywhere they act everywhere in combination and differently, depending on changing natural conditions.

The most general regional laws of groundwater resource generation are governed by the effect of climate, geomorphological, geological, structural, and hydrogeological conditions of individual regions. The influence of some factors can be more clearly established by studying in detail conditions of groundwater generation in an individual region.

As pointed out by Walton (1970) and other researchers, the quantity of infiltrating water ranges widely and depends on the permeability and thickness of deposits through which percolation occurs, the difference in head between recharge sources and aquifers, and the extent of the area through which infiltration occurs. The amount of precipitation reaching the saturated zone depends on several factors. Among them the main factors are the nature and thickness of soil and rocks of the vadose zone, topography, vegetation cover, land use, soil moisture content, depth to water, the intensity, duration and seasonal distribution of rainfall, solid or liquid precipitation (snow or rain), meteorological factors, air temperature, moisture content and wind.

The principal factors affecting groundwater runoff and resources may be divided into several groups (Zektser, 1977). The first group includes meteorological factors, which govern the potential for infiltration/recharge of groundwater. These factors include the types and forms of atmospheric circulation which define moisture transfer, precipitation, and evapotranspiration. In some arid regions as well as in some areas of intensive karst development, where surface runoff is removed at high rates, the river discharge value should be considered a factor of groundwater resource generation. The above factors may be grouped with hydrometeorological factors.

The second group includes geological and hydrogeological factors: the thickness and composition of rocks of the vadose zone and aquifer deposits as well as the non-uniform character of the structure of the soils and rocks of the vadose zone. The transmissivity and hydraulic gradient of aquifers, characterize the conditions of groundwater movement.

The third group comprises geomorphological factors: the general nature of topography, erosional dissection of areas, density of the river network, i.e., factors determining the distance from areas of recharge to areas of discharge and the character of the hydraulic connection between ground and surface water, defining, together with factors of the first and second groups, conditions of groundwater recharge and discharge. It is more correct to consider the factors of the second and third groups to be conditions of groundwater runoff and resources generation since they change on the geologic time scale and remain practically constant for study periods.

The fourth group includes cosmogenic factors which characterize the activity of the planets of the solar system and the character of the earth's rotation around the sun its axis. Solar activity is the principal factor controlling changes in the earth's atmospheric circulation and hydrosphere. Among cosmogenic factors influencing the hydrological cycle and, therefore, groundwater runoff are the quantity of sun-spots, expressed by the Wolf number, geomagnetic disturbance index, number of magnetic storms and some others.

The fifth group comprises biogenic factors governing the effect of vegetation cover (forest for the most part) and living organisms on groundwater recharge and storage.

The sixth group includes anthropogenic (man-induced) factors characterizing the impact of human activity on the formation of the groundwater regime.

Cryogenic (permafrost) factors may be distinguished into a separate group because the nature, thickness, and continuity of occurrence of perennially frozen ground define rock permeability and the process of icing which regulates groundwater runoff and resources.

Freeze (1972) points out that groundwater discharge to rivers largely depends on the structural and hydrogeological conditions, transmissivity of the main aquifers of a basin, and characteristics of the soils and rocks of the vadose zone. For some basins with uniform hydrogeological conditions, groundwater discharge to rivers largely depends on the intensity and duration of precipitation, rainfall localities and precedent moistening conditions. In Freeze's opinion, the mechanism of groundwater resource generation and the effect of various natural conditions of drainage basins on groundwater runoff may be quantitatively estimated on the basis of a deterministic mathematical model, involving three-dimensional unsteady groundwater flow in saturated and unsaturated zones and one-dimensional flow in an open channel.

Zektser (1977) used statistical methods of factor analysis for quantitative assessment of the effect of various factors on groundwater natural resources in the Baltic artesian basin. The paired and multiple correlations of groundwater runoff and resource values and various other factors made it possible to find for individual regions and aquifer systems, the major and minor factors, which govern the generation and areal distribution of groundwater resource values. The correlation analysis method was used for establishing the dependence of groundwater runoff on hydrometeorological and cosmogenic factors changing over time. The dependence of groundwater resources on factors, relatively constant for the periods of time under study (geological, hydrogeological and geomorphological factors, normal precipitation and evaporation) was determined by regression analysis, using the method of least squares of the areal distribution of long-term groundwater natural resource values and average factor values.

Regression equations, obtained in this way, may be applied to computations (with a certain error) of groundwater resources values from known factor values as well as to probabilistic prediction of groundwater runoff values from predicted factor values.

These studies resulted in establishing a close relationship between the groundwater discharge of major aquifer systems and geological and hydrogeological factors. As one would expect the largest correlation coefficients (up to 0.8 and larger) characterize the relationship between groundwater natural resources and the thickness of the vadose zone (for uppermost aquifers) or the thickness of the confining strata (for deep aquifers). Both factors are indicators of the permeability of rocks at the upper boundary of aquifers and determine the conditions of their recharge.

Close relationships have been found between groundwater resource values and hydraulic gradient, representing the seepage properties of water-bearing rocks and determining specific groundwater discharge rates. Meaningful values of correlation coefficients (up to 0.7–0.8) were obtained in 11 out of 15 cases.

The thickness and composition of the vadose zone (or those of overlying deposits, if the aquifer is not the uppermost) have a very important effect (in many cases the governing effect) on groundwater natural resource generation conditions and define the amount of infiltration of rainfall into aquifers.

It should be also borne in mind that rainfall infiltration through the vadose zone depends not only on its structure (thickness and lithological composition), but also on the initial moisture content of the soil and rock since vertical permeability is largely determined by moisture content and may range broadly.

Numerous examples may be given for the case where a vadose zone, composed of clayey and loamy semipermeable rocks, appreciably reduces groundwater recharge conditions. Other conditions being equal, this leads to a decrease in groundwater natural resource values (average annual specific discharge values, groundwater runoff coefficients, and baseflow/total river runoff ratios). For instance, in South East Siberia, the decrease in the permeability of rocks in the vadose zone results in a 10-fold decrease in the specific groundwater discharge compared to that of the adjacent area, where rocks of the vadose zone have high permeability.

The role of the vadose zone is particularly evident in regions, where water-bearing rocks having good storage properties are overlain by semipermeable rocks. In these cases, specific groundwater discharge values, other conditions being equal, decrease with an increase in the thickness and area of overlying strata. For this reason, for example, the specific groundwater discharge values within the area of the aquifer of the Ustkutian series in East Siberia range from 5.5 to 1 l/s.km^2.

Everything said above, with respect to the effect of the vadose zone on groundwater runoff, is also applicable to strata overlying aquifers. With an increase in the thickness and area of confining strata and with a decrease in rock permeability, aquifer recharge conditions deteriorate and, consequently, groundwater natural resources decrease. For instance, in the Angara-Lena interfluve area, the specific groundwater discharge values of the main aquifers decrease four times with an increase in the thickness and area of the confining clayey rocks.

The influence of transmissivity and hydraulic gradient on groundwater generation conditions is evident since it is these parameters that define the permeability properties of water-bearing rocks, i.e., the specific and total value of groundwater resources. Numerous facts are known when with an increase in transmissivity (as a result of change in the facial composition of water-enclosing rocks of higher fracturing or karstification of rocks) specific groundwater discharge values increase.

The effect of the lithological composition of water-bearing rocks on groundwater natural resources is evident from studies made in southwestern Massachusetts. There, the specific discharge values of the Great Brook aquifer system, determined from values of groundwater discharge to rivers, may be divided into two groups: 1) those where the fraction of loose fluvioglacial deposits accounts for 15% of the area; here, discharge values are equal to about 1.1 l/s.km^2, and those where the fraction of fluvioglacial deposits is over 50% of the area; here, discharge values amount to 6.6 l/s.km^2.

A similar phenomenon was also observed within the Atlantic lowland in the United States of America. In regions, where aquifers are mainly composed of sands, specific groundwater discharge values are twice as large as in regions, where the percent of sands, composing aquifers, is small (Tarver, 1968).

Streamflow data, published by the US Geological Survey, were used to determine annual groundwater runoff from 109 drainage basins in Minnesota and to define the extent of the effect of geology and some other factors on groundwater resources. Groundwater runoff was determined by streamflow hydrograph separation and analysis of flow-duration curves for stream gaging stations. Estimates were obtained for years with near-, below-, and above-normal precipitation. The studies made it possible to determine the contribution of water-bearing rocks of different origin and permeability to groundwater discharge to streams. Also the studies allow one to characterize the effect of natural factors such as forest cover, wetland, and buried-bedrock valleys on groundwater resources generated within basins where surficial gravel deposits are underlain by permeable bedrock and limited groundwater resources in glaciated areas with lakebed sediments underlain by impermeable bedrock (Walton, 1970).

The presence of buried valleys ambiguously influences groundwater resource generation. Major buried valleys in bedrock, filled with thick permeable sediments, as a rule, increase

groundwater resources. At the same time, thick till deposits with low permeability in buried rocks impede upward vertical groundwater flow to rivers, which only partially cut the upper strata. In a general case, it is evident that upward vertical groundwater flow to rivers is at maximum in a low-water period, when the difference in head between the water table and the piezometric surface of deep confined aquifers is small.

The effect of neotectonic movements, current volcanism and earthquakes, on groundwater generation conditions manifests itself not so distinctly and has been studied poorly until now. Neotectonic movements occur relatively slowly and their influence on groundwater runoff may be revealed only by very long special observations in regions with intensive uplift or subsidence of the earth's crust. Data on the effect of earthquakes and recent volcanism on groundwater resource generation conditions are lacking now. However, there is information indicating the appreciable influence of seismic activity on the groundwater regime. Thus, in some earthquake regions (e.g., in Mongolia, in 1957, and in the Tashkent, in 1971), the change (several times) in discharge of springs, sharp fluctuations in groundwater levels, the appearance of new springs and the disappearance of existing ones, were observed.

The relationship between groundwater natural resources, the depth of erosional down-cutting and river network density, has been established; these factors determine the length of the groundwater flow path and the degree of rock drainage. High and statistically meaningful coefficients of correlation (up to 0.7–0.8) have been obtained approximately in half of all the computation cases.

The topography and erosional ruggedness of terrain are important factors in groundwater generation. Difference in elevations, high uplands and vast depressions are responsible for: a) substantial gradients of precipitation (the so-called orographic precipitation) often over small areas that is particularly relevant to mountains; b) irregular character of rainfall distribution due to the preferential exposure of slopes toward the direction of prevailing moisture-carrying winds; c) different rainfall conditions and different flow gradients on uplands, slopes, and in depressions. The effect of topography, causing an increase (up to certain limits) in precipitation with altitude, leads to an increase in groundwater runoff and resources which is particularly vivid in mountain areas.

The closeness of relation between groundwater runoff values and cosmogenic factors as well as types of atmospheric circulation substantially increases when a time shift is taken into account, though on the whole correlation relations of groundwater runoff and these factors are insignificant. Of the cosmogenic factors, the closest relations between groundwater runoff and the total area of sun-spots have been established (meaningful coefficients of correlation are obtained in 58% of all computations, their values amount to 0.7).

It has been found that groundwater natural resources increase with the occurrence of lakes, swamps, outwash plains, loess deposits, coarse detrital sediments, and permeable bedrock. Groundwater runoff in years with normal precipitation or below it heavily depends on the presence of lakes and swamps. In basins, where lakes and swamps account for 5% of the total area, the groundwater natural resources value is over twice as large as in basins with a smaller number of lakes. However, in years with precipitation above normal a large number of swamps and lakes, has little influence on groundwater runoff (Walton, 1970).

The impact of human activity on conditions of groundwater recharge by rainfall and groundwater resource generation is observed mainly in urbanized areas. This impact consists of the following (Custodio, 1982): deforestation and subsequent soil erosion, changes in vegetation cover, engineering construction and groundwater development, major mining activities that move and remove great quantities of soil and rocks, drainage, soil compaction, and disposal of wastes on land surface, etc.

It should be emphasized that natural and artificial factors have a combined effect on

groundwater runoff. The influence of an individual factor may be lost. The analysis of the relation between fresh groundwater runoff and resources of some regions and various factors must be made on a quantitative basis.

Regional and global estimations of groundwater natural resources permit us to perform quantitative analysis of groundwater resource generation and distribution in different areas. Hydrodynamic methods for computation of lateral flow of groundwater as well as the combined hydrological and hydrogeological methods for regional evaluation of groundwater resources together with the analogy method are the best for this purpose. However insufficient and very poor knowledge of the hydrogeological conditions of some regions appreciably limits and often excludes the use of hydrodynamic methods (due to lack of data of initial flow parameters). At the same time, the hydrodynamic method has been successfully applied to computations of groundwater natural resources in some areas which has made it possible to establish the main behavior of groundwater resource formation and distribution (Zektser and Dzhamalov, 1989).

The distribution of specific values of groundwater natural resources in Asia and nearby islands shows that they are minimal in subarctic regions, gradually increase in the temperate zone, sharply rise in humid subtropics and tropics, and then again decrease in semi-arid and arid regions of the Near East. Consequently, the climatic factor has a major effect on conditions of groundwater resource generation and governs its dependence, (at the continental and global scale), on which general physiographic latitudinal zones.

This general effect, which defines the distribution of groundwater resources, is also influenced by local factors and natural features of areas. This results in appreciable variation of specific groundwater discharge values within a climatic zone. For example, on the coast of the Sea of Okhotsk the groundwater discharge amount does not exceed 2 l/s.km^2. Compared to this value, the modulus groundwater flow on the Kamchatka Peninsula is much larger, equal to 10–11 l/s.km^2. This is explained by heavy precipitation, particularly in the warm period of the year, the mountainous topography, and the high permeability of surficial effusive and terrigenous formations.

Highly favorable conditions for groundwater resource generation have been observed on the Japanese Islands. Monsoons, a combination of latitudinal zones, excessive annual precipitation (up to 200 mm) over evaporation (1,000 mm), wide distribution of permeable surficial formations (coarse gravel, sands, sandstones, effusive rocks) generate high-rate groundwater discharge ranging from 10 to 12 l/s.km^2. Extremely favorable climatic conditions together with the development of karstified carbonate rocks on some islands of Southeastern Asia lead to the formation of very large groundwater discharge rates exceeding 20 l/s.km^2.

In the arid regions of Asia, groundwater is thin unconfined aquifers is mainly lost by evaporation. In these regions the principal portion of highly insignificant groundwater discharge (up to 0.1 l/s.km^2) consists of regional confined water flow in carbonate, sedimentary, and volcanogenic formations of artesian basins.

Similar conditions of groundwater resource distribution exists in many regions of Africa. Minimal groundwater discharge (up to 0.1 l/s.km^2) is characteristic of the coast of the Red Sea, Somali Peninsula, and Western Sahara. Compared to these small values of groundwater discharge, the Gulf of Guinea is noted for highly intensive groundwater flow. The total groundwater discharge from the African continent amounts to 236 km^3/yr, the discharge from the coast of the Gulf of Guinea equals about 170 km^3/yr. This is due to the combination of climatic, physiographic, geological, and hydrogeological conditions which are favorable for groundwater recharge and resource generation.

Particular consideration must be given to the conditions of groundwater discharge to the Mediterranean Sea where submarine groundwater discharge processes are very intense. The Sea is a unique basin because of the number of submarine springs. The island position of the

Mediterranean Sea allows one to compare its submarine groundwater discharge with other water-balance components: precipitation amounts to 980 km^3/yr, river runoff 280 km^3/yr, and submarine groundwater discharge 52 km^3/yr. In other words, the direct groundwater outflow to the sea amounts to 19% of the river runoff that is not observed in other sea basins. Most of the groundwater discharge to the Mediterranean Sea is generated within Europe. This is due to favourable climatic, orographic, geological, and hydrogeological conditions. The annual precipitation often exceeds 1,000 mm. Its maximum is observed in winter, which contributes more groundwater recharge. The mountainous topography of the coasts increases the moisture supply. But the main factor favoring intensive groundwater discharge is broad karst development. Karst cavities and hollows accept rainfall and surface water. The karst spring discharge rates commonly amount to over 10–20 m^3/s. In this regard, the groundwater discharge values sometimes amount to 10–20 l/s.km^2 and larger.

The American continent differs from Eurasia because of greater humidity which results from the effect of extensive intrusion of air masses from the ocean. This explains why groundwater flow and resources in America are larger than those for the other continents. Because of the elongation of the American continent in a meridional direction, the latitudinal zonality in distribution of specific groundwater discharge values is particularly vivid. Climatic and general physiographic conditions govern the potential for groundwater recharge. However, the actual values of groundwater resources depend to a large extent on specific geological, structural, and hydrogeological conditions of drainage basins, seepage and storage properties of water-bearing rocks. The effect of hydrogeological factors leads to zonal values of groundwater flow, which are observed in the Mississippi Lowland (up to 1.6 l/s.km^2), Florida Peninsula in the Unitesd States of America (over 6 l/s.km^2 , and the Guiana Upland (up to 10 l/s.km^2).

In Australia, an arid climate and the domination of flat desert areas, do not contribute to the formation of significant groundwater resources. Groundwater discharge for major areas of the continent commonly ranges from 0.1 to 0.3 l/s.km^2 and seldom amounts to 0.5–1.0 l/s/km^2 (on the Kimberly's Plateau). At the same time, the natural resources of groundwater from the artesian basins of the Great Dividing Range increase up to 1 l/s.km^2 and in individual regions of the Australian Alps are 3 l/s.km^2.

An analysis of the conditions of the generation of groundwater resources within continents shows that global process depend on the complex combination of various natural factors among which the main factors are climate, topography, geological, structural and hydrogeological features. The hydrodynamics of groundwater discharge, seepage and storage properties of the vadose zone and saturated zone have a substantial effect on groundwater flow. All these factors are closely related and define the conditions of recharge, movement and discharge of groundwater in different natural zones. Groundwater discharge depends on the composition of inflow and outflow elements of the water balance of drainage areas which, in turn, are defined by the heat/moisture ratio as the main indicator of the natural physiographic location. In this regard, distribution of specific values of groundwater discharge on a global scale is subjected to latitudinal physiographic zones. The values gradually increase from subarctic regions to the medium-latitude zone, sharply increase in humid subtropics and tropics and decrease in semiarid and arid regions. Local orographic, geological, structural and hydrogeological features of areas complicate this general picture of the distribution of groundwater discharge and resource values and sometimes may cause their appreciable divergence from average values typical of a given latitudinal zone. However, in the zone atypically high or low values of submarine groundwater discharge, caused by the repelling effect of mountains on atmospheric circulation, wide occurrence of karst formations, the drainage influence of river valleys, and other local factors, are confined to local areas and generally do not disturb the general dependence of groundwater resource generation on latitudinal physiographic zones (Dzhamalov et al., 1977).

Principles of areal subdivision of continents, sea basins and large river basins on the basis of conditions of generating groundwater

Hydrogeological areal subdivision requires finding groundwater distribution and generation by systematically mapping areas of fairly hydrogeology. The use of certain features for areal subdivision depends on the scale of mapping, its purpose, and methodology. However, a common requirement involved is an understanding of hydrogeological conditions of an area and the necessity for development of groundwater.

In regional hydrogeological studies, there are two basically different approaches to areal subdivision. Some investigators subdivide unconfined and confined groundwater areas separately. Others proceed from the idea of a single underground hydrosphere, wherein they consider these areas together. At present, the majority of hydrogeologists prefer the second approach because it is founded on the structural and hydrogeological principle of subdivision involving systematization of not only groundwater, but also natural water-bearing reservoirs.

The structural-hydrogeological principle of systematizing hydrogeological regions proceeds, first of all, from the structural-geological principle of delineation, which when applied to basins (reservoirs) of groundwater take into account: the size and structure of a geological body containing groundwater; the composition of rocks determining the character of groundwater; and specific features of groundwater recharge, runoff, and discharge. The other factors (climate, topography, hydrography, etc.) should also be taken into consideration because reservoirs, having a similar geological structure, may be in various climatic zones or have a different geomorphological structure and drainage network, which will determine the position of the groundwater runoff drainage divide. These procedures of areal subdivision primarily depend on the tasks and purposes of hydrogeological investigations (Fidelli, 1980).

The main task of areal hydrogeological subdivision, when compiling groundwater runoff and resources maps, is to distinguish areas, which are sufficiently uniform in the character of groundwater distribution and groundwater generation. Fulfilling this task requires, apart from the structural-geological principle, representation of distinctive features of a geologic medium, and also requires observance of the hydraulic principle of areal subdivision which complies with the hydraulic (hydrodynamic) nature of groundwater resource generation (Fidelli and Karpova, 1976).

Mapping of hydrogeologic regions demands a clear idea of the objectives of areal subdivision and their mutual dependence. When establishing this dependence, drawing boundaries between hydrogeological regions of different taxonomic order becomes the main difficulty in areal subdivision.

Subsequent to the realization of the structural-geological principle of subdivision, boundaries of hydrogeologic regions are drawn in all cases on the basis of the position of boundaries of structural elements of various orders. Consequently, the principal geostructural elements of the earth's plates, crystalline shields and massifs, and mountain-fold areas, determine the main features of groundwater runoff and resource generation and distribution, and may be considered in areal subdivision as groundwater runoff provinces or taxonomic units of the first order (*Groundwater Flow of Area of Central and Eastern Europe,* 1982).

Besides, in hydrogeological areal subdivision, it is importance to represent the relative balance independent of adjacent areas and should be determined by the existence of various base levels and the appropriate direction of groundwater runoff processes. In this case, the main boundaries should be hydrodynamic (hydraulic) drainage divides of groundwater flow of various orders, and the subdivision elements should be groundwater basins, characterized by relative hydraulic and balance independence and a common groundwater runoff base level.

The hydrogeological subdivision scheme of large areas based on the conditions of groundwater generation proceeds from the unity principal of ground and surface waters. Constantly

acting processes acting on the interrelation of surface and groundwater runoff permit the consideration of groundwater basins as a unit with large systems of total runoff generation such as sea basins. This creates a necessary basis for the integrated study of water resources and the total water balance. In keeping with this idea, groundwater runoff provinces should be subdivided into runoff areas, corresponding to sea basins and major drainless lakes. In turn, runoff areas are composed of hydraulically independent groundwater basins, which include artesian basins and massive hydrogeological rock formations.

When studying conditions of the formation and spatial distribution of groundwater runoff and resources in more detail, it is necessary to take into account the history of the development of a groundwater basin distinguished as a geological and tectonic structure. The main features of present topography, erosional ruggedness, and mesoclimatic features are generated, in many respects, by recent tectonic development.

The hydraulic boundaries or drainage divides of groundwater flows are often related to zones of neotectonic highs, i.e. they are of a specific geological character. It is known that the groundwater resources of the upper hydrodynamic zone greatly depends on the orographic features of an area which, other factors being equal, define the rate of groundwater flow and control conditions of groundwater discharge. In this connection, in regional investigations of groundwater runoff and resources, it is advisable to distinguish within groundwater basins the so-called groundwater runoff regions; river basins of different orders, depending on the scale of investigations, are generally classed with this category.

Orographic drainage divides, conditioned by internal structural features, should be considered above all to be groundwater runoff region boundaries. In other words, these regions are groundwater basins of the second order with respect to artesian basins and hydrogeological massifs (Shestopalov, 1981).

The close relation of groundwater runoff and resource regions to river systems makes it possible to consider the pattern of formation of groundwater runoff on the basis of the principle of unity of natural waters and, using water balance proportions, control all specific and absolute groundwater resources values to be estimated.

One of the important criteria for distinguishing hydrogeological basins is groundwater runoff type, depending on the groundwater flow medium structure. There are two different types of groundwater flow media – the stratified type with relatively uniform permeability within a bedding element and the fractured type noted for sharp irregularity of permeability due to irregular development of fracturing in a rock massif. So, it is apparently reasonable to consider two main types of groundwater generation – the stratification type characteristic of the artesian basins of plates, platforms, intermountain areas and the fracture type typical for regions of crystalline schields and massifs. The complicated blocky heterogeneous character of groundwater flow medium structure within mountain-fold areas is frequently responsible for the development of groundwater flow of the above types.

Thus, the principles presented of areal hydrogeological subdivision of continents, sea basins and large river basins are founded on the laws of groundwater runoff and resource generation and, in turn, may be a reliable tool for predicting the distribution of fresh groundwater resource values in keeping with the geological and hydrogeological characteristics of distinguished taxonomic regions.

3.4 Groundwater resources and water quality

Water quality is a term, which expresses the suitability of water for various uses. These uses may be human or ecological. Terms such as ‘safe’, ‘pure’ and ‘polluted’ have been widely used to

describe water quality. More precise descriptions are based on criteria and standards for various types of water use.

Groundwater has long been regarded as the best water resource for all types of use. The stresses on groundwater, both in terms of quality and quantity, are growing rapidly. Over the past two decades there has been a growing worldwide concern about water quality issues and this has lead to an increased emphasis on a better understanding of groundwater contamination and groundwater quality management.

Broadly based scientific advances in the field of water resource quality includes new theoretical and practical concepts on the occurrence of contaminants in the sub-surface. 'Contaminant Hydrogeology' addresses the problems of contamination by nonaqueous phase liquids (NAPLs) and Multiple fluids in general (Dominico and Schwartz, 1998). Contaminant Hydrogeology, examines also the issue of risk assessment as a basic tool for decision making about the management of contaminated sites.

Contaminant transport in groundwater systems is an issue which has received special attention in the past two decades. Contaminant transport is a special application of mass transport in groundwater flow. Thermodynamic concepts are essential for the understanding of mass transfer. The rate at which transfer occurs is kinetic rather than a state of equilibrium and is influenced by the rate of groundwater flow.

During the 1980s and nineties there has been a continued interest in transport processes, which include mass and heat transport in groundwater systems.

Groundwater dissolves solids, liquids and gases in the subsurface. Inorganic constituents in groundwater are classified according to their concentrations as major constituents (greater than 5 mg/l, minor constituents (0.01–10 mg/l) and trace constituents (concentrations less than 0.0l mg/l).

Organic constituents are typically present in groundwater in minor or trace quantities. The natural environment provides the characteristics of groundwater composition. The natural base line should, therefore, be defined to distinguish natural from man-made hydrogeochemical changes. Deficiency or excess in certain trace element such as fluorine, selenium and arsenic, causes health problems, and serious problems in this context were observed in Africa, China and Arabian Peninsula. Deficiency in iodine may also be a major problem in some areas. High salinity is often the main result of natural processes, particularly in arid and semi-arid zones, and is usually the main limitation to potability and use.

Significant geochemical processes that control and modify groundwater contamination comprise solution, volatilization, precipitation, hydrolysis and complexion. Acid-base reactions are also important in groundwater because of their influence on pH. Redox reactions are mediated by microorganisms, acting as catalysts for speeding up what otherwise are extremely slow reactions.

Dissolution more than any other process is responsible for groundwater mineralization. Processes like gas exsolution, volatilization and precipitation remove mass from groundwater. In arid zones salinity is a major problem (Khouri, 1982, 1993). Low recharge and high evaporation result in increased salinity. In Ethiopia and Somalia saline bodies are formed by evaporation of surface and shallow groundwater in extensive flood plains. Saline coastal belts of aquifers extend along significant parts of the coasts of Tanzania, Libya, Egypt and Tunisia. Regional aquifers underlying the Sahara in Algeria, Morocco and Tunisia contain brackish or saline groundwater. Recent or geological deposits of evaporites are a major cause of salinization in arid zones. Sabkhas are typically characterized by the occurrence of saline water bodies, and overexploitation of groundwater could lead to sea water intrusion into coastal aquifers.

Environmental laws and groundwater protection legislation in particular has provided new impetus for the development of contaminant hydrogeology as a principal branch of the science of hydrogeology. Contaminant transport is a special application of mass transport in groundwater.

The simplest case of groundwater contamination is the development of a plume of dissolved constituents without nonaqueous phase liquids (NAPLs). Contamination by NAPLs (oil, gasoline) results in a complex situation because contaminants can migrate as a separate liquid phase, vapor phase and dissolved phase. The introduction of dense nonaqueous phase liquids leads still to a more complicated situation. In this case, contamination can occur as a pure organic liquid and a vapor in the vadose zone, displace water in the saturated zone and accumulate within the pores or on low-permeability layers. However it is worth noting that attenuation processes in the vadose zone can constitute an important barrier to the passage of contaminants to the saturated zone.

Modeling the transport of dissolved constituents provides a powerful tool for evaluating the response of an aquifer system to a contamination event. Quercia (1993) reviewed available models for groundwater flow and contamination migration and proposed a tentative classification. The processes described by these models include fluid flow, mass transport by convection and dispersion and some geochemical processes.

The starting point in modeling is the equations of mass transport. Analytical and numerical approaches have been developed for solving the contaminant transport equations. But due to the complexity of most groundwater flow systems, the solution to the flow and transport problems is generally derived by a numerical treatment of the equations. Numerical approaches could deal easily with the flow and transport parameters as well as complex boundary conditions (Domonico and Schwartz, 1998), thus, it is possible to simulate the complex plume shapes that frequently develop in aquifer systems.

The techniques for solving mass transport equations are varied. The most common techniques are the direct solution techniques. They involve a numerical solution of the advection-dispersion equation, and comprise the well known finite difference (FDM), finite element (FEM) techniques and the method of characteristics (MOC) (Quercia, 1993, Zhang and Schwartz, 1995, Domonico and Schwartz, 1998). A particle tracking model can be used with a numerical flow model to calibrate the flow model, to assist in visualizing flow lines and to integrate the results of the flow model simulations with the analysis of the geochemistry (Parkhurst et al., 1996).

The method of characteristics is a useful approach since it involves the breaking down of the advection-dispersion equation into simpler differential equations that are simpler to solve. The method has been used for the study of salt water intrusion (Pinder and Cooper, 1970), and groundwater contamination (Pinder, 1973). Research is continuing to develop improved approaches for solving mass transport equations.

Although simulation models can be very complex in their formulation, they remain a highly simplified representation of contamination problems in aquifer systems. Difficulties may arise in data collection of certain parameters, but in spite of difficulties encountered in the modeling process, the real benefit lies in their ability to provide development scenarios in a quantified manner which help decision makers in examining management options.

An indicator can represent the pressure on, the state of, or effect on a system. Environmental indicators representing the pressure on the environment are of socio-economic nature. Whereas indicators representing the state of the environment generally have biological, physical or chemical character, and when they represent the impact on the environment they may have either of these characters (Rotmans et al., 1994). An indicator could represent constraints connected to the socio-economic system, such as 'resource per inhabitant' which can be used to classify countries according to their water 'wealth' (Margat et al., 1996).

Forecast analysis has been based on the concept of a water poverty threshold or 'vital minimum' of water resources per inhabitant. A pressure index or 'wear index' defined as the ratio between the sum of restitutions (withdrawals – final water consumption) and the water avail-

ability after consumption (renewable resources – sum of final consumption) depicts the wearing down or degradation of natural water quality.

Thus the wear index or pressure index according to water availability is computed by (Margat, 1996):

$$\frac{R}{Q_t - C} \times 1000$$

R: sum of restitutions, the main sectors are domestic and industrial;
Q_t: renewable water resources. Total runoff;
C: final consumption (annual consumption).

A system of indices (leaching indices) have been developed to predict the potential of a substance to contaminate groundwater. GUS (Groundwater Ubiquity Score) is computed as follows (Pallas, 1995):

$$GUS = \log t_{1/2} (4 - \log K_{OC})$$

$t_{1/2}$: half time of the pesticide in the soil in days

K_{OC} : partition coefficient between organic carbon in soil and water

Threshold values used to classify organic chemicals in this context are:

Leachers:	GUS > 2.8
Non-leachers:	GUS < 1.8
Transition compounds:	B < GUS < 2.8

Primary and secondary indicators of groundwater quality were proposed by W. M. Edmunds (1996). Six indicators are given high priority; they include in addition to water level, two variables CO_2 and pH, measured in the field and five (HCO_3, Cl, NO_3, SO_4 and DOC) measured in the laboratory (Table 3.4.1). Three of these (HCO_3, Cl, NO_3) may be used to study historical trends in the evolution of groundwater quality. Eh and Fe^{2+} were recommended as secondary indicators (Table 3.4.1). Nitrate having high mobility, is a significant pollution indicator. Other components (pesticides, herbicides, fertilizers) could also be used as pollution indicators.

Cl, HCO_3 and DOC (dissolved organic carbon) are mobile indicators. An increase in these three indicators from fermentation of organic matter serve as an early warning of pollutant migration (Edmunds, 1996). The vadose zone has importance for recording environmental change.

Sustainability of groundwater resources has been introduced within the context of the general concept of sustainability to address problems of contamination and depletion of groundwater resources. In the search for effective tools to address the problems of groundwater contamination the concept of vulnerability was introduced in the late 1960s and further developed during the past two decades.

The original concept was concerned with groundwater quality and it was subsequently developed to include the quantitative aspects of vulnerability. Emphasis has been placed on the hydrogeological properties of aquifers. On the basis of a comprehensive review of recent development in this regard, the IAH/IHP joint working group on mapping groundwater vulnerability proposed the following definition: *'Vulnerability is an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts'.*

However, distinction is made between intrinsic vulnerability and specific vulnerability assessed in terms of risk of the groundwater system upon exposure to contaminant loading.

The concept of groundwater vulnerability has gradually evolved from a mere assessment of

Table 3.4.1 General characteristics of major water quality issues on a global scale

Quality issues	*Water bodies mostly concerned*		*Major problem areas*		*Time lag between causes and effects*	*Space scale of issues* [a]
Pathiogenic agents	++ + +	rivers lakes ground waters	++	health	< 1 year	local
Organic pollution	++ + +	rivers lakes ground waters	++	aquatic environment	< 1 year	local
Salinization[b]	++ +	ground waters rivers	++ + +	most uses aquatic environment health	1–10 years	regional
Nitrate pollution	++ +	ground waters rivers	+	health	>10 years	regional
Heavy metals		all water bodies	+ + +	health aquatic environment ocean fluxes	<1 to >10 years	local to global
Pesticides and industrial organics		all water bodies	+ + +	health aquatic environment ocean fluxes	1–10 years	local to global
Acidification [a]	++ +	rivers, lakes ground waters	+ +	aquatic environment health	>10 years	regional
Eutrophication [c]	++ +	lakes rivers	++ + +	aquatic environment most uses ocean fluxes	>10 years	local
Sediment load [d]	+	rivers	++ + +	aquatic environment most uses ocean fluxes	1–10 years	regional
Hydrological modifications [e]	+ + + + +	rivers lakes ground waters	+ + +	aquatic environment most uses	1–10 years	regional

+ + Very important issue on a global scale;
+ Important issue on a global scale.

(a) Including atmospheric transport of pollutants;
(b) Including high fluoride or arsenic contents;
(c) Including river nutrient loads;
(d) Increase or decrease of loads;
(e) Water diversion, damming and over-pumping of aquifers.

Source: UNEP, 1991. EARTHWATCH, Global Environmental Monitoring System. WHO/UNEP Report on Water Quality.

hydrogeological factors to an assessment of the contamination risk placed upon the groundwater system by human activities.

Risk assessment involves an evaluation exposure assessment, toxicity assessment and health-risk assessment. Although risk assessments are used commonly to examine risk of human health the approach can be applied to evaluate 'environmental risk assessment'. The objective is to determine whether the contaminant detected at a particular site has the potential to adversely affect the existing biological community (plants, wildlife…). The USEPA prepared a guideline (1989) which can be used in this respect.

The health impact of a contaminant depends on the dose that the body receives. To determine this dose the intake (E) is multiplied by a factor, 'the bioavailability factor', thus the total dose (TD) of a contaminant is obtained (Dominco and Schwartz, 1998):

$$TD = E_1 . B_1 + E_2 . B_2 + \ldots + E_n . B_n$$

where B_1 is the bioavailability factor (available from medical literature) and TD units (mass/time) is normalized by dividing by the body weight; mg/kg Bw day.
The hazard quotient HQ for the human receptor is assessed by comparing the total daily dose (TD) to reference standards.

$$HQ = \frac{TD}{R_f D}$$

HQ > 1 indicates risk to the receptor.
When thresholds do not exist, as is the case with cancer, even a small dose may have health implications.

In arid zones there are several factors that influence groundwater vulnerability (Khouri, 1989). Due to high temperatures a large portion of organic compounds released at a surface spill might be released to the atmosphere. Higher groundwater and air temperatures may lead to accelerated biochemical processes. Low rates of recharge results in very slow movement of contaminants. The result is a delayed detection (Khouri and Miller, 1994). In this context Margat proposed the term sensitivity to natural impacts instead of vulnerability and he proposed to reserve the latter term for human impact.

Adams and MacDonald (1995) examined the susceptibility of aquifer systems to over-explaintation side effects (aquifer susceptibility) and suggested further development of this concept to produce aquifer susceptibility maps to be used by planners in parallel with aquifer vulnerability maps.

There is a growing recognition of the significance of the quantitative aspects of groundwater vulnerability since it is often difficult to separate the qualitative and quantitative aspects of vulnerability. Overexploitation of an aquifer system, therefore, need not to be expressed only in quantitative terms but also in a changed composition of groundwater (Vrba and Zaporozec, 1994). Vulnerability in terms of quantity is of special importance in arid regions. It would be equally pertinent to consider groundwater vulnerability to desertification and drought since desertification tends to increase runoff and decrease infiltration. However, because of low recharge the main quality problem is likely to be salinization (Khouri, 1993, 1996; Edmund, 1996). These concepts are of particular significance for groundwater protection in semi-arid regions. Groundwater indicators suggested for temperate regions need to be applicable to semi-arid regions.

3.5 Fresh groundwater protection from pollution and depletion; groundwater 'over-exploitation'

It is difficult to define what is intensive exploitation and overexploitation of aquifers since there are many elements involved such as water balance, water quality, economic, environmental, managerial and social elements. A first attempt compares extraction with recharge, considering the natural and artificial variability of these figures. When extraction is less than, but close to aquifer recharge, there is intensive exploitation. It can be sustainable if other issues do not reduce the extraction difference, such as excessive cost of pumping or too much environmental damage.

Overexploitation includes more negative results and often assumes that exploitation is close to or exceeds recharge, although this is not always the case. A large excess of extraction over recharge is also called water mining.

When groundwater extraction exceeds total recharge, it is not possible to attain a stable final situation if pumping is not reduced. In this case, after a period of continuous groundwater extraction that causes the natural aquifer outflow to decrease and finally cease, a period follows in which all the water extracted in excess of the recharge comes from storage (reserves). The physical limit is storage depletion in some areas of the aquifer, which means that pumping cannot take place because of insufficient, saturated thickness or because of low yield of the wells. This implies a reduction of extraction and a trend towards stabilization. However, there are other limits that depend on impairment of extracted groundwater quality such as salinity increase or undesirable chemical changes. Also there is an economic limit when water costs become unaffordable. However, an increased water price may induce reduction of water use due to savings or process changes, making higher water costs affordable. The limit of exploitation may be the failure of the aquifer as a freshwater source. More often however, a progressive reduction of extraction is seen as technical and economic water use efficiency is increased to accommodate to renewable aquifer resources, or because local welfare allows for developing other freshwater resources. This is the case in the area around Tarragona. The final sustainable flow is uninteresting only in arid climates, where recharge is very small, or when the initial pumping is much higher than the recharge, a rare situation, or when water quality is impaired beyond reasonable limits and there is no other water source for dilution. Even in this last situation brackish water desalination may allow the use of part of an aquifer once residual brine disposal problems are solved.

The sometimes long transient period of groundwater extraction in many practical situations, or the slow movement of poor quality water masses, blur the difference between intensive exploitation, in which there is a final equilibrium situation, and strict overexploitation of aquifers. There is in any case a conspicuous use of groundwater reserves. A strict economic analysis shows that often the best water resource strategy is to start the economic development of a region as aquifer exploitation, although other social and political considerations may discourage this. There are clear advantages in starting with limited aquifer overexploitation. This allows the construction of other more expensive water works to attend the water demand generated by this economic development or delays the construction of expensive works, thus improving economic efficiency. The ultraconservationist attitude, often heard, involves extracting from the aquifer only the return (recharge) amounts without using the capital (storage). Beside being physically unfeasible, this approach involves two false propositions. One is that the recharge water will not disappear with the use of the reserves, but will probably increase due to the enlarged extraction area or induced recharge. The other is that using the term 'capital' for a natural resource is a semantic distortion: it is the use of the resource that allows one to convert it into economic or financial capital.

Thus, most researchers consider that groundwater depletion occurs in all cases when its withdrawal is followed by a constant level decline and exceeds groundwater resources recharge. Thus, these specialists identify the notion ' groundwater depletion' with its storage use. As a result, it is recommended to use groundwater in amounts, not exceeding its recharge, in all cases without, any exception.

Some investigators (Bindeman and Yazvin, 1970; Minkin, 1972; Yazvin, 1984) consider that groundwater depletion, is a direct consequence of irrational exploitation and occurs when the amount exceeds a fixed value of its safe yield in the process of groundwater abstraction. Groundwater storage depletion includes numerous cases of groundwater cutoff to rivers, and under mined mineral deposits. Other cases of inefficient groundwater use are also considered as depletion, for instance, potable groundwater use for industrial purposes, when requirements for groundwater quality are not too high.

From a practical viewpoint, it is important to subdivide depletion processes, causing groundwater storage decrease into processes, requiring special measures use. In this situation, it is possible to affirm, that in those cases, when groundwater exploitation is calculated for depletion of storage for a certain time period, despite the fact, that its total volume is decreasing, special measures for groundwater protection from depletion are not needed.

Based on to the above, it is reasonable to single out two notions: 1) groundwater depletion and 2) groundwater safe yield depletion.

All the cases of groundwater storage decrease, caused by prevalence of groundwater consumption over its recharge, should be considered as groundwater depletion. A change of groundwater recharge conditions, as well as groundwater abstraction can also be reasons for groundwater depletion.

Those cases, where the rate of groundwater level decline is higher, than those fixed by calculating its safe yield, should be considered as groundwater safe yield depletion. Most often, these conditions can result from exceeding the volume of groundwater safe yield by its abstraction (this process is also called 'overexploitation' in the hydrogeological literature). The difference between these two notions lies in the fact, that if safe yield depletion requires obligatory measures for its protection (decrease of groundwater withdrawal according to its safe yield volume, artificial groundwater recharge), then under groundwater depletion requiring these measures are needed only in separate cases (for instance, groundwater run off that was abstracted under active mining deposits).

As outlined above, groundwater depletion occurs in all cases, when natural and artificial groundwater discharge exceeds its recharge. Continuous groundwater level decline is a depletion indicator, in unconfined and in confined aquifers.

It should be noted that continuous level decline at a certain well field is not an indicator of groundwater depletion in the whole aquifer. In practice, continuous level decline occurs often enough, during a long time period, despite the fact that the volume of groundwater abstraction is essentially less than the aquifer recharge. This results from the fact that flow of dynamic groundwater to the well fields is caused by a number of hydrogeological and technical factors (aquifer transmissibility, distance from the well fields to recharge areas, discharge profiles, etc.). In this connection the notion of 'groundwater depletion' should be applied only to a closed hydrogeological area (that is, to the area within which a complete discharge of the aquifer water occurs).

Groundwater depletion can result from both natural and artificial factors. Climatic changes which cause the volume of groundwater recharge to change and changes of groundwater discharge level due to developing neotectonic processes, are classified as natural factors. Different human activities, such as the utilization of forests, hydrotechnical projects, direct groundwater abstraction for water supply and irrigation, as well as mining activity are classified as artificial factors.

Groundwater withdrawal and water level decline from special projects are the main reasons for depletion. Exploitation of water well fields and groundwater level decline is followed by groundwater balance changes that results in the formation of depletion areas in the exploited and adjacent aquifers which can result in a change of groundwater flow direction and the transformation of discharge areas into recharge areas. Groundwater exploitation changes not only hydrogeological conditions, that cause depletion, but also affects other components of the environment.

It should be once again noted that groundwater withdrawal for water supply and irrigation is very rational. It is a direct use of this valuable resource, though, in some cases, it causes groundwater depletion. At the same time, serious groundwater depletion occurs under mining areas and within the arid zone.

Safe yield depletion occurs in the following circumstances: 1) under groundwater

withdrawal, exceeding estimated safe yield; 2) under a change of conditions in the areas of water supply and; 3) under inefficient, irrational use of abstracted water. No doubt, that from a practical viewpoint, excessive, over its safe yield volume, groundwater abstraction ('overexploitation') is the most dangerous. This process can quickly cause water level decline during exploitation. In other situations, water withdrawal exceeding safe yield, can result in a considerable reduction in groundwater quality.

Ineffective irrational exploitation of groundwater safe yield plays a negative role in its depletion. This is particularly true for the so-called self-discharging wells, not equipped with regulating devices. The use of potable groundwater for purposes, not connected with drinking and domestic water supply of the population can also be considered as safe yield depletion.

The following main ways of groundwater safe yield protection from depletion should be based upon:

1. Determining groundwater safe yield in hydrogeological regions and separate areas as a limit of their rational exploitation, basing on special hydrogeological investigations;
2. Managing the groundwater exploitation regime, with regard to its interaction with surface water and the complex use of all water resources, basing the data on groundwater safe yield and control for its withdrawel and use;
3. Artificial recharge of groundwater storage in operating well fields and making artificial groundwater storage;
4. Complex groundwater use under drainage of mine areas and protection of areas from groundwater rise;
5. Increased legistative control for groundwater use.

4 Scientific and methodologic principals of the regional assessment of groundwater resources

4.1 Methods for assessing groundwater safe yield

4.1.1 General aspects

According to Chapter 2, volume of groundwater safe yield, is the criterion for its use. In some countries this is understood to be groundwater discharge that is obtained at a certain part of an aquifer, using geologically and economically proven well fields exploitation conditions, water quality, groundwater use, and considering protective measures to nature (Borevsky et al., 1989).

Groundwater safe yield assessment is a combination of hydrogeological predictions, which are made to prove the possibility of groundwater exploitation in combination well fields. In this case, the assessment can be made both for a certain well field and for a large hydrogeological structure or administrative-territorial complex. Regional assessment of groundwater safe yield forms the hydrogeological basis for schemes for the complex use and protection of groundwater resources.

So, the notion of 'groundwater safe yield', as given above, means that assessment consists of determining the possible productivity of the well fields under an assigned water level decline or prediction of level decline under an assigned productivity of the well fields. In this case, the possibility should be proven for groundwater exploitation based on geologically and economically based well fields for a certain time period, provided that water quality is acceptable, and the predicted changes of different components in the environment are within the limits set up.

Based on the above, the assessment of groundwater safe yield includes the following set of estimations:

1. assessment of groundwater safe yield from different formation sources (natural and artificial resources, groundwater storage, etc.);
2. calculation of well field productivity and groundwater level decline;
3. calculation of the interaction with other well impacted fields;
4. prediction of possible groundwater quality changes and determination of the boundaries of well field sanitary protection zones;
5. assessment of geological-hydrogeological changes, including estimation of changes in surface runoff;
6. technical-economical assessment of groundwater use and well field operations.

Depending on the purpose, peculiarities of the planned ground-water use, and the hydrochemical and sanitary situation, different aspects of the list given above can be considered with a different degree of detail while some aspects may be fully excluded. Calculation of the well field productivity is the key element for groundwater safe yield assessment. Calculation of all the other elements is actually dictated by calculating the productivity of well fields and are directly connected with them.

Due to the fact that in most cases a consumer must be supplied with a certain volume of water, the well field calculation involves the dynamic depth level and the corresponding values of drawdown by the end of the exploitation period. The value of admissible drawdown is determined by hydrogeological, ecological and technical-economical factors in every case.

Assessment of groundwater safe yield is made, in most cases, for an unlimited term of exploitation. However, as was indicated in Chapter 2, well field exploitation, rated as groundwater storage depletion during the period assigned in advance, is permitted in specific hydrogeological and social-economical conditions. Usually, this term is long enough (25–50 years) to compensate for investments to search for other water supply sources.

In all cases of groundwater safe yield assessment, the impact should be estimated for a planned well field and single wells in the area under study. Recommendations should be made to arrange the water supply for consumers, when operating well fields and wells, are shut down as a result of over exploiting the well field.

4.1.2 General characteristics of methods for assessing groundwater safe yield

To make hydrogeological predictions, when assessing groundwater safe yield, the following methods should be used: hydrodynamic, hydraulic, balance, hydrogeological analogues and expert estimations (Borevsky et al., 1989; Bindeman and Yazvin, 1970; Yazvin, 1984). A choice of a method for prediction depends on the complexity of hydrogeological conditions, volume of information, water demand, purpose of calculations made and experience in exploitation of operating well fields. When making hydrogeological predictions for separate elements of groundwater safe yield assessment, one of the methods listed can be used as well as their combination. It depends on both the theoretical basis of the methods for prediction and the required reliability and detail of the predictions.

Hydrodynamic methods are based on the solution of differential equations for groundwater filtration. Solution of these equations is made in the form of analytical calculations for simple hydrogeological conditions. In a more general case (including complex conditions), methods of mathematical modelling on computers are used. If analytical solutions are made for heads or level decline in separate points of a water-bearing layer, then modelling is made relative to the level changes within the whole filtration area.

Differential equations for groundwater flow simultaneously consider both resistance to its filtration in the layer and water balance in any infinitely small element of the flow, and when integrating the equations, they are considered in the flow on the whole within the assigned boundaries. Therefore, these equations are simultaneously dynamic and balanced, and the predicted calculation, made by solving these equations under the assigned initial boundary conditions (Borevsky et al., 1989), account for groundwater balance. So, when the initial boundary conditions and parameters in the filtration area are assigned correctly, then provision of safe yield with balanced formation sources are simultaneously considered in predicting groundwater level decline.

The second advantage of hydrodynamic methods in mathematical modelling, is that the complexity of the hydrogeological conditions are not restricted (heterogeneity of filtration and storage properties of water bearing rocks, geometric outline and character of the layer boundary, number of aquifers in a multilayered system, variability of groundwater recharge and discharge conditions, changeability of water withdrawal, etc.).

According to the groundwater flow structure during exploitation, using hydrodynamic methods, predictions of groundwater quality changes can be made.

Some disadvantages of hydrodynamic methods limit their application for estimating groundwater safe yield. This is due to the fact, that the accuracy of the safe yield estimation, depends on the accuracy of determining the initial hydrogeological parameters and the boundary conditions. In natural conditions these characteristics are determined and then considered in a calculated filtration scheme with more or less errors. That is why it is natural that hydrodynamic calculations give approximate results.

To increase the accuracy of calculations by hydrodynamic methods, mathematical modelling methods should be used. In this case, complex conditions of safe yield formulation in a real hydrogeological situation can be considered more completely and thoroughly than in calculations by analytical formulae. Besides, the reliability of the initial calculated filtration scheme can be substantially improved by solving the inverse problems. But in the case of applying mathematical modelling methods, computations are approximate due to insufficient previous information on boundary conditions, filtration and storage properties of water-enclosing rocks, i.e. due to approximation of natural conditions in the model.

As was already mentioned, the use of mathematical modelling methods is reasonable in complex hydrogeological conditions. When hydrogeological conditions are simple, analytical functions accurately enough for most applications.

Hydraulic methods for estimating groundwater safe yield are based on the immediate use of well pumping data or experience in exploiting active well fields. In this case empirical formulae, that are based on the test data, are widely used. Actually, a well field calculation by the hydraulic method is in an extrapolation of the test data by yield curves (graphs for the yield dependency on the level decline) or by graphs of the drawdown dependence on time. Hydraulic methods can also be used for predicting groundwater quality changes if data on the rate of contaminated water front movement and (or) changes in mineralization or separate components content were obtained under natural conditions. The range of possibilities to extrapolate test experiments should always be strictly limited.

The main advantage of using hydraulic methods for well field calculations is that there is no need to calculate hydrogeological parameters and to quantitatively describe boundary and initial conditions. Fixed values of yield and water level decline under test and pumping conditions that generally consider filtration properties of the water enclosing rocks. Resistance to water movement in the well and near it, due to deviations from a linear regime of filtration, are the initial calculated initial characteristics. The advantage of hydraulic methods is the expediency of their broad use for calculating groundwater safe yield in complex hydrogeological conditions, when difficulties appear in designing a calculated hydrogeological scheme, including the schematization of fields for filtration and storage parameters (for instance, in fissured and karstified rocks). Hydraulic methods are also widely used in determining potential discharge of single wells under conditions of guaranteed groundwater recharge.

Hydraulic methods possess some essential disadvantages. First of all, these methods cannot be used for estimating the provision of groundwater safe yield, since empirical dependencies consider groundwater flow balance only under its different components (dynamic resources, storage, and induced groundwater reserves), corresponding to experimental well field under a level decline reached during the experiment. Safe yield in this case is calculated by the joint use of hydraulic and hydrodynamic or balance methods.

Another disadvantage of hydraulic methods is the limited possibilities for extrapolating the test data. This is caused by the fact, that in the process of exploitation, even with a constant withdrawal, and a growing cone of depression, the boundary conditions for groundwater discharge can significantly change when compared with conditions under active pumping. Therefore,

empirical dependence between yield (debit) and level decline or level decline and time under exploitation conditions can differ and are, determined by the test data.

The essence of water balance methods, used for estimating groundwater safe yield, lies in calculating groundwater balance in the area of operating well fields. Well field exploitation yield is formed due to groundwater storage depletion, entrapment of dynamic resources and inflow of induced groundwater resources from additional recharge sources, caused by the formation of a cone of depression (for instance, water filtration from surface water streams and reservoirs).

Water level decline in specific pumping wells cannot be determined with the balance method, but a mean value of water level decline can be estimated in a balance area (input/output) or in a particular balance site at the end of an estimated period of well field exploitation. At the same time, only water balance methods make it possible to obtain safe yield calculated by other methods (for instance, hydrodynamic or hydraulic). This allows us to treat water balance methods as independent in many cases. It is possible to assess the limit of common exploitation potential for groundwater withdrawal at one or other sites using this method. It also can give a qualitative assessment of the reliability of predictions, made by other methods.

Hydrodynamic, hydraulic and water balance methods, considered above, possess their own advantages and disadvantages, as has already been mentioned. Therefore, either one of these methods or all of them, or their different combinations can be used for assessing groundwater safe yield. A choice of the method depends on specific hydrogeological conditions and previous investigations.

Thus, a combination of hydraulic and water balance methods is often used in hydrogeologic conditions, when parameters of the exploited aquifer which are necessary for a hydrodynamic method (due to their considerable variability over the area) are difficult to determine.

Method of hydrogeological analogy is based on transferring one or another aquifer characteristics and other factors of groundwater safe yield formation from more studied sites (analogies) to less studied ones. The method requires data similarity in the two studied areas relative to the characteristics transferred (analogous boundary conditions, hydrogeological cross section, conditions of recharge, regularities in water transmissivity changes, etc). Similarity of compared sites by absolute values for particular factors is not necessary, as their relation can be considered with coefficients or scales of similarity.

The analogy can be complete (integral) or partial. The identity of hydrogeological conditions for the compared areas can be determined by several factors. Determining the value of groundwater safe yield should be observed under complete analogy. Only particular factors are considered under partial analogy. Only data that can be transferred from the site-analogue are used for calculations. The other data, necessary for estimating the reserves, are determined, using other methods. The use of the hydrogeological analogy method is particularly effective if operating well field sites can be used as a site-analog, and the groundwater safe yield module (groundwater discharge, that can be obtained by well fields at 1 km^2 of aquifer) can be used as an analogy indicator.

Many factors used in determining safe yield (aquifer recharge, leakage of water from other aquifers, etc.), affect yield, level decline and water quality under exploitation. These factors are not commonly manifested at a full scale and it is difficult to estimate them by only pump test data or sometimes even by the first period of well development data.

Based on the method of hydrogeological analogies, the following problems can be solved: 1) assessment (or reassessment) of groundwater safe yield in an operating well field, thus determining the possibility to increase or necessity to decrease water withdrawal; 2) identify new areas for exploring and exploiting groundwater; 3) obtaining more reliable data for assessing

groundwater safe yield in newly explored sites, where conditions are analogous to exploited or explored ones.

Method of expert assessments. Groundwater safe yield assessment is a kind of prediction, the reliability of which, necessary to take up a solution, is not high in many cases. It is mainly caused by impossibility to get all the necessary information during exploration, as the most part of this information is not possible 'to measure', it should be estimated. Method of expert assessments is used in science and technology for solving problems when information reliability is not sufficient. Expert assessments, in this case, are probabilistic, based on the ability of a person to give useful information in conditions of uncertainty. Unknown quantitative characteristics of a studied phenomenon (in our case it is potential yield of a well field, level decline, water quality changes, surface runoff decrease, etc.) is considered, in these conditions, as a random value, individually assessed by an expert and concerns the reliability or significance of one or another event. If these assessments are prepared by a group of experts, then it is supposed, that a 'true' value of unknown quantity is within a range of suggested values and that a generalized opinion of an experts' group is more reliable, than the opinion of one specialist.

When using the method of expert assessment, it is necessary to consider not only the value of the assessment, given by one or another expert, but also the subjective peculiarities of an expert making an assessment. Thus, when using the method of expert assessments, it is extremely important to thoroughly form the staff of experts, from individuals who have significant authority in solving a specific problem. Any expert can be given a specific coefficient of significance, determined on the basis of his previous estimations, his experience, qualification, etc.

All the methods mentioned above, except the hydraulic method, can be used both for groundwater safe yield assessment in specific sites and for the regional assessment of groundwater safe yield. The hydraulic method is used only for estimating reserves in separate sites.

A detailed evaluation of the methods used for assessing groundwater safe yield and the peculiarities of their use in different natural and man-made conditions, is given in the work by (Borevsky et al., 1989; Bindeman and Yazvin, 1970; Yazvin, 1984).

4.2 Methods for the quantitative assessment and mapping of groundwater discharge to rivers, lakes and seas

4.2.1 Hydrological and hydrogeological methods for estimating groundwater discharge to rivers

This group of methods is based on the fact that the groundwater discharge (or recharge) of the upper hydrodynamic zone in regions with a constant river network is largely generated under the drainage influence of river systems. The separation of the subsurface component (base flow) of total river runoff allows one to estimate the amount of regional groundwater runoff. This hydrological and hydrogeological approach is based on river runoff hydrograph separation. The river-runoff or streamflow hydrograph is separated into two portions. The first one includes surface runoff (overland flow), interflow (subsurface flow), and channel precipitation. All these components form the so-called direct runoff. Groundwater discharge to streams (base flow, groundwater flow) is considered to be the second portion of the hydrograph.

At present, there is a number of techniques and procedures for hydrograph analysis. The

majority of authors believe that sustained dry-weather streamflow is formed at the expense of groundwater flow (except for rivers with predominant natural or artificial regulation). The necessary condition for separation of sustained dry-weather streamflow is the absence of summer precipitation and winter thaws during the period which exceeds the time of the flood wave passing through the estimated hydrometric section.

The main difference in existing methodologies is found in hydrograph separation during floods (storms). The approaches used may be conditionally divided into three groups: 1) not taking into account the effect of bank storage during flood; 2) reducing the bank storage effect to an insignificant decrease in groundwater discharge to a stream; and 3) admitting cessation of groundwater discharge to a stream under the effect of bank storage. The experience in hydrograph separation points to the necessity to consider specific hydrogeological conditions of interaction of surface water and groundwater, i.e. the extent of their hydraulic connection.

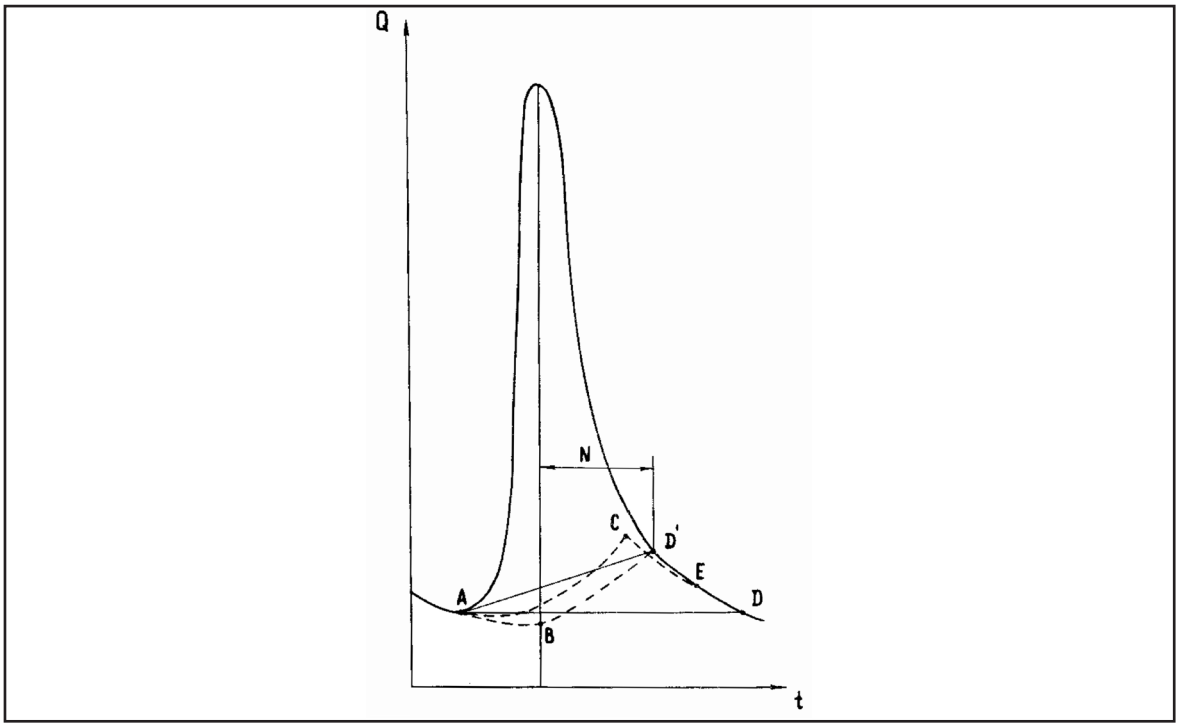
Techniques for total river runoff hydrograph separation, using various constants, which characterize distinctive features of river basins, are discussed in hydrological and hydrogeological literature (Linsley et al., 1949; Chow, 1964; De Wiest, 1965; Freeze and Cherry, 1979).

The simplest of all these methods is river runoff hydrograph separation by the horizontal line AD (Fig. 4.2.1.1). However, this procedure commonly leads to overestimation of flood duration at the expense of subsequent dry-weather flow. Therefore the line AD′ is drawn. The point of intersection of this line with the flood recession curve D′ is obtained by computation of the number of days N from the peak of the flood to its cessation. The N value depends on the distinctive features of the drainage basin (area, slope and roughness), as well as on the amount of precipitation or snow melt. To find the value of N, formula (4.2.1.1)

$$N = (A_d)^{0.2} \qquad (4.2.1.1)$$

is used, in which N is the time in days and A_d is the drainage area in square miles (Linsley et al., 1949; De Wiest, 1965).

Figure 4.2.1.1 Various procedures for river runoff hydrograph separation (after De Wiest, 1965)



The line ABD' has been generally adopted in hydrograph separation (see Fig. 4.2.1.1). The line AB represents an extension of groundwater flow recession existing prior to the storm of thaw to a point under the peak of the flood curve. The line BD' connects point B with the hydrograph point indicating the discharge N days after passing the flood peak.

In the course of hydrograph separation, the groundwater flow depletion curve is extended after the flood. For this, a period should be considered sufficiently long after cessation of any precipitation to justify the assumption that river runoff is generated by groundwater flow exclusively. The depletion curve extended graphically or analytically gives the point of cessation of surface runoff (point E) and the groundwater flow curve ACED (see Fig. 4.2.1.1). For this purpose, an intercept of sustained dry-weather flow, immediately following the flood, is considered. This hydrograph section graphically represents the regime of groundwater flow depletion and it is extended for the flood period to point C, corresponding to the groundwater flow peak. The time of the groundwater flow peak and the shape of the rising limb of the groundwater (line AC) are selected arbitrarily.

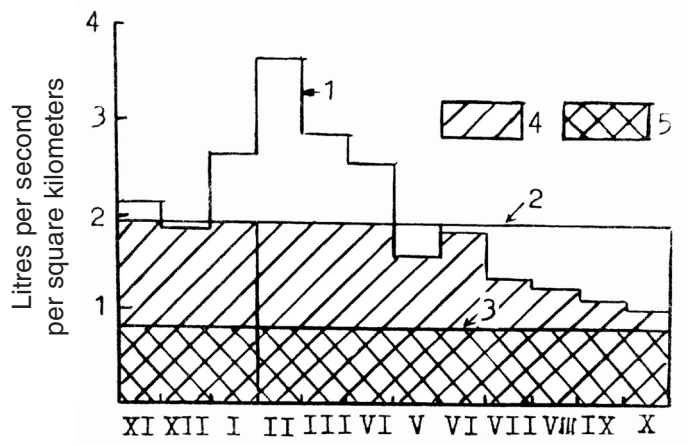
For rivers with a flood regime, the hydrograph separation procedure, suggested by Natermann and Friedrich (Friedrich, 1954; Keller, 1965) is often used. Here, the lower envelope line passing through low hydrograph points (like the line AD in Fig. 4.2.1.1) is the line for separation of surface and groundwater runoff.

A fairly simple procedure for estimating groundwater discharge to rivers, using long-term observation data on minimal river runoff, suggested by W. Wundt, deserves attention (Keller, 1965). The sustained groundwater runoff (artesian flow) is separated from minimal river runoff for a long-term period and unconfined groundwater flow is determined from average minimal monthly river runoff values (Fig. 4.2.1.2)

For more substantiated estimation of the groundwater component of river runoff, Wundt's method may be supplemented by construction of a unit groundwater flow hydrograph (Linsley et al., 1949). Unit hydrographs are widely used in flood runoff routing. However, the complexity of the process of groundwater flow generation in flood periods, its dependence on drainage-basin characteristics as well as on the hydrogeological parameters of water-bearing rocks do not permit the wide use of unit hydrographs. Construction of a unit groundwater flow hydrograph requires labor-consuming detailed study of hydrological and hydrogeological characteristics of a drainage basin.

Based on hydrodynamic methods, Verigin et al. (1977) suggested a computation procedure for flood hydrograph separation, when river discharge prior to flood (q_H) and river discharge

Figure 4.2.1.2 Specific river discharge values as indices of grounwater flow (after W. Wundt in: Keller, 1965)



(1) Average monthly minimal discharge values

(2) Average annual minimal values

(3) Average long-term minimal discharge value

(4) Unconfined groundwater flow

(5) Sustained groundwater (artesian) flow

after flood (q_k) are exclusively provided by groundwater discharge. At first, using the following formula, unconfined groundwater flow during flood peak (q_m) is determined:

$$q_m = q_H - (q_k - q_H)\, M(\xi; \eta) \qquad (4.2.1.2)$$

where $$M(\xi;\eta) = \frac{1}{\beta\sqrt{\eta - 1} - \sqrt{\eta}};\ \xi = \frac{\alpha_1 (2 - \alpha_1)}{1 - \alpha_2^2};\quad \beta = \frac{\xi}{\eta - 1} + 1;\ \alpha_1 = \frac{\Delta C}{h_n + \Delta C};\ \alpha_2 = \frac{h_n}{h_n + \Delta h}$$

$\eta = t_s/t_n$; t_s: flood duration; t_n: duration of rise period; h_n: average thickness of aquifer drained by river; and Δh and ΔC: heights of river stage rise and recession during flood.

For estimating the groundwater flow distribution on a hydrograph, it is sufficient to draw straight lines, connecting discharges q_H and q_k with discharge q_m at flood peak moment. Under the bank storage effect the value of q_m is less than 0. This is pattern b (Fig. 4.2.1.3). If $q_m > 0$, bank storage is not observed at flood, and the hydrograph is separated according to pattern a.

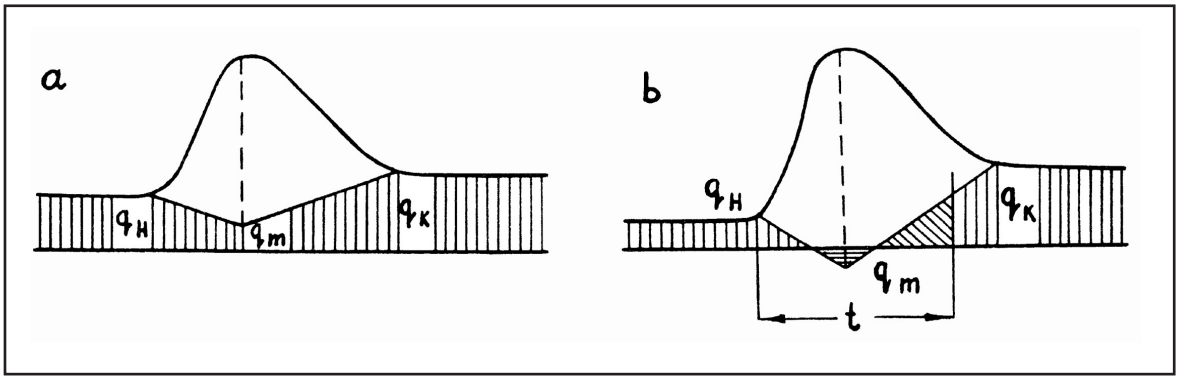
It should be noted that when deriving these equations the proportionality of total and specific groundwater discharge to a river was assumed that is intue of a number of groundwater development areas (particularly in mountain regions) due to the asynchronism of runoff processes and the different nature of the river-water-groundwater interaction in separate river channel stretches.

The above techniques for river runoff hydrograph separation are approximate. Their low accuracy is related to the very formal approach to the complicated natural process of runoff generation in a drainage basin. The errors of these methods are due to the tendency to determine groundwater discharge to streams, using river runoff data, exclusively without proper studying the hydrogeological conditions of the basin. This is their main limitation because hydrometric data do not represent all the complexity of the geological and hydrogeological conditions in a river basin and, what is most important, do not make it possible to give a vigorous scientific validation of hydrograph separation methods that may be done on a hydrogeological basis.

To obtain reliable data of groundwater discharge to rivers, integrated examination of the regimes of surface and groundwater runoff within a drainage basin and validation of the nature and extent of their interaction are required. The studies, performed by a number of specialists, have shown that in a flood period bank storage is responsible for a substantial decrease and sometimes cessation of groundwater discharge to rivers, and this should be taken into consideration in hydrograph separation (Kudelin, 1960; Waltion, 1970; Lvovich, 1974).

In this connection, Russian specialists have elaborated on the integrated hydrological and hydrogeological method for river runoff hydrograph separation that has been successfully used for regional assessment of groundwater runoff of territories in the former USSR and some

Figure 4.2.1.3 River runoff hydrograph (after Verigin et al., 1977)



countries of Central and Eastern Europe (*Map of Groundwater Runoff of the USSR*, 1975; *Groundwater Flow Map of Central and Eastern Europe*, 1983; Kudelin, 1960; Zektser, 1977; Lebedeva, 1972; Dzhamalov, 1973; Vsevolozhskii, 1983; Vsevolozhkii et al., 1977; *Groundwater Flow of Area of Central and Eastern Europe*, 1982; Zektser and Dzhamalov, 1989).

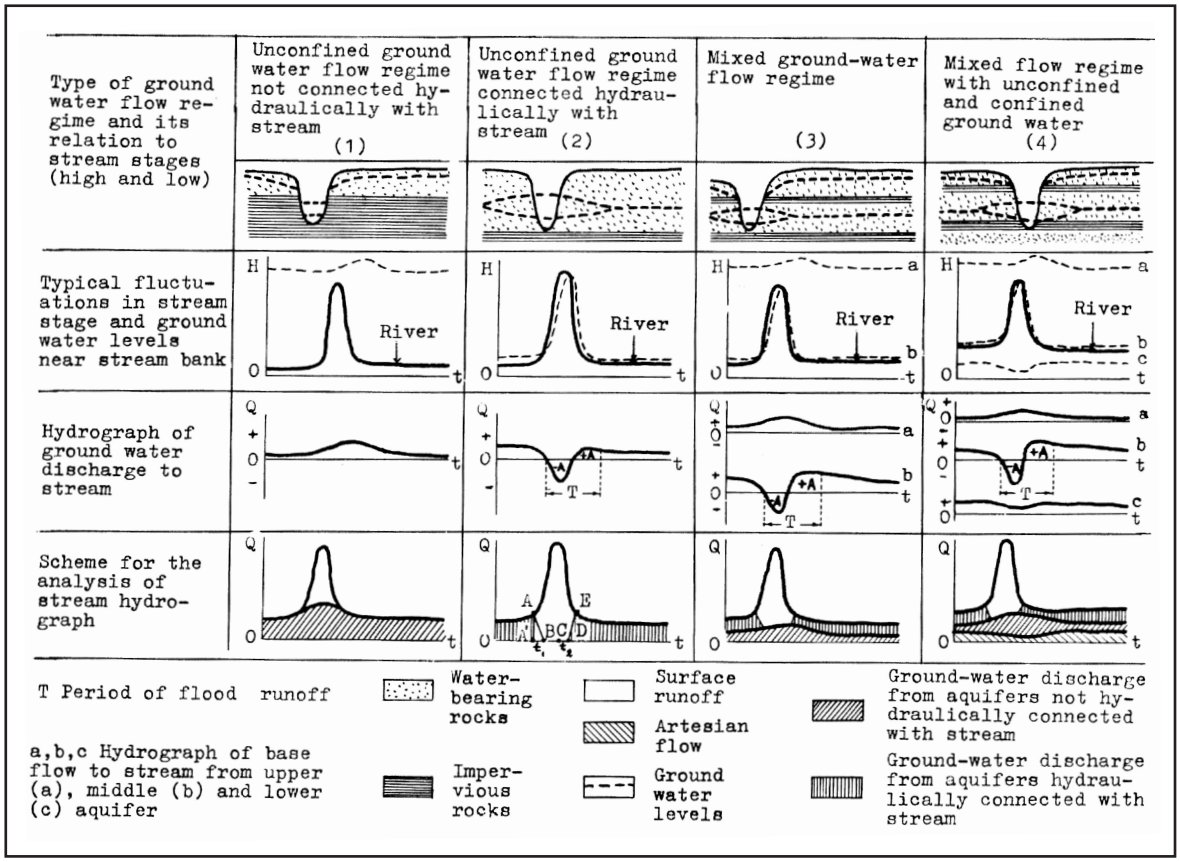
The principal distinctive feature of this method is the account of the nature and extent of the interrelation of surface and groundwaters in a river basin which are determined by accurate examination of the available geological and hydrogeological data. In complex cases, reconnaissance of a river valley is made. Based of literature and field data, typical drainage patterns for various areas of a river basin are drawn up. These patterns represent drained aquifers and their lithological composition as well as groundwater levels and river stages for seasons of the year. The nature of the hydraulic connection of a river with aquifers, depending on the relation of groundwater levels and river stages, governs the regime of groundwater discharge to a river and suggests various patterns of hydrograph analysis, which are discussed below in succession of patterns (1), (2), (3), and (4) in Fig. 4.2.1.4.

The groundwater discharge to a river from aquifers, not connected hydraulically with a river, is evaluated on the basis of survey and study of the dynamics of key springs. In this case, the following formula is used:

$$Q_{gw} = qK_1 + \ldots qK_i + \ldots + qK_n \qquad (4.2.1.3)$$

where q: low-water river discharge; K_1, ..., K_n: monthly coefficients of spring discharge dynamics, which characterize the regime of groundwater discharge to a river and are determined from

Figure 4.2.1.4 Analysis of stream hydrograph separation under different hydrogeological conditions in a stream basin (*Groundwater studies*, 1972; Kudelin, 1960)



observations of the discharge of springs during the year (Makarenko, 1948; Lilich, 1970). However, data of spring discharge dynamics coefficients are unavailable for many poorly studied areas. At the same time, it is known that due to groundwater replenishment by flood a general increase in groundwater runoff with a dynamics coefficient of 1.5–3 is observed toward the end of the flood period. Therefore, Voskresenskii's river hydrograph separation procedure may be applied to poorly studied areas. This procedure takes accounts for a certain rise in groundwater runoff toward the end of the flood period. The comparison of this somewhat modified separation method with more accurate procedures with allowance for the spring dynamics coefficient showed a mere 10–15% discrepancy in the specific groundwater discharge values obtained.

River runoff hydrograph separation with allowance for bank storage is widely used for computation of the discharge of aquifers, which are hydraulically connected with rivers. The methodology consists in separation of the groundwater component of river discharge in spring flood and autumn flood periods, using data on the regime of river discharge and the flood wave lag rate (Fig. 4.2.1.4). In the summer and winter low-water period, groundwater flow is assumed to be equal to river runoff. Groundwater discharge to a river is considered to cease at the rising flood stage (point A). However, groundwater, drained by the river upstream prior to the beginning of flood, continues to pass through the river section. The time t_1, in which this groundwater flow terminates, is determined from the rate of flood wave passing. The groundwater discharge through the section will smoothly decrease along the line AB. The point C corresponds to the end of flood in an upstream section and to the beginning of groundwater flow. The groundwater drained comes to the section earlier than it terminates (point D). In this case, the groundwater flow increase will occur along the line DE (t_2 is the time of the flood-wave lag).

The river runoff hydrograph in the case of a mixed groundwater discharge to a river from aquifers hydraulically connected and not connected with a river is separated in two stages. In the first stage, the groundwater discharge from aquifers hydraulically connected with a river is determined. After this, the discharge of aquifers, not connected hydraulically with a river, is superimposed on the lower part of the hydrograph (Fig. 4.2.1.4).

The separation of a river runoff hydrograph in the case of mixed groundwater discharge to a river from unconfined and confined aquifers presents difficulties. Confined groundwater discharge to a river may be evaluated from the regime of artesian springs. The concealed artesian water discharge through a river channel is determined by analytical calculations or modelling, using additional hydrogeological information.

Total river runoff hydrograph separation techniques are largely used for relatively small river basins, under natural conditions. The estimated area of drainage basins should be limited proceeding from the amount of groundwater drainage and the character of passing flood wave. The analysis of groundwater discharge conditions within the Russian Platform showed that discharge values generally increase with an increase in the river basin area up to about 1,000 km^2. With a greater area, specific groundwater discharge values become stable and do not depend further on the rise in drainage area. However, the upper limit of the estimated drainage area for rivers on plains should be restricted to 50,000 km^2. Within this range, flattening of the flood wave does not happen, otherwise the hydrograph separation would be difficult.

The selection of an estimated drainage area depends on the analysis of the geological, structural and hydrogeological conditions of generating groundwater runoff, which govern the nature of the groundwater-surface-water relationship and the extent of the area drainage.

Data on groundwater runoff within the former USSR show that the plain areas of platforms with the depth of erosional cuts of up to 60 m, are noted for poor groundwater drainage. Therefore typical estimated drainage areas may amount to tens of thousand square kilometers. Shields and mountain-fold areas with erosional depths of 100–150 m and larger are classed with

medium and greatly drained areas where estimated areas of river basins are as small as thousands or even hundreds of square kilometers.

In the case of regulated rivers with long-term observation series, river discharge measurements prior to runoff regulation should be used. In regions where the density of stationary hydrometric stations or duration of observations are insufficient for obtaining groundwater runoff values with the required accuracy, special hydrometric computations are carried out. This results in the evaluation of groundwater runoff in the outlets of small drainage basins distinguished for a homogeneous hydrogeological structure.

The effect of lake storage and swamps in river basins on groundwater runoff conditions should be discussed separately. When estimating groundwater discharge by the stream hydrograph separation method, the influence of regulating lake storage may be ignored if the ratio of lake surface to drainage area is no more than 15%. With larger ratios, the lake storage effect should be excluded by conducting a special hydrometric survey.

The effect of swamps on groundwater runoff dynamics in the low-water period is practically absent. This is due to the fact that the hydrological regime of a stream is influenced only by the upper (up to 60 cm) active layer of upland and lowland swamps, which accumulates and yields water in flood periods. That is why the low-water discharge of swamp drainage basins is generated at the expense of groundwater that should be considered when separating a stream hydrograph.

In some cases, the groundwater runoff value may be determined by calculation of the variation of low-water river discharge in a stretch between two hydrometric stations. The value of river discharge in a stretch without tributaries (or minus the total of tributary discharges), determined in the sustained low-water period, will characterize the groundwater discharge from drained aquifers or the amount of groundwater recharge as a result of intakes of river water. Hydrometric stations should be selected so that the difference in river discharges at the first and second stations exceeds the total value of errors in the river discharge measurements.

Direct hydrometric measurements in river basins have a number of advantages. They make it possible to find the character and extent of the groundwater-surface-water interrelationship in separate river stretches, delineate zones with the effect of special conditions of groundwater runoff (karst, faults, icings, etc.), and evaluate the influence of the natural and artificial regulation of river runoff on groundwater discharge to rivers. The latter seams to be particularly important since hydraulic structures built on rivers appreciably hinder or exclude the possibility of using methods for stream hydrograph separation.

Occasional hydrometric measurements or seasonal surveys have to be performed in a sustained low-water period when the volume of possible flood runoff accounts for a mere 10–15% of the total runoff. Measurements at all temporary gauges should be carried out as quickly as possible to minimize the effect of possible changes in meteorological conditions on runoff.

Selection of sites for hydrometric measurements is made with allowance for the geological and hydrogeological conditions of a river basin. It is desirable that these measurement sites would represent various conditions of the groundwater-surface-water interrelation along the river course, include areas of groundwater recharge and discharge, and characterize the effect of different natural and artificial factors on groundwater discharge to streams.

Occasional measurements in a low-water period provide a rough estimate of minimal groundwater runoff, therefore the ones obtained have to be converted into annual or average long-term ones with allowance for the ultra-annual dynamics of this process. To do this, hydrometric sections with long-term observations should be a part of temporary measurement sites.

Temporary hydrometric sections in a river basin ought to be located to meet demands for measurement accuracy. Measurement errors depend above all on ratios of drainage areas to discharges in temporary sections. Even if it is assumed that measurement errors do not exceed 5%,

then with a ratio of two adjacent watersheds ranging from 0.5 to 0.9 the possible discharge difference errors may increase from 15% to 95%. In the case of a 1.1–50 times increase in the ratio of discharges in neighboring sections, measurement errors can decrease from over 100% to 5%.

The reliability and unambiguity of interpretation of occasional river runoff measurements are substantially greater, if the discharge measurements are made together with groundwater observations and hydrochemical and isotopic determinations of natural waters.

Hydrochemical and isotope methods for estimating groundwater discharge to a river have been developed and applied (Zektser, 1977; Freeze and Cherry, 1979; Valdes, 1985). These methods are based on a comparison of the total dissolved solids content of surface, ground and river waters (or concentrations of some ions or isotopes) in various seasons of the year. Hydrochemical processes, which occur in the course of groundwater discharge to a river, are usually not considered when applying these methods and that makes the calculations somewhat conventional.

The method is based on using two main equations:

$$CQ = C_gQ_g + C'_gQ'_g + C_aQ_a + C_sQ_s \qquad (4.2.1.4)$$

$$Q = Q_g + Q'_g + Q_a + Q_s \qquad (4.2.1.5)$$

where C, C_g, C'_g, C_a and C_s are values of total dissolved solids content or concentration of an ion (isotope) of river water, groundwater from aquifers not connected hydraulically with a river, groundwater from aquifers hydraulically connected with a river, artesian water, and surface (overland) water, respectively; Q, Q_g, Q'_g, Q_a and Q_s are values of total river runoff, groundwater discharge from aquifers not connected hydraulically with a river, groundwater discharge from aquifers hydraulically connected with a river, artesian water discharge, and surface (overland) flow, respectively.

The above equations allow us to derive formulas for determining total groundwater runoff (Q_{gw})

$$Q_{gw} = Q\frac{C - C_S}{C_{gw} - C_S} \qquad (4.2.1.6)$$

as well as for any aquifer discharging to a river.

Groundwater discharge to rivers may be also evaluated by comparison of the electrical conductance in ground, river and surface (overland) waters because this parameter is generally a characteristic of water salinity (Kunkle, 1965; Visocky, 1970). When applying the hydrochemical method, one should use conservative ions, which do not enter into chemical reactions with river water and, therefore, do not change their concentration.

In river hydrograph separation, it is essential that data for the period of observations of natural runoff in the estimated section, be used. If the observation period is fairly long (over 20 years), an average long-term groundwater discharge value may be determined and sometimes an estimation of normal annual groundwater runoff may be approached. In this case, all the available hydrometric data are utilized. This is a rather labour-consuming approach.

In Lvovich's opinion (Lvovich, 1986), when computing average long-term values of groundwater runoff, it is sufficient to use data for four years: one dry year, one wet year, and two intermediate years. Intermediate years should be selected not only on the basis of an average annual discharge value, but also should be typical of intra-annual runoff distribution. Dry and wet years have to correspond approximately to years with a 75–85% and 20–25% probability (Lvovich, 1974).

4.2.2 Analytical calculations and modelling for estimating regional groundwater discharge

Analytical calculations and modelling are used to estimate groundwater runoff (recharge) under complicated hydrogeological conditions and when approximate estimates are required. For example, the hydrogeodynamic method is principally used in quantitative evaluation of submarine groundwater discharge.

Flow-net construction and Darcy's equation are widely used in studying and estimating groundwater runoff. Potentiometric surface and transmissibility maps are constructed for each aquifer. Total groundwater flow is determined from Darcy's relationship using streamlines.

Under complicated hydrogeological conditions when the available data for characterizing groundwater flow conditions are sufficient, various methods of calculation and modelling are used for assessment of groundwater discharge. The method of estimating the relationship of aquifers in artesian basins (which allows one, with a known areal distribution of heads and transmissivities, to obtain in each point the horizontal and vertical components of groundwater runoff (Zektser et al., 1984)) is the most applicable to these calculations.

Where aquifers occur in a stage-like manner (in the majority of cases), the process of steady-state flow may be described fairly accurately by differential equations in partial derivatives with the following boundary conditions:

$$\frac{\partial}{\partial x}\left(T_0 \frac{\partial H_0}{\partial y}\right) + \frac{\partial}{\partial y}\left(T_0 \frac{\partial H_0}{\partial y}\right) + C_1 (H_1 - H_0) + W = 0$$

$$\frac{\partial}{\partial x}\left(T_1 \frac{\partial H_1}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_1 \frac{\partial H_1}{\partial y}\right) + C_1 (H_0 - H_1) + C_2 (H_2 - H_1) = 0 \qquad (4.2.2.1)$$

$$H_i\big|_{\Gamma 1i} = f_i\big|_{\Gamma 1i}; T_i \frac{\partial H_i}{\partial n_i}\bigg|_{\Gamma 2i} = q_i ; i = 0, 1, ..., n; x,$$

where H_i: head in i-th aquifer below land surface, in m; T_i: transmissibility of i-th aquifer, in m^2/day; W: rate of recharge (discharge) of groundwater through the water table, in m/day; Q: rate of recharge (discharge) through the bottom of the last estimated aquifer, in m/day; C_1: coefficient of leakage through semiconfining layer, in day^{-1}; f_i and q_i: known coordinate functions; Γ1i and Γ2i: boundaries of I and II kinds for i-th aquifer; D: lateral seepage area.

The coefficient of leakage through confining clay layers (C) is the most difficult to determine parameter in this system. The leakage coefficient is directly proportional to the coefficient of permeability of semiconfining rocks (perpendicular to their bedding) and is inversely proportional to their total thickness.

To solve the system of equations (4.2.2.1) for C one should have data on the distribution over the flow domain of head values, transmissivity, and recharge (discharge) through the upper, lower and lateral boundaries of the aquifer system. Determination of the C coefficient is an inverse groundwater flow problem. At the same time, these methods are classed with direct methods for solution of inverse problems since the C coefficient is defined directly from the system of equations (4.2.2.1) without using additional information. Such a statement is recognized as incorrect. The solution obtained may be unstable because small errors in the determination of initial data lead to large errors in the solution. In this case, the error in determining the head of the aquifer being estimated affects more appreciably the solution results as compared to the possible error involved when adopting transmissivity values. The cause of possible errors in determination

of the leakage coefficient consists of calculating the derivative of the experimental function H_i (x,y). This procedure is surely incorrect.

To obtain a stable solution, one should smooth the fields of head and transmissivity distribution. In a general case for estimating errors, the distribution of the main initial parameters of the flow domain, which is to be estimated, should be in the form of functional relationships. However, the determination of the polynomial, (which describes with sufficient accuracy the variation of parameters over the flow domain), involves certain difficulties. Smoothing fields of initial parameters occurs to a certain extent in the interpolation of the parameter data.

In addition, when adopting parameters in a discrete form, one should seek the least net step, i.e., for closing the division of the flow domain where the functions H_i (x,y) and T_i (x,y) are definitely not monotonic (large flow gradients, sharp change in the lithological composition of enclosing rocks or their thickness). In this connection, the scale of the division of the flow domain should be selected in accordance with the density of distribution of the experimental points (wells) with initial information. This should also take into consideration the analysis of the most complicated areas presented on groundwater flow maps.

The description of groundwater runoff within drainage basins in total river runoff generation models is of great practical importance (Kuchment et al., 1983; Freeze, 1972). There are approaches which suggest the combined use and solution of differential equations for moisture transfer, groundwater flow, and water movement in a river channel (e.g., the Saint-Venant equation). Another approach is based on the application of the unsaturated-saturated flow equation that reduces the number of equations used.

Let us discuss the unsaturated-saturated flow equation (Khublaryan et al., 1987).

$$\frac{\partial\theta}{\partial\psi}\frac{\partial\psi}{\partial t}=\frac{\partial}{\partial y}(K\frac{\partial\psi}{\partial y})+\frac{\partial}{\partial z}(K\frac{\partial\psi}{\partial z})+\frac{\partial K}{\partial\psi}\frac{\partial\psi}{\partial z}+F(\theta, y, z, t) \qquad (4.2.2.2)$$

where

t: time; θ: volumetric moisture of soil; ψ: pressure head; K: coefficient of moisture transfer; F: source or sink.

The boundary conditions for equation (4.2.2.2) are:

on the soil surface and on the confining layer

$$\frac{\partial\psi}{\partial z}=-1+\mu,\ 0\le Y\le Y_1,\ z=z_c;\ \frac{\partial\psi}{\partial z}=-1,\ 0\le Y\le Y_2,\ z=0 \qquad (4.2.2.3)$$

on the left boundary of the flow domain

$$\frac{\partial\psi}{\partial Y}=0,\ Y=0,\ 0\le z\le z_c \qquad (4.2.2.4)$$

on the right boundary of the flow domain in the unsaturated zone

$$\frac{\partial\psi}{\partial Y}=0,\ Y=Y_1,\ HD\le z\le z_c \qquad (4.2.2.5)$$

in the saturated zone above the level of open flow

$$\psi=0,\ Y=Y_1,\ H\le z\le H_D \qquad (4.2.2.6)$$

below the level of open flow

$$\psi=H_W-z,\ Y=Y_1,\ z_1\le z\le H_W \qquad (4.2.2.7)$$

under open flow

$$\frac{\partial\psi}{\partial Y}=0,\ Y=Y_2,\ 0\le z\le z_1 \qquad (4.2.2.8)$$

Here, μ: evaporation (precipitation); H_W: flow depth; H_D: depression curve level.

The method for modelling groundwater runoff using recharge/discharge relationship equations deserves attention. The recharge of unconfined groundwater from the unsaturated zone and subsequent groundwater discharge to a stream is treated as water flow from one reservoir to another. A total of three parameters define the model: effective drainage area, the recharge/discharge relationship for unsaturated storage and that for saturated storage. The values of these parameters are determined from the analysis of topographic and hydrogeological maps, groundwater regime data, and meteorological and hydrometric information. The method is noted for its simplicity. It may be recommended to computate stream recharge by unconfined aquifers, which are characterized by short-term recharge of storage and subsequent depletion.

Groundwater discharge calculations using the groundwater regime and water balance observation data

Various methods for determining recharge of groundwater by infiltration, using the groundwater regime and water balance observation data, have been elaborated.

If fairly long observations of groundwater level fluctuations under natural conditions have been made, groundwater recharge may be evaluated by processing and analysis of these data. The groundwater recharge value is estimated for individual wells with an average annual amplitude of water-level fluctuations (for a long-term period) with allowance for the type of the groundwater regime and the value of the saturation deficit of the water yield. Water yield or saturation deficit values are calculated from the results of pump tests or are taken from literature sources, which appreciably lowers the accuracy of determining infiltration recharge values.

The method for determining infiltration recharge of groundwater, based on the study of moisture transfer in the vadose zone, has been widely applied. Moisture movement is described according to the Darcy-Clute law

$$U_Z = K\left(\frac{\partial\psi}{\partial z} - 1\right) = -D\frac{\partial\theta}{\partial z} - 1 \qquad (4.2.2.9)$$

where

Ψ: suction pressure value; θ: volumetric moisture content; $D = K(\delta\Psi/\delta\theta)$: coefficient of hydraulic conductivity; K: moisture transfer coefficient that substantially depends on soil moisture content and may be related to it through a dependence of a power character.

$$K = K_0\left(\frac{\theta - \theta_0}{\theta_m - \theta_0}\right)n \qquad (4.2.2.10)$$

where

θ: current water content of rock; θ_m: total moisture capacity; θ_n: maximum molecular moisture capacity.

Equation (4.2.2.10) may be directly used for determining the groundwater recharge rate for deep groundwater and steady-state moisture transfer in the vadose zone. In the case of unsteady-state moisture transfer and shallow groundwater levels (that influences the moisture regime in the zone of aeration), numerical or simulation modelling is used. It consists of the solution of the differential equation for moisture transfer:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial Q}{\partial z}\right) + \frac{\partial K}{\partial z} \qquad (4.2.2.11)$$

This equation is directly related to equation (4.2.2.2).

Where the water table is close to the vadose zone, it is necessary to consider both the equations for moisture transfer in the vadose zone and for groundwater flow. One may consider equation (4.2.2.11) alone for all the flow domain on the condition that for the zone of saturation the coefficient of moisture transfer is replaced by the coefficient of permeability.

Lysimeters have been used for over 200 years for studying the infiltration recharge and evapotranspiration losses of groundwater. In some researcher's opinion, storage lysimeters with sustaining natural groundwater levels are the best for determination of groundwater recharge to obtain groundwater discharge (runoff) estimates.

In these studies, regional subdivision of the area under investigation according to groundwater discharge generation conditions should be made preliminarily for more substantiated interpolation and extrapolation of point data on groundwater recharge. Within distinguished regions, it is advisable to estimate groundwater recharge in key areas whose natural conditions represent all geological, hydrogeological and physiographic characteristics of a given region. These studies should involve measurements of groundwater discharge and water balance at observation stations with appropriate instrumentation (Fig. 4.2.2.1).

Infiltration recharge values allow us to determine groundwater discharge only in the case of simple hydrogeological conditions, where infiltration is the only source of groundwater recharge. Under more complicated conditions where, in addition to infiltration recharge, evaporation and leakage from underlying aquifers and lateral inflow or outflow occur determination of infiltration recharge should be included in the program of monitoring groundwater runoff.

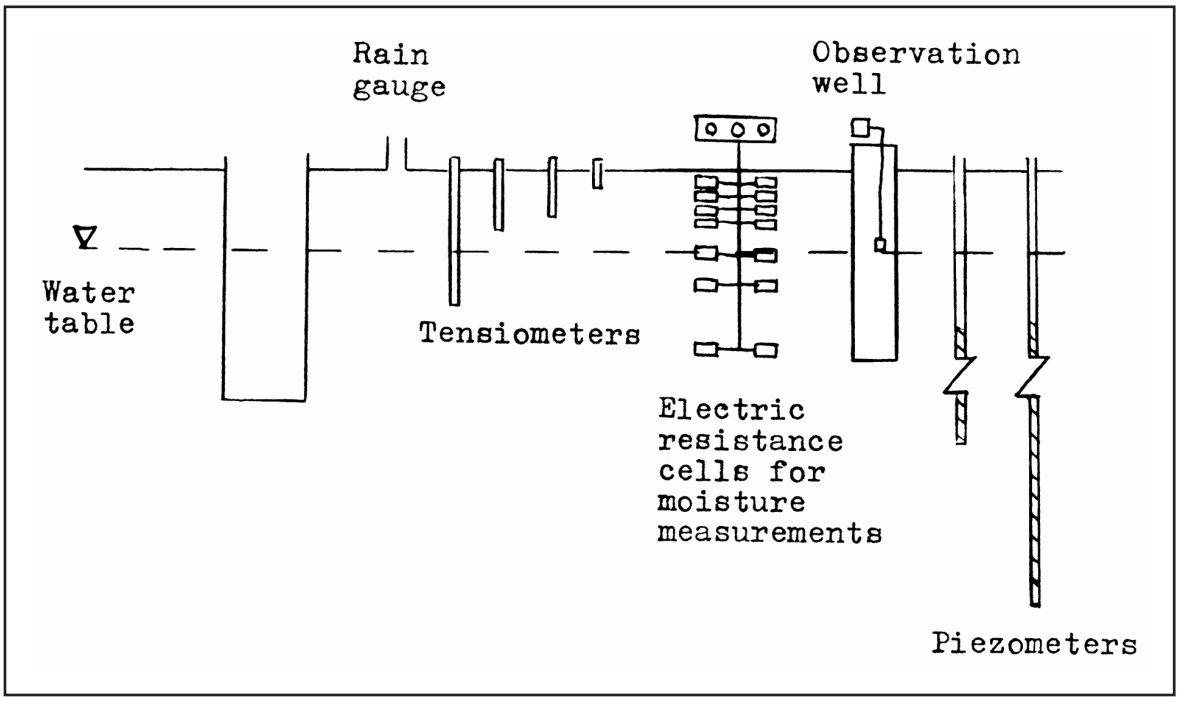
The discharge of deep aquifers, located below the zone of drainage by a local river network, may be evaluated by derivation and solution of equations for the long-term water balance of a river basin or a portion of a basin.

To do this first requires the structural and hydrogeological analysis of a territory for delineation of areas with predominant groundwater recharge or discharge. Then, the regions separated are divided into balance areas, corresponding to river basins or parts of basins. The value of deep groundwater flow for a long-term period is estimated from the equation:

$$\pm W = P_o - R_o - E_o \qquad (4.2.2.12)$$

where W: long-term (normal annual) value of recharge (discharge) of aquifers; P_o: normal precipitation; R_o: normal river runoff; E_o: normal evaporation.

Fig 4.2.2.1 Diagram of a groundwater balance observation station (after W. Wundt in Keller, 1965)



The main requirement of this method to estimate the infiltration recharge of deep groundwater is the determination of all the principal terms of the water balance equation (P_o, R_o, E_o) by independent methods. It is essential that the value of W is larger than the total error in computation of the other components of the water balance. In view of the low accuracy of determination of the principal components of the water balance (precipitation and evapotranspiration, in particular) the possibility of application of this method is limited.

In regions with a regime of groundwater and surface water, heavily disturbed by human activities, the use of the above methods of estimating groundwater runoff is complicated.

The natural groundwater regime may be disturbed on a regional scale, first of all, as a result of hydraulic dam construction, reclamation measures, large-scale groundwater development and all other types of human activities. If river runoff is regulated, base flow is evaluated from data, collected prior to dam construction, and the hydrometric data of the low-water discharge in natural runoff areas. In regions with intensive irrigation and drainage operations, groundwater recharge may be evaluated using data of special observations, involving direct determination of infiltration, evapotranspiration, and specific groundwater discharge.

It is well known that substantial perturbations of the natural regime of groundwater runoff occur in the zone of development of large cones of depression where processes of infiltration, leakage, and river runoff depletion are active.

However, in the case of steady withdrawal of groundwater and the absence of appreciable influence of groundwater resources, groundwater recharge may be evaluated using the method elaborated for regional estimation of the natural groundwater resources of North German Lowland (Zieschang, 1977). This method is based on the application of empirical ratios of groundwater discharges (in litres per second per square kilometer) to annual precipitation for regions with various types of vadose zone structure and water-bearing rocks. A diagram is constructed based on the analysis of data on the regime of groundwater withdrawal areas, located under various geological and hydrogeological conditions, and infiltration values, obtained from lysimeters. This diagram makes it possible to determine groundwater recharge on a regional scale, proceeding from the knowledge of geological and hydrogeological conditions and annual precipitation within the area under study. This method seems to be fairly conventional and may lead to substantial errors. Therefore, it should be supplemented and controlled by existing hydrodynamic techniques.

4.2.3 Remote-sensing methods for groundwater discharge research

The application of remote-sensing methods to regional hydrogeological investigations permits the study of large territories, the collection of diverse information and allows repeated examination of different areas. These methods based on land size, factorial, and dynamic integration of the earth's image, make it possible to find the relationship between various components of the geosphere, trace the latter in time and space, and reveal different natural phenomena while using stable direct and indirect indicators.

Among the problems of hydrogeological interpretation of satellite photographs and images for regional evaluation and mapping of groundwater runoff, of particular importance are the delineation of groundwater recharge and discharge sites. This reveals the nature and degree of groundwater-surface-water interrelation, types of groundwater flow media and tectonic structure features.

In this connection, outer space photography and television imagery in the visible and near infrared wavelength bands from 0.4 to 1.1 μ are of particular interest. Using spectral differences in reflection of sunlight by the earth's surface elements, it is possible to identify reliably various natural formations. Studies have shown that the structural plan of large areas, if closely connected

with topographic features, maybe most reliably interpreted on images in the 0.6–0.7 μ range. Faults, individual blocks, geological boundaries, deformation and dissection of geological structures are clearly seen on images in the 0.8–1.1 μ range. Therefore, the combined consideration of images in these ranges is recommended for hydrogeological interpretation. In detecting smaller hydrogeological events, processes, and phenomena, particular attention should be given to such direct and indirect interpretation features as groundwater discharge sites, rock lithology, vegetation cover, etc. Water features are most frequently detected in the 0.8–1.1 μ range, loose Quaternary formations in the 0.5–0.6 μ range, and their genetic forms and structural features of basement rocks in the 0.6–0.7 μ range. For delineation of plant communities and specifying their phenological condition one should compare images in the 0.6–0.7 and 0.8–1.1 μ ranges. Plots of melting snow and ice are identified in the 0.8–1.1 μ range, while moist areas are distinguished by a relatively dark phototone and retain its optical contrast in all the ranges of the spectral region from 0.4–1.1 μ (Dzhamalov et al., 1974, 1983).

Revealing interpretation conditions and finding their indicator role as to groundwater runoff generation conditions are based on the analysis of the pattern of the image of a territory under investigation as a single geosystem with interrelated processes and events.

At the first stage, direct, indirect, and complex conditions, which do occur incidentally and form regular combinations in various natural territorial complexes, are revealed. These conditions are correlated with available materials (different general and special maps), and thus become refined.

At the final stage, all the data obtained are combined and presented in the form of hydrogeological maps and diagrams. On these maps and diagrams, morphostructural units stipulated by geological and structural conditions of the area are singled out and the relations between geological and geomorphological elements and different conditions showing groundwater generation conditions are found. These conditions, above all, include medium and small elements of topography, typical vegetation and its density, lithological and facial characteristics of surficial deposits, bedrock outcrops, groundwater outlets and their location, direction of tectonic disturbances, the extent of rock fracturing, and surface manifestations of different natural events and processes (karst, landslides, solonchaks, takyrs, icings, taliks, swampings, etc.).

The above data allow the interpreter to delineate within the area under study, groundwater regions with areas of recharge and discharge, to evaluate the influence of different factors on the processes of groundwater generation, movement, and discharge and to make a preliminary judgment, on the basis of known natural relations, about the regional qualitative and quantitative characteristics of groundwater runoff (Dzhamalov et al., 1983).

Studying the geological structure in the course of hydrogeological interpretation has to be aimed, above all, at revealing potentially water-bearing deposits (limestones, gravels, conglomerates, sands and other rocks) as well as finding the occurrence, fissuring and general weathering of rocks. Distinguishing the above lithological varieties and approximate determination of their thickness and physical conditions permit preliminary quantitative estimates of their permeability and storage, i.e. allow us to make some judgment about groundwater runoff and groundwater storage. The foundation for obtaining preliminary estimates may be the use of relationships between the composition and the origin of the deposits.

Therefore, singling out various geological-genetic and facial complexes often permits prediction of their composition. In doing so, one should remember that regular spatial changes in lithological varieties and respective changes in their permeability are characteristic of the sedimentary cover of any region.

Calculations show that groundwater runoff values change as a result of gradual changes in the water-conducting properties of geological media from areas of ablation to the center of hydrogeological structures. The latter permit not only tracing the qualitative changes of water-

conducting properties of a medium but also obtaining the quantitative characteristics of these properties at substantial distances from the main areas of ablation. The range of changes in groundwater runoff may amount to 1–2 orders of magnitude.

The study of topographic features makes it possible to judge the composition and genesis of geological formations. Undulated talus fans are composed of loose alluvial and proluvial sediments; dunes in arid regions are composed of eolian sands; river valleys and buried valleys are filled with loose alluvial deposits, etc. So, topographic features give an indication of the seepage and storage properties of geological formations via the composition of the rocks from which they are composed.

Vegetation is an important indicator of groundwater flow media. At present, a great number of individual plants and plant associations, confined to definite rock types, have been found. Vegetation distribution may fairly accurately indicate the position of faults and fractures. Groundwater discharge sites are often confined to faults and thus may be detected from the character of vegetative cover.

The structure or pattern of the drainage network, its density, degree of uniformity, orientation, angles of tributaries attachment, and bending or angularity of river channels give reliable information about the structure of the geological medium and its water-conducting properties.

The drainage network density is closely related to specific surface runoff discharge and the latter, in turn, depends on such factors as climate, topography, vegetation and the permeability of surficial deposits. It may be supposed that within some climatic zones a fairly close correlation between the composition of deposits and the drainage network density may be observed.

Proceeding from the above, the results of interpretation of aerial photographs and satellite images makes it possible to delineate regions where metamorphogenic, magmatogenic or lithogenic-fracture types of groundwater flow media occur as well as regions with a thick cover of loose sedimentary rocks (the sedimentogenic-pore type of groundwater medium).

The identification of a groundwater flow medium type (or the composition of deposits), boundaries of rock occurrence and rock thickness allows the investigator to roughly determine rock permeability and storage, i.e. to obtain approximate values of groundwater discharge and resources. Additional information required include data on precipitation in the region and known approximate values of infiltration into the rocks identified.

Remote-sensing techniques are being increasingly used for assessment of groundwater discharge to streams on the basis of a systems approach to the analysis of the drainage network structure. Some researchers have found the relation between the drainage network structure, distinctly revealed when interpreting aerial photographs or satellite images, and normal annual and minimal surface water discharge values. In view of the fact that base flow is provided by aquifer drainage such characteristics as drainage area, channel length and density are used as indicators of groundwater discharge to streams. Types of groundwater flow media and the tectonic structure of the area under study are taken into consideration in this case (Antipov et al., 1981).

In a number of basins in Western Siberia where the drainage area ranges from 350 to 65,400 km^2, the close relationship of groundwater discharge to data on ruggedness of topography (the value of the structural and informative measure of a river system, H) have been found. Studies showed that the coefficient of correlation for some streams amounted to 0.9 (Trofimova, 1986).

The problem of quantification of groundwater discharge to streams of poorly studied regions is very complicated due to the effect of dome factors and requires further examination. The solution of this problem may be approached by using the relationship

$$Q = f(H) \qquad (4.2.3.1)$$

where

Q: mean water quantity delivered by a river system for a certain period of time; H: structural measure taking into account the diversity of correlations of the apex of the graph (root) of river systems. This relationship may be applied to hydrological computations, if observation data are unavailable or lacking. If structural information is available for the graph of a river system, runoff may be determined at any point of the system (Linsley et al., 1949; Ivanov, 1987).

When studying the interrelationship between ground and surface waters, using remote-sensing data, particular attention should be given to interpretation of lineaments, often representing faults, which generally define the hydrogeological conditions of large areas. A complicated pattern of tectonic disruptions in an area of broad surface occurrence of crystalline rocks is indicative of the high fracturing and complex block structure of these rocks, appreciably influencing the drainage network configuration, and conditions of groundwater recharge, discharge, generation, and movement.

The interpretation of aerial photographs and satellite images together with land surface investigations make it possible to reveal the hydrogeological role of faults and zones of high fracturing. Investigations have shown that specific groundwater discharge values in fault zones were an order of magnitude greater than those values in other areas. The comparison of groundwater discharge values of adjacent drainage basins having similar landscape and geological conditions indicated that the presence of a high fractured zone in a basin may increase the groundwater discharge value by 15 times.

Visible remote-sensing techniques, described above, are improved by infrared imagery. Infrared survey permits obtaining images of the thermal emission of the earth's surface. The use of infrared imagery gives valuable information on the hydrogeological situation in a region. Because of the difference in the surface temperature of natural objects, thermography enables the investigators to delineate the distribution of shallow aquifers, groundwater outflow to the land surface, and pin-point water leakage from canals (Kruck et al., 1975; Nellis, 1982).

Infrared imagery is also successfully applied to studying subaqueous discharge of groundwater on sea shelfs and in lakes. Since the temperature of groundwater differs from that of surface and sea waters, groundwater outflow at sea or lake bottom on infrared images is seen as feather-like plumes.

Thermography allows one to delineate areas were groundwater may be developed, to make a preliminary qualitative and quantitative evaluation of discharging groundwater, to improve hydrogeological maps of coastal regions, and to organize special marine hydrogeological investigations (Gandino and Tonelli, 1983). Infrared imagery also helps in the location of areas with hydrothermal activity. Thermal springs and geysers as well as shallow thermal water circulation areas are clearly seen on images as light and gray patches. High-yield thermal springs are traced by white spots.

Another remote-sensing method, applied to studying groundwater discharge and its effect on natural processes and events, is the use of equipment recording radiation in microwave and VHF (very high frequency) bands. Microwave radiometry, based on detecting the microwave radiation of matter, makes it possible to record the minute changes in soil or rock temperature. It has been found experimentally that if soil moisture content is over 20% the linear decrease in radiation temperature with an increase in soil moisture is observed. The penetration ability of microwaves may amount to some meters and this permits detection of ground water by colder anomalies and by a characteristic polarization contrast at different depths.

VHF radiolocation surveys, an active technique since it involves radiowave emittance, may cover large areas, and record the distinctive features of topography and tectonic activity, which are of use in hydrogeological studies (Carver et al., 1982).

Each separate type of satellite survey gives specific, but often limited and insufficiently

reliable information about the geological and hydrogeological conditions of an area under investigation. Therefore, only combined application of remote-sensing techniques in various spectrum bands will allow researchers to obtain regular, diverse, and comparable information about hydrogeological objects, events and processes. Remote-sensing data make it possible to carry out monitoring of groundwater as a component of the environment.

4.2.4 Methods for mapping groundwater runoff in large regions

A groundwater runoff map is a special thematic hydrogeological map whose main content is information on the distribution of one or several quantitative characteristics of groundwater runoff and geological and hydrogeological conditions which generate groundwater.

When developing small and medium-scale maps of groundwater runoff, distinguishing aquifers is a severe problem. Therefore it is necessary to distinguish principal aquifer systems and groundwater flow media-types of rocks with common groundwater generation condition and spatial distribution of water-conducting properties (Vsevolozhskii, 1983).

A groundwater flow medium type is determined by the genesis of water-enclosing rocks or the genetic type of the open space (pore, fracture, karst and other media). A groundwater flow medium subtype is determined by processes (generating conditions) controlling the character and extent of the non-uniformity of medium permeability.

Distinguishing groundwater flow media makes it possible for various hydrogeological maps not only to simplify the stratigraphic basis in geologically complicated regions, but also to consider the genesis of water-enclosing rocks, to suggest a certain quantitative regularity of spatial variation of seepage parameters.

Thus, distinguishing groundwater flow media is founded on a genetic approach, when on the basis of the analysis of sedimentation conditions, epigenetic rock transformations and tectogenesis processes, the regional variability of the main properties, and seepage in particular, of rocks is determined and predicted.

Four principal types of groundwater flow, media-sedimentogenic-pore, sedimentogenic-fracture, karst and magmatogenic-metamorphogenic, are suggested to be shown on a map.

The sedimentogenic-pore type comprises unconsolidated and weakly consolidated sand, gravel, pebble and other rocks, which were not subjected to processes of compaction and lithification. The permeability of these deposits is governed by primary sedimentogenic porosity. This type of medium includes marine, coastal-marine sandy and sandy-clayey deposits, continental-lagoon deposits, glacial, surficial and water-glacial formations, alluvial and lacustrine-alluvial strata, and forms marine and continental subtypes of the sedimentogenic-pore medium type. The seepage properties of this type are characterized by their regular or irregular lateral and vertical variation that is finally determined by sedimentation conditions. In regional mapping, areas with mostly regular varying, the main medium parameters may be delineated. At the same time, in the case of facial change of sediments and on the boundaries of genetic types, sharp changes in seepage properties and pertinent changes in conditions of groundwater generation may occur.

The sedimentogenic-fracture type of groundwater flow medium is widely developed in mountain-fold areas and in the lower structural stage of platforms. It is composed of sandstones, argillites, siltstones, marls and other consolidated sedimentary rocks. The permeability of these rocks practically depends on the degree of fracturing. Postsedimentation processes (diagenesis, lithification, weathering, and tectogenesis) are responsible for the different fracturing of lithified sediments. The permeability uniformity of these rocks is formed by exogenic and tectonic fracturing. However, the size of fractures, the depth of their penetration, openness and density depend, all other conditions being equal, on the genetic type of rocks, range of their particle

dimensions and cement composition. The scale of permeability non-uniformity, in this case, also depends on primary and secondary porosity that determines the formation of groundwater flow media with double porosity. Distinguishing medium subtypes is motivated by both the lithological composition of water-bearing rocks and by conditions of flow space formation. In this connection, a sandy subtype (sandstones, conglomerates, breccias, etc.) is distinguished. This subtype is noted for substantial fracturing and high effective porosity that in combination determines potentially favourable conditions of groundwater runoff generation. Another subtype comprises clayey consolidated rocks (argillites, siltstones, marls, etc.) which, when compared to the rocks of the first subtype, have more inferior seepage properties.

Karst rocks (limestones, dolomites, gypsum, anhydrites, etc.) are characterized by special conditions of groundwater runoff generation. They have a high permeability due to solution of water-bearing rocks and formation of large fractures and karst cavities. This gives ground to distinguish the karst type of groundwater flow medium. Present karst and ancient karst (paleokarst) intensively develop in carbonate rocks having considerable primary fracturing and porosity as well as in zones of regional and local faults. The high permeability of these rocks is responsible for the existence of favourable conditions of groundwater recharge that, in turn, results in karst intensification. In this connection, the carbonate rocks of humid, subtropical and tropical regions are noted for the largest specific values of groundwater discharge and are mapped as the most favourable areas for groundwater runoff generation. At the same time, karst salt-bearing rocks generally have a low permeability (they often form semiconfining layers) and contain, as a rule, water with a high dissolved solids content. For this reason, the karst type of groundwater flow medium is subdivided into carbonate and sulphate-carbonate subtypes, which determines their various hydrogeodynamic and geochemical conditions of groundwater generation.

Metamorphic, intrusive and volcanogenic rocks are grouped into the magmatogenic-metamorphogenic type of groundwater flow medium because they are characterized by similar seepage uniformity conditions. In contrast to the above medium types, this type has a predominantly fracture permeability. Depending on rock genesis and formation of fracture space, it seems to be reasonable to distinguish metamorphic, intrusive and volcanogenic subtypes of groundwater flow medium. The first two subtypes are noted for a block-fracture structure of seepage space, when regional tectonic conditions lead to formation of individual blocks which, in turn, are broken to a different degree by fractures of endogenic and exogenic origin. In this connection, groundwater runoff, here, has a complex pattern: the most intensive regional groundwater flows are confined to linear faults, limiting the blocks, while local runoff is formed in structural disturbances of lower orders and exogenic fractures. In the volcanic subtype, of particular interest are lava-sheet formations distinguished for favourable conditions of groundwater runoff generation. As known, lava sheets, tuffs, tuff breccias and other igneous rocks are characterized by relatively high syngenetic fracturing and porosity, which are subsequently affected by processes of weathering and tectognesis. Under favourable groundwater recharge conditions, intensive groundwater runoff is generated in these rocks.

Thus, distinguishing the types and subtypes of groundwater flow media on the basis of genetic approach both to the origin of water-bearing rocks themselves and their seepage seems to be a reasonable and effective way for elaboration of the principles and legend of groundwater runoff maps at small and medium scales. Proceedings from the scales of the *Groundwater Flow Maps*, being compiled, has distinguished the above groundwater flow media, which in more detailed studies of processes of groundwater flow generation, groundwater resources and runoff may be subjected to further division, depending on local natural conditions and problems of concern. However, distinguishing groundwater flow medium types and subtypes should be based on a single principle complying with the laws of the process under study.

The *World Map of Hydrogeological Conditions and Groundwater Flow* on a 1:10 000 000 scale, being completed is a special thematic map, where data on areal distribution of quantitative groundwater runoff characteristics – specific groundwater discharge values and coefficients are presented. The combined cartographic representation of these two quantitative characteristics, appreciably improves the usefullness of a hydrogeological map. This proved to be possible using two different models of representation – a color cartogram (for normal annual specific groundwater discharge values) and isolines (for groundwater runoff/precipitation ratios). However, in contrast to previosity published maps of groundwater runoff, where each color corresponded to a certain interval of specific discharge values, on the map this function is performed by color intensity while color proper is 'given' a groundwater flow medium type. For example, blue color shows variation in specific groundwater discharge in karst groundwater flow medium and color density indicates seven ranges of discharge (from less than 0.1 to 10–20 and more litres per second per square kilometer). A system of monochromatic (black) hatch and dot conventional conditions, which has been widely applied to construction of various cartographic models, was used for mapping of groundwater flow medium subtypes. The color cartogram, showed gradation of specific discharge values, permits tracing and visual representation of the role of geological and hydrogeological factors in the generation and distribution of groundwater runoff. This procedure is most convenient when the specific discharge value does not practically change within a balance region or has a slight tendency to vary from point to point while at the same time is strongly disturbed on the boundaries of adjacent regions with substantially different hydrogeological conditions (Fig. 4.2.4.1).

The boundaries of distribution of groundwater flow media are indicated by a black contour and their stratigraphy is represented by using an index of the international geochronological scale. Within the boundaries, water-bearing rocks are characterized by the degree of contribution to generation of groundwater runoff: main contribution (over 50%) by a wide belt (25 mm) and minor contribution by a narrower belt (7 mm). If two subordinate groundwater flow media are distinguished, they are shown as narrow belts in succession. Belts are placed vertically in a single grid; in narrow and wide belts geological indices are shown (one for each groundwater flow medium).

It is important to represent, in the groundwater flow medium type or subtype, special conditions of groundwater runoff generation affected by human activities, intensive karstification, areas of surface runoff engulfing river channels, rift zones and regional faults, occurrence of semipermeable rocks, etc.

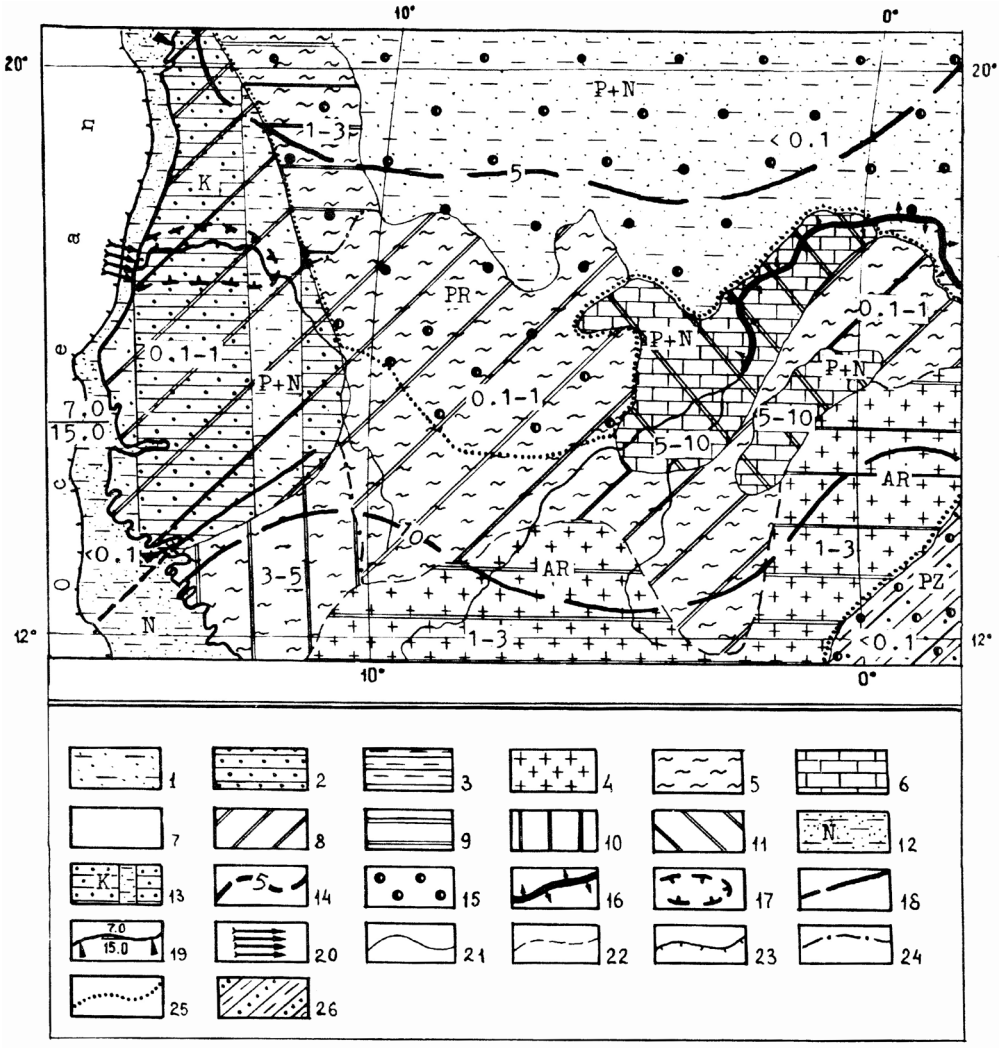
Conventional conditions for indicating the total dissolved solids content of groundwater are used in the upper hydrodynamic zone when groundwater has a TDS of over 1 g/l. There are red conditions with gradation and are located in a sparse net.

It is wise to represent, on modern groundwater flow maps, conditions of groundwater discharge to seas and oceans together with quantitative characteristics of this process, expressed in specific and absolute values. The main mapped components are quantitative characteristics of submarine groundwater discharge and conditions of occurrence and distribution of groundwater flow media within the study area of a shelf. Submarine groundwater flow media in a shelf are generally the continuation of coastal hydrogeological structures. Coastal aquifers protruding into the shelf show hydrogeological conditions which are similar to those inland. This similarity facilitates regional hydrogeological generalizations and marine hydrogeological mapping.

However, when compiling submarine groundwater flow maps, one should not extend indiscriminately the coastal geological and hydrogeological information to sea areas. Particular attention ought to be given to hydrogeological subdivision of areas and extension of subdivided elements to sea areas and to identification of groundwater flow media defined in the shelf.

The identification of groundwater flow media on the sea bottom is based on examination of

Figure 4.2.4.1 A model of the World Groundwater Flow Map on a 1:10 000 000 scale



Types of groundwater flow media:
(1) sedimentogenic-pore (unconsolidated sediments); (2, 3) sedimentogenic-fracture (consolidated sedimentary rocks: sandstones, breccias, conglomerates (2) and argillites, marls, clay shales (3)); (4, 5) magmatogenic and etamorphogenic; (6) karst (carbonate subtype); normal annual values of specific groundwater discharge (in litres per second per square milometre); (7) less than 0.1; (8) 0.1–1; (9)1–3; (10) 3–5; (11) 5–10; contribution of groundwater flow media to groundwater flow generation; (12) principal; (13) subordinate; (14) isolines of groundwater runoff/precipitation ratios, in per cent; (15) groundwater dissolved solids content 1–3 grammes per litre; specific conditions of groundwater flow generation; (16) areas of intensive river water contribution to groundwater flow; (17) areas of intensive human impact on groundwater flow generation; (18) fault zones with local groundwater discharge areas; (19) coastal areas with various submarine groundwater and dissolved solids discharge value in km^3/yr (upper figure) and total value of dissolved solids discharge values; total groundwater discharge values; total groundwater discharge value in km^3/yr.

geological cross-sections obtained by seismoacoustic profiling and drilling on the shelf. It is desirable that seismoacoustic profiles be correlated to coastal lithological and hydrogeological wells and boreholes on the shelf. This correlation enables one to identify submarine groundwater flow media and link them with coastal aquifers.

Groundwater flow media identified within a shelf laterally and vertically are correlated with bottom topography, geomorphology, and tectonics. Tapering out of submarine groundwater flow media, reduction in their thickness, change in lithological composition, and dislocation are most probable in areas of conjugation of geomorphological elements and boundaries of tectonic structures.

A substantiated map of distribution of submarine groundwater flow media results from a combined analysis of seismogeological profiles and geomorphological and structural schemes.

It should be emphasized that when mapping submarine groundwater discharge values, one should avoid methods of direct interpolation or extrapolation, and consideration must be given to the specific geological, hydrogeological, structural, and geomorphological conditions on the sea bottom.

Thus, the *World Map of Hydrogeological Conditions and Groundwater Flow* show integrated information on the geological and hydrogeological conditions of groundwater runoff generation and on distribution of quantitative characteristics of the main groundwater runoff parameters.

Regional quantitative assessment of groundwater discharge, accompanied, as a rule, by compiling a series of specialized maps at a different scale, is of considerable interest for some sciences on the earth, primarily, hydrogeology and hydrology. The results of such assessment make it possible to reveal the main regularities of forming and spreading groundwater discharge in different natural climatic and hydrologic-hydrogeologic conditions, that can serve a basis for predicting changes of underground hydrosphere (primarily a zone of active water exchange) under climate changes and increasing anthropogenic impact on the environment. Quantitative data on groundwater discharge allow for determining groundwater function in total water resources and water balance of different regions: river basins, separate territories, areas, countries, and aquifer systems that is of great value for elaborating schemes of water resources use and protection.

In the practice of hydrogeological studies the results of quantitative assessment of groundwater discharge allows for characterizing the most important groundwater resources component – the component that is constantly renewed in the process of total moisture circulation which is groundwater discharge provided by recharge. This extremely important indicator of unlimited potential for groundwater use is normally called natural resources. In practice natural groundwater resources are an indicator of groundwater recharge and characterize the upper limit of possible perennial groundwater withdrawal without depletion (except coastal well fields of the infiltration type).

For the first time groundwater was regionally assessed and mapped in the former USSR at the beginning of the 1960s by a large group of hydrogeologists and hydrologists under the guidance of B. I.Kudelin. The maps (*Map of Groundwater Discharge in the USSR* and *Map of groundwater Discharge in the USSR in per cent of the Total River Runoff*) published at a scale of 1 : 5 000 000 served as a basis for working out schemes of water resources use and protection in the country and in specific regions. Compiled and published in the following years, works on regional groundwater assessment and mapping including the *Map of Groundwater Discharge in the USSR Territory* at a scale of 1 : 2 500 000, the *Map of Groundwater Discharge in the Central and East Europe* at a scale of 1 : 1 500 000 and the recently published *Map of Hydrogeological Conditions and Groundwater Discharge* in the World at a scale of 1 : 10 000 000 should be noted. The two latter maps have been compiled and edited by an International Expert Group guided by and with immediate participation of Russian specialists, according to the International Hydrological Program of UNESCO. Let's consider in detail the main content of the *Map of Hydrogeological Conditions and Groundwater Discharge in the World* at a scale of 1 : 10 000 000 (Chief editors are R. G. Dzhamalov and I. S. Zektser). The map was compiled based on the direction given by UNESCO and published in the United States of America in 1999. The technique, legend and the main content of the *Map* has

been worked out by specialists in the Water Problems Institute, Russian Academy of Sciences, under scientific and methodical guidance of R. G. Dzhamalov and I. S. Zektser. It has been edited by an International Editorial Stuff – experts from Australia, Argentina, Brazil, Germany, United States of America, India, France, Italy, China, Indonesia, and other countries. The map as an essential scientific investigation, has been awarded a special premium from Academician F. P. Savarensky in 2001 by the Russian Academy of Sciences.

The *Map of the World* is a special thematic hydrogeological map, the main content of which covers quantitative groundwater discharge characteristics, and also geologic and hydrogeologic conditions of the formation of groundwater. Under a small-scale mapping, singling out aquifers and complexes in vast territories is difficult. That is why the main geofiltration media are shown in the *Map* – genetic types and subtypes of the rocks with common conditions of filtration properties and spatial spreading. Medium type is caused by the water-enclosing rocks genesis or free space genetic type (pore, fissured, karst media, and etc.); a subtype – by the processes (formation conditions), controlling a character and scale of the medium filtration heterogeneity. Singling out geofiltration media makes it possible for different hydrogeologic maps, not only to simplify a stratigraphic basis in geologically complex areas, but also, for considering the water enclosing rocks genesis, to suggest a certain quantitative regularity of filtration parameter spatial changes. There are four main types of geofiltration media shown in the map: sediment-fissured, karst and magnatogenic-metamorphogenic ones that, in turn, are subdivided into subtypes. In the *Map* water-enclosing rocks are characterized by their degree in forming the groundwater discharge: the main participation degree (>50%) – a wide stripe (25 mm), subordinate – a narrow one (7 mm). If two subordinate geofiltration media are singled out, they are shown in narrow stripes in turn.

Special information on areal spreading of quantitative groundwater discharge characteristics (modules and coefficients) are given in the *World Map*. A combined cartographic picture of the two noted quantitative characteristics considerably increase the map information content. But in contrast to the earlier published groundwater discharge maps where every color corresponds to a certain interval of module change, in the elaborated legend this function is fulfilled by its intensity, and the color itself is 'given' to the geofiltration medium type. For instance, a blue colour indicates groundwater discharge module changes in the karst geofiltration medium, and colour thickness denotes seven ranges of changes (from 0.1 to 10–20 $l/s.km^2$ and more).

There are special conditions of the formation of groundwater on the *Map*: active anthropogenic impact, surface water runoff absorption areas in river beds, rift zones, regional fractures, etc.

For the first time in the practice of regional hydrogeologic mapping, conditions of groundwater discharge into seas and oceans are indicated in the *World Map* with quantitative characteristics of this process from submarine groundwater discharge modules within the most studied water area, i.e. shelf. Common conditions of groundwater occurrence, formed in the land and discharged directly in the water can be seen within hydrogeological structures opened to the sea. These peculiarities of coastal hydrogeological structures makes regional generalization and marine hydrogeological mapping considerably easier. The result of global assessment and mapping of groundwater discharge allows for solving a number of scientific problems on groundwater formation in different natural conditions and are based principally on a new quantitative approach. The investigations revealed the main global and regional regularities of groundwater and its form of discharge and correlated them with specific geologic-hydrogeologic conditions and natural-climatic zones.

Thus, the *World Map of Hydrogeologic Conditions and Groundwater Discharge* forms the basis for extensive investigations in hydrogeology, hydrology and regularities of water resources and water balance formation for global hydrologic-hydrogeologic generalizations and activities in adjacent fields.

The work of compiling this map can serve as an example of joint efforts by scientists from different countries in solving important scientific problem.

A principle difference from all the previously published hydrogeological maps is that regional quantitative characteristics of groundwater natural resources (in l/s.km^2) and their function in the total water resources and water balance (in per cent of the mean perannial values of atmospheric precipitation and river runoff) are shown for the first time.

Groundwater discharge maps, at different scales, permit solving the following important practical problems connected with complex groundwater resources use and protection:

- determining the amount of groundwater discharge and natural resources for planning use and protection;
- determining the value of groundwater recharge for assessing their function in common water resources and balance of separate areas, basins of large rivers and seas;
- determining the underground constituent of total river runoff (as the most stable part of discharge) and predicting changes in river runoff under the impact of large-scale groundwater withdrawal;
- determining the function of groundwater natural resources in computing the safe yield of separate economic and administrative areas for assessing groundwater long-term use without depletion;
- determining the values of direct groundwater discharge to seas and oceans for assessing groundwater function in the water and salt balance of the seas.

It should be noted in conclusion that the principles for compiling groundwater discharge maps and their different variants were repeatedly discussed in different International Conferences of UNESCO, IAHS and IAH and have been widely acknowledged. A further improvement of technique for regional assessing and mapping the groundwater discharge was jointly carried out by the Water Problems Institute, RAS; Chair of Hydrogeology, MGU; State Hydrological Institute and VSEGINGEO (All-Russia Institute for Hydrogeology and Engineering Geology).

4.2.5 Methods for studying and assessment of groundwater discharge to seas and lakes

The study and quantitative evaluation of groundwater discharge to seas and lakes should be based on reliable methods of research, which can locate groundwater discharge sites and determine of discharge values. These methods may be fairly distinctly subdivided into two groups: 1) methods based on quantitative analysis of the generation of conditions of groundwater discharge to the sea within a drainage area and, above all, within the coastal area of land and 2) methods for marine hydrogeological studies.

Methods, based on studying the drainage area adjoining the sea, comprise the analysis of geological and hydrogeological conditions of the coastal area. These methods are: hydrogeodynamic method for computation of specific groundwater discharge (analytically and by modelling), combined hydrological and hydrogeological method, and the method of average long-term water balance of groundwater discharge areas. These methods and those based on studying processes of groundwater movement, are principally used for direct quantitative estimation of groundwater discharge to seas within the zone of the geological section for which data on hydrogeological parameters are available.

The dynamics of groundwater in artesian basins adjacent to seas indicates that the groundwater flow of the upper hydrodynamic zone is commonly directed to the sea and generates submarine groundwater discharge. Submarine groundwater discharge occurs as concentrated outflow along faults and in fractured and karst areas, as well as leakage through semipermeable deposits have been established for many artesian basins within regions with a natural and

disturbed hydrogeological regime. Leakage processes define the dynamics of the groundwater of an artesian basin on the whole or by its major parts. In other words, leakage plays an important role in submarine groundwater discharge.

The ***hydrogeodynamic method*** is principally used in the quantification of submarine groundwater discharge. For delineated aquifers, potentiometric and transmissivity maps, reflecting the conditions of submarine groundwater discharge, are constructed. The submarine groundwater discharge along the coast is determined by using Darcy's relationship for streamlines. This simple traditional method permits obtaining fairly reliable values of groundwater discharge to the sea from any aquifer. Particular attention should be given to the reliability and representativeness of initial hydrogeological parameters and hydrogeodynamic maps, constructed from this data.

The analysis of the hydrogeodynamic situation of the coastal region allows one to distinguish a number of areas with similar hydrogeological conditions. Within these areas, specific groundwater discharge is calculated from streamtubes with an allowance for all main initial parameters for the relatively narrow coastal band of groundwater discharge. As a result, initial hydrodynamic parameters are not averaged for large areas. They are refined and detailed for an estimated area and for each streamtube.

Another important way for direct groundwater contribution to seas is through discharge by leakage through semiconfining layers and bottom sediments. Therefore, it is of great interest to determine areas with the most intensive groundwater discharge and to clear up the understanding of the distribution of submarine groundwater discharge. To distinguish these submarine areas, based on maps of head distribution in the aquifer, piezometric profiles are constructed for some streamlines. Then, these profiles are extended into the sea area, which requires determination with a sufficient accuracy of the function $y = f(x)$. This approximation of piezometric curves of various types can be made by using standard computer programs.

Applying equations for approximating curves, piezometric profiles may be extended to the sea area as far as any assumed elevation, i.e. up to the boundary of possible groundwater discharge through leakage. This procedure permits construction of a fairly substantiated map of the potentiometric surface of an aquifer within the coastal zone of the sea. Such maps may be used for quantitative estimation of groundwater leakage within the sea area by mathematical modelling.

If sufficient data representing regional conditions of groundwater flow are available, various calculation and modelling methods may be used for estimating groundwater discharge to seas. The method, based on the interrelation of artesian aquifers should be considered the most suitable for this purpose. The method permits obtaining at each estimation point, the horizontal and vertical components of groundwater flow with known areal distribution of head and transmissivity values. The division of the groundwater flow area into blocks and subsequent computations may be carried out using finite-element methods. The groundwater discharge to the Caspian Sea has been determined by this technique.

The ***combined hydrological and hydrogeological method*** within the coastal zone of the sea basin under study uses the procedure of separating the hydrograph of river runoff for a long-term period and determines the specific groundwater discharge values for the main aquifers. Then, using the analogy approach, the discharge values are extended to coastal areas, having similar hydrogeological conditions, whose groundwater discharges, directly to the sea (bypassing the river network). The groundwater flow to the sea from the upper hydrodynamic zone is evaluated by multiplying the specific groundwater discharge values by the respective areas of the coastal zone. This method is applicable only to basins with a well-developed river network. In this case, the discharge from the upper hydrodynamic zone, largely fresh groundwater rather than the

entire groundwater outflow to the sea, is evaluated. Therefore the above method is reasonable to use together with others, e.g., the average long-term water-balance method or the hydrogeodynamic method.

The ***average long-term water-balance method*** can be used for estimating groundwater discharge to seas from deep artesian aquifers, which have a distinct area of recharge. A long-term water-balance equation is composed for the area of recharge and, using the difference between rainfall, evaporation and river runoff, the value of deep percolation, i.e., the portion of rainfall that recharges artesian water, is determined. This method is temptingly simple, however, its application is restricted by some circumstances. First, it is useful for computation of the specific discharge from aquifers that are safely isolated by confining layers from overlying and underlying aquifers, i.e., one should be aware that aquifer flow reaches the sea rather than leaks to other aquifers. Second, this method may be reliably applied where the estimated deep percolation value exceeds the accuracy in determination of other components of the water-balance equation (precipitation, evaporation, and river runoff).

The methods for quantitative evaluation of groundwater discharge to seas and lakes enable us to determine, with a sufficient accuracy, the total submarine groundwater outflow from all estimated aquifers and to obtain a picture of its distribution in the coastal areas of land and sea with allowance for aquifer interrelation. The groundwater discharge estimates, obtained by one of the methods, should be subsequently proved and controlled by other methods. Combined use of several methods permits obtaining the most reliable results.

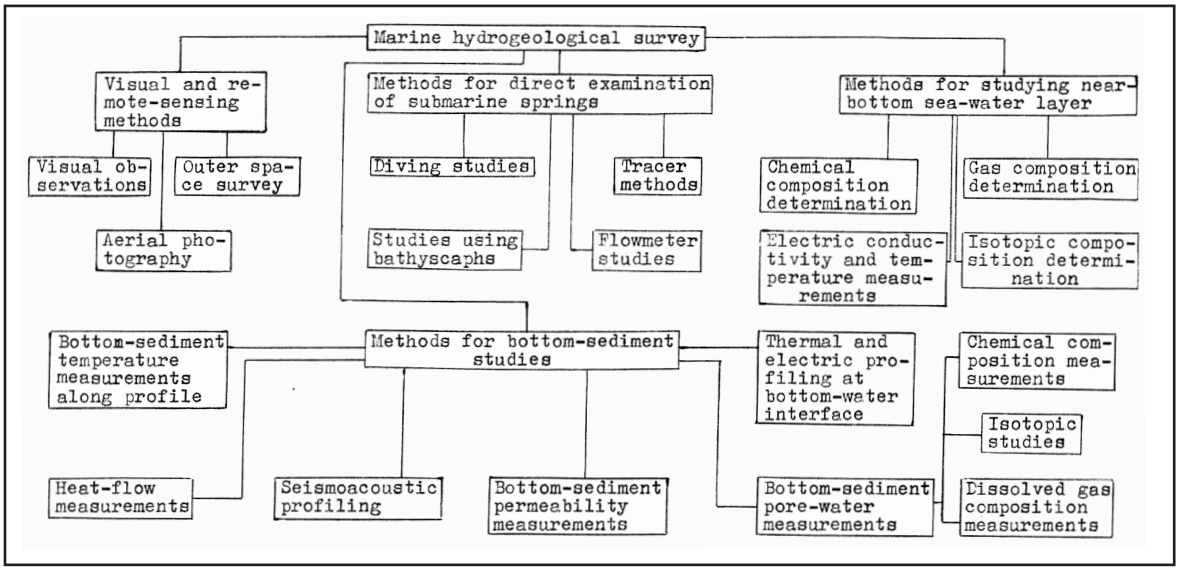
Methods for marine hydrogeological studies. Groundwater discharge causes various anomalies in sea water and bottom sediments, whose study makes it possible to locate groundwater discharge sites and to obtain groundwater discharge estimates. Therefore, marine hydrogeological studies mainly include examination of direct indicators, characterizing variations in physical and chemical fields due to groundwater movement through the sea bottom.

The research on the effect of submarine groundwater on the formation of anomalies in the physical and chemical fields of bottom sediments and the near-bottom layer of sea water is the methodological basis of marine hydrogeological studies. Today's technological level of marine investigations makes it possible to measure with a high accuracy such hydrogeologically important factors as temperature, heat flow, electric conductivity, natural electric and electromagnetic fields in bottom sediments, as well as to determine the chemical, minor-element, gas and isotopic compositions of pore solutions in bottom sediments and of sea water. However, anomalies in the distribution of each of these parameters are not a direct indicator of groundwater discharge to the sea bottom. Hydrogeological understanding appreciably enlarges, if simultaneous measurements, at one point, of parameters of several physical and chemical fields or various components of the same field and frequent measurements (ideally continuous profiling), are made. Methods for marine hydrogeological investigations are presented in Figure 4.2.5.1.

Visual observations of submarine groundwater discharge at the sea surface are noted from ancient times. Large submarine springs are responsible for different changes at the sea surface. They include the formation of water domes, 'boiling' of water at the sea surface, change in the color of sea water, and appearance of gas bubbles. The change in sea-water color may be caused by various chemical reactions occurring from groundwater discharge at the sea bottom. Submarine springs have been detected by a change in sea water color near Indonesian shores on the fumarole fields of the Banu Wuhu volcano; here, water became red due to the oxidation of iron transported by discharging thermal groundwater (Zelenov, 1964). A large number of submarine, mainly karst, springs have been located in some parts of the world by visual observations.

Visual observations make it possible to only locate submarine springs having large

Figure 4.2.5.1 Methods for marine hydrogeological studies



discharge rates and occurring mainly in the coastal area. Even major large-discharge submarine springs can remain undetected, if their depth exceeds tens of meters. At present, the potential for visual observations has been substantially broadened by remote-sensing techniques and diving.

Remote-sensing methods are highly promising for studying submarine groundwater discharge. Above all, they are multi-spectral and infrared survey of sea surface from aircraft or spacecraft. For instance, in the 'green' range V (0.5–0.6 μ) sea water is transparent and space images in this range represent sea-bottom topography, turbidity and various pollutants in water. This permits detecting major karst springs whose water commonly contains suspended particles or air bubbles. Such springs are detected on aerial photographs of the coast of Jamaica, where upwelling karst water forms turbid areas of oval shape at the sea surface (Deutsch, 1974). Multispectral photography was used by the US Geological Survey for studying submarine springs near Jamaica, Sicily and the Hawaiian Islands.

Infrared imagery is based on measuring the intensity of thermal radiation of various natural surfaces, including sea surface, in the infrared range of electromagnetic waves. Using modern infrared radiometers, it is possible to measure from artificial satellites or aircraft the temperature on the sea surface with an accuracy as much as tenths or hundredths of a Celsius degree. Infrared imagery is most efficient in locating submarine groundwater discharge sites. Groundwater and sea water usually have different temperatures. In this connection, submarine groundwater discharge on infrared images is detected by characteristic contrasts which have the shape of plumes.

It should be noted that the application of infrared imagery for mapping of groundwater discharge sites in the sea is possible only if the temperature anomalies, caused by submarine groundwater discharge, reach the sea surface and differ from the surrounding sea-water temperature by a value exceeding the sensitivity of the radiometers.

Groundwater discharge was studied, using a combination of remote-sensing techniques, on the salt lake, Big Qwill, in Saskachewan in Canada (Whiting, 1976). An aerial survey using the reflected wave method, a space survey using four wavelength ranges from Landsat I, and an infrared aerial survey made it possible to locate on the bottom of the lake, nine groundwater discharge sites with a total area of 4 km^2. Combined application of remote-sensing methods in this region permitted the investigators to accurately map subaqueous discharge of groundwater and to delineate anomalies caused by groundwater discharge and by spiral-like currents in the lake.

When studying submarine springs, direct underwater observations using light diving

equipment are important. Such studies were performed on the Black Sea shelf in the area of the Gagra group of submarine springs in order to examine the mechanism of groundwater discharge through karst springs at the sea bottom (Korotkov et al., 1980).

Divers made interesting investigations of a submarine karst spring in the Port-Miou Bay not far from Marseilles. They mapped in detail water-filled karst galleries for over a one-kilometer distance. The network of galleries was at a depth of about 20 m below sea level and the spring outlet was at a depth of 45 m. In addition to reconnaissance, accurate instrumental measurements were made: divers installed recorders of current velocities, pressure gauges and resistivity meters (Potie, 1973).

The discharge and head of submarine and subaqueous springs is measured by various flowmeters and piezometers. Special piezometers for measuring the head of groundwater discharging through bottom sediments were used on Utah Lake (*Hydrology of Utah Lake,* 1980). Here, studies of the subaqueous discharge of water from deep confined aquifers to the lake included the use of a combination of methods: infrared imagery from aircraft, aerovisual observations, hydrochemical measurements of lake water along a profile, and direct measurement of groundwater head at the lake bottom.

Application of flowmeters of various designs is promising for estimating the rate of groundwater seepage through bottom sediments. Flowmeters were used for the evaluation the of subaqueous discharge of groundwater to Lake Sally, Minnesota (Lee, 1977), the Great South Bay, Long Island (Bokuniewich, 1980), and Lake Taupo in New Zealand (Lock and John, 1978).

The examination of groundwater discharge sites at large depths is possible using bathyscaphs. Existing systems of bathyscaphs and other deep submersibles make it possible (for long periods of time and practically at any depth) to collect sediment samples, take underwater photographs, and perform other observations.

The methods for studying groundwater discharge to the sea include the application of tracers. This method allows one to determine the location of submarine springs, discharge conditions, and in a number of cases, discharge rates from data on dilution of various tracers injected into spring outlets or karst hollows on land. The tracers may be fluorescent dyes, colored spores, various isotopes, or spring fresh water that dilutes sea water.

There are methods for studying submarine groundwater discharge, which are based on the detection of anomalies in the composition and properties of sea water. These methods include the use of electrical conductivity measurements. This method is based on the relationship between salinity and the electrical conductivity of water. To detect groundwater discharge to the sea, sea water electrical resistivity is measured by resistivity meters along profiles at various depths. Temperature is recorded simultaneously with resistivity measurements. By converting resistivity values into salinity values, maps of sea water salinity distribution can be constructed. The position of submarine springs is then determined from the configuration of resistivity and temperature isolines.

Anomalies in the chemical composition of sea water are measured along profiles for detecting submarine springs and in a number of cases for preliminary estimation of their discharge. These studies are based on the substantial differences in the salinity and chemical composition of ground and sea waters.

Sea water samples for chemical analysis are commonly taken along several parallel profiles at sea bottom, at water surface and at intermediate depths. This technique has been used in studying submarine karst springs in the vicinity of the Black Sea coast (Buachidze et al., 1967) and in the Mediterranean Sea (Burdon, 1964; Potie, 1973). Highly promising application of automatic analyzers, mounted on board a research vessel, permit the determination of some chemical components in sea water.

In recent years, sea-water isotopic composition analysis has been applied to studying sub-

marine groundwater discharge. Variations in tritium, deuterium, and radiocarbon, concentrations in the water of submarine springs allow one to judge the origin, recharge sources, movement velocity, and circulation periods of this water.

Anomalies in bottom sediments are studied by various geophysical methods, using determinations of the permeability of bottom sediments and analyses of pore solutions. The combined geophysical method, including continuous measurements of the temperature and salinity of the near-bottom layer of water, using a special sounder (Zektser et al., 1984, 1986), is successfully being applied. This method obtains a geological profile of bottom sediments and plots of water temperature and salinity fluctuations at sea bottom along a profile. Integrated analysis of these findings allows one to find and delineate groundwater discharge sites at sea bottom, and computations using established relationships make it possible to estimate quantitatively the amount of submarine groundwater discharge.

At present, several techniques have been developed for computing the rates of groundwater discharge at sea bottom, using data on the salinity of sea and groundwaters at discharge sites. The conditions where data of combined geophysical profiling are possible to apply to estimating the submarine groundwater discharge rate are considered by Zektser et al. (1986). The convective-diffusion process of salt transfer between waters of bottom sediments and the near-bottom water layer is assumed to be steady, since temporal salinity fluctuations at the water-rock interface practically do not occur at a groundwater leakage rate of 10^{-5}–10^{-2} m/day. In this case, the mass transfer in bottom sediments is described by the equation

$$V \frac{\partial S}{\partial z} + D \frac{\partial^2 S}{\partial z^2} = 0 \qquad (4.2.5.1)$$

where

V: groundwater seepage rate; D: coefficient of salt diffusion in pore water; S: pore water salinity.

It is assumed that on the bottom, at z=0, the salinity is equal to that of sea water in the near-bottom layer, while at a relatively large depth, in such sediments, it corresponds to the salinity of discharging submarine water:

$$S(0) = S_W;\ S(\infty) = S_d \qquad (4.2.5.2)$$

At these boundary conditions, the solution of equation (4.2.5.1) is

$$S(z) = (S_W - S_d)\, e^{-\frac{V}{D} z} + S_d \qquad (4.2.5.3)$$

In the course of combined profiling, a special probe transported by a vessel measures salinity at the water-rock interface, the probe being placed at a depth h:

$$f = \frac{1}{h} \int_0^h S_d\, z \qquad (4.2.5.4)$$

With allowance for equation (4.2.5.3), it is possible to obtain an equation for determining the seepage rate of submarine water creating an anomaly:

$$f = \frac{D}{hV} (S_W - S_d)\, (1 - e^{\frac{-V}{D} h}) + S_d \qquad (4.2.5.5)$$

In order to calculate the reliable submarine water seepage rate values, it is necessary that salinity anomalies measured by the probe differ from the salinity of sea water by no less than 10%.

In this case, the true seepage rate may vary from 10^{-4} to 10^{-2} m/d, since at larger and smaller rates the required contrast salinity anomalies do not emerge in the near-bottom layer.

In conclusion, it should be pointed out that combined use of several methods for evaluating groundwater discharge to the sea appreciably enhances the reliability of the obtained results.

4.3 Principles of assessment and mapping of groundwater quality

The chemical composition of groundwater and its quality is a result of the physical, chemical and biochemical processes which occur on the atmosphere (precipitation) – soil-rock-water system. The rock environment, particularly the solubility of minerals, travel time, and area of contact of groundwater with geological material have a decisive influence on the chemical composition of groundwater. Amount and type of dissolved solids are considerably variable and reflects the nature and effects of bio-geochemical processes on groundwater composition as it moves along its flow paths. Biological processes accelerate the extent and rate of geochemical processes and are particularly intensive near the earth surface in the soil – vadose zone, where oxygen is usually available and supports respiration of organisms and breakdown of organic matter. However the supply of nutrients significantly effects microbiological activity (especially nitrogen, sulphur compounds, iron, manganese and some other metals). Microbial decomposition is an important process in reduction of groundwater pollution contaminated by oil, chlorinated hydrocarbons, pesticides, pathogenic bacteria and viruses.

Differences in the evolution of groundwater chemical composition exist in the horizontal (recharge and discharge areas) and the vertical (shallow – oxidation and deep – reduction zones) scale of groundwater flow systems. Groundwater chemical composition is decidedly affected by rock – mineral availability, solubility and rock permeability which controls residence time and surface contact of groundwater in a rock system. However, generally, it can be said, that groundwater in recharge areas and shallow zones has a lower level of dissolved solids than groundwater in discharge areas and deeper aquifers. The increasing content of total dissolved solids and anion evolution sequence $HCO^{3-} \rightarrow SO_4^{2-} \rightarrow Cl^-$ which expresses the change from oxidising conditions to reducing conditions, is usually very visible in the vertical profile of groundwater flow systems. Dominant anion evolution sequence from shallow to deep zones of groundwater flow systems was expressed by Chebotarev (1955):

Travel along flow path →

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow$$
$$SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$$

Increasing age →

The above described hydrogeochemical processes and changes, as a result of physical and biochemical reactions in soil-rock-water system, do not consider the impact of man-made pollution on groundwater. Human affects on groundwater quality are not assessed in this section.

The chemical composition and quality of groundwater limit its utilization – as a source of drinking water, or use for agricultural, industrial or other purposes. Dissolved solids in groundwater are formed by macro (major), secondary and minor elements – Table 4.3.1. The following major elements are mostly used by graphical and numerical methods applied in the assessment, classification and mapping of groundwater quality: $Na^+ + K^+$, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-} and Cl^-. Some methods also include Fe^{2+}, Mn^{2+}, NO_3^- and SiO_2.

Table 4.3.1 Occurence of inorganic dissolved constituents in groundwater (Todd, 1980)

Major constituents (1.0 to 1.000 mg^{-1})	*Secondary constituents* (0.01 to 10.0 mg^{-1})	*Minor constituents* (0.001 to 0.1 mg^{-1})
Sodium	Potassium	Arsenic
Calcium	Iron	Barium
Magnesium	Aluminium	Bromide
Bicarbonate	Carbonate	Cadmium
Sulphate	Nitrate	Chromium
Chloride	Fluoride	Cobalt
Silica	Boron	Copper
	Selenium	Iodide
		Lead
		Lithium
		Manganese
		Nickel
		Phosphate
		Strontium
		Uranium
		Zinc

4.3.1 Groundwater quality assessment

Groundwater quality assessment depends strongly on the amount and quality of the groundwater analysis available. When studying in situ aquifer conditions, design and installation of sampling (monitoring) wells and particularly groundwater sampling procedures (purging methods, sampling equipment, sample preservation, shipping and storage) and field and laboratory analysis of water samples (field screening parameters, accuracy and precision of laboratory methods, validity and reporting) significantly influence the groundwater data used for quality assessment. A groundwater quality control program used as a base for groundwater quality assessment, is expressed in a simplified form on the Table 4.3.1.1.

A groundwater quality control program can be understood as a continuous, methodologically and technically standardized process of observation, measurements and analysis of selected variables of groundwater. The objective is:

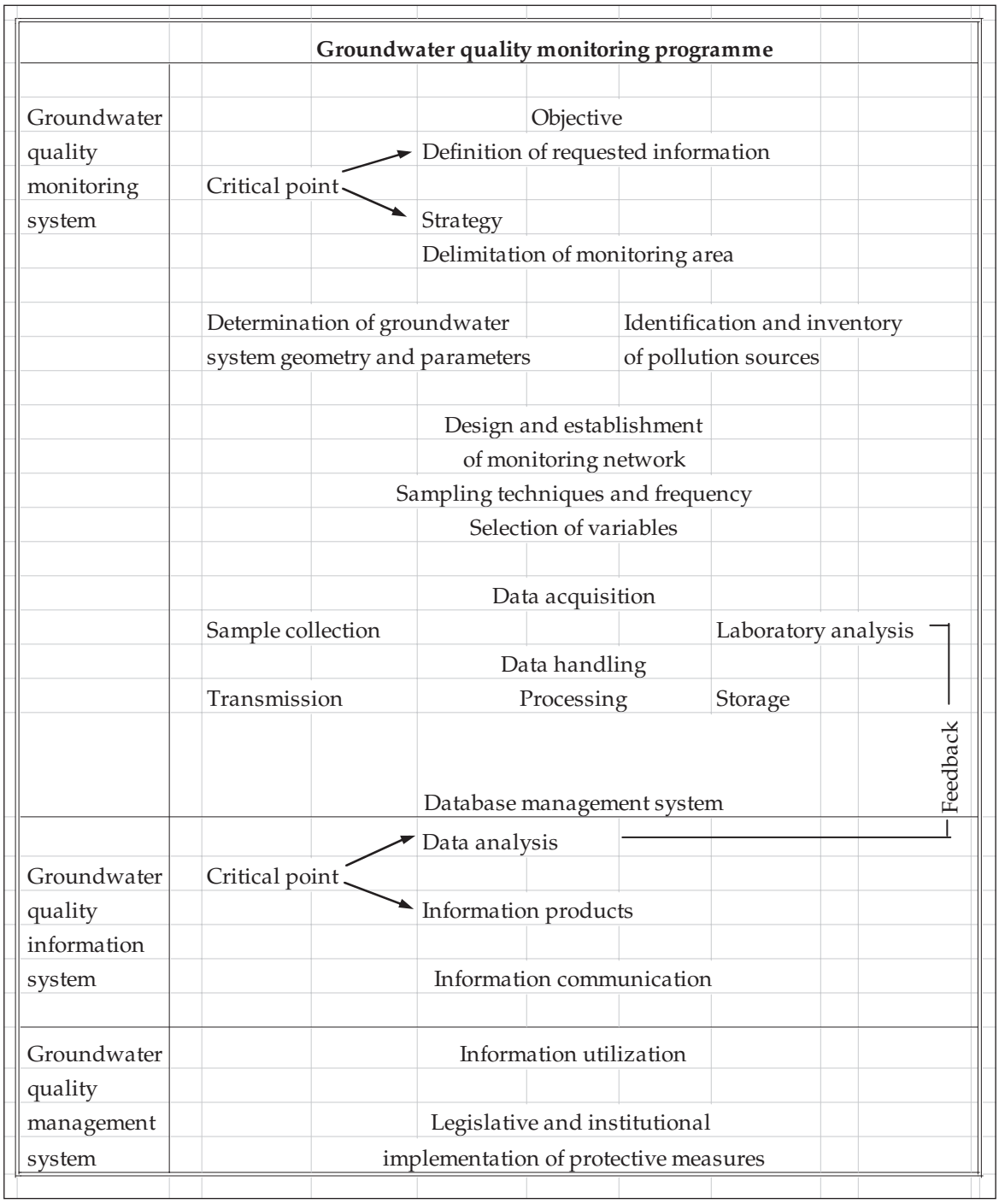
- to collect, process and analyze the data on groundwater quality as a baseline for assessing the current state and anticipating changes and trends in groundwater quality
- to provide information for improvements in the planning, policy, strategy and management of groundwater resource protection and quality conservation.

Groundwater quality assessment of wells in a water supply system, which are usually continuously pumped, pursue other objectives, including different techniques, frequency of groundwater sampling, and laboratory analysis.

Quality Assurance/Quality Control (QA/QC) procedures for groundwater sampling and laboratory analysis support the quality of groundwater chemistry assessment.

Data processing is an important task when groundwater chemical analysis are available from different laboratories and from various periods or seasons of the year. When a data base

Table 4.3.1.1 Groundwater quality monitoring program



system is established and data analysis made, feedback to improve data acquisition and handling methods is an important part of the assessment process of groundwater quality (Table 4.3.1.1).

The assessment of groundwater chemistry and related classification methods and correlation procedures include simple inspection and evaluation of groundwater chemical data as well as more complex graphical and numerical visualization methods including sophisticated statistical procedures. Different graphical methods can be applied when groundwater quality maps are depicted.

4.3.2 Graphical and numerical methods of groundwater quality assessment and classification

Assessment and classification methods are divided accordingly the expression of groundwater chemistry which may be pictorial, punctual, linear or numerical.

Pictorial methods are helpful particularly on the correlation of groundwater chemical analysis. The values of major chemical parametres are depicted in columns and circular or radial diagrams. The length of the column or the diameter of the circle show the level of TDS. The values of ions are expressed in meq% or meq/l, values of TDS in meq/l or mg/l.

Column diagrams, applied in groundwater chemistry by Collins (1923), are usually formed by two columns, the left one is expressing the values of cations and the right anions. The two columns of the diagram should be completed in the center by the column presenting salinity and alcalinity according to Palmer's classification, or by other parametres like hardness values, silica concentrations, etc.

Circular diagram may be adapted as two concentric circles: in the smaller circle are expressing values of some components (SiO_2, F^-, etc.) typical for the region. The bigger circle is subdivided on the basis of meq% of major ions. Usually values of major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) are expressed in the upper part and major anions (HCO_3^-, Cl^-, SO_4^{2}) in lower part of the circle. Carlé (1956) developed a special diagram in which values of selected elements are depicted in the form of individual eccentric circles.

In radial diagrams the concentrations of major elements (in meq/l, meq% or exceptionally in mg/l) are expressed in four or six axes. The values of ions presented on individual radial lines are joining and form irregular polygon whose shape is typical for main chemical types of groundwater. At one radial diagram is possible to depict several groundwater analysis. Most frequently are used hexagonal diagrams of Tickel (1921) and six-axis radial diagram od Dalmady (1927). In Maucha (1949) vector diagram are six major ions plotted on six vectors, the length of each vector expresses the concentration of particular ions.

In this group should be also included Stiff diagram (1951). The values of mayor ions which form the chemical type of groundwater are expressed in meq/l on horizontal rayes drawing each other in equal distance. On the left side of vertical central axis, which represents the zero level, are plotted cations, on the right side anions. The shape of diagram, as a result of joining of points-values of individual ions, is typical for specific chemical type of groundwater. Stiff diagram is especially applied when vertical hydrochemical profiling of groundwater system is graphically visualized.

Punctual methods are suitable to compare a sizable number of chemical analysis of groundwater of different origin and types in one diagram. There are several limitations of punctual methods. Results of chemical analysis (major ions) are expressed as points in triangle, rhombus and square diagrams or their combination. Values of variables are presented in meq%. By color or various size of points the content of total dissolved solids (in mg/l) could be expressed. Position of points in diagrams corresponds to chemical type of groundwater. Using the triangle, the groundwater chemistry is plotted in two-diagrams, one for cations ($Na^- + K^-$, Ca^{2-}, Mg^{2-}) and other for anions (HCO_3^-, Cl^-, SO_4^{2-}). However presentation of other variables is also possible.

Expression of groundwater chemistry in two points, as a disadvantage of triangle diagrams, improved Hill (1940) and particularly Piper (1944). Piper diagram, which is a combination of two triangles (with expression of cations and anions points) with rhombus (third scoring point indicates the chemical type of groundwater as a result of the relationship among the major ions

– alkalies, alkaline earths, alkalinity and salinity), is frequently applied in groundwater chemistry assessment. Durov (1948) combined two triangles with square.

square diagram developed Tolstichin (1939) and Langelier and Ludwig (1942). The following combination of ions is mostly used: on vertical ordinate are plotted $Na^{-} + K^{-}$ against Ca^{2+}, Mg^{2+}, on horizontal ordinate are mostly depicted $Cl^{-} + SO_4^{2-} + NO_3^{-}$ against $HCO_3^{-} + CO_3^{2-}$. Through various symbols for points (or size of points) groundwater of different origin or types of aquifers or different content of total dissolved solids could be expressed.

In all geometrical diagrams, one side of each vertex represents always 100 meq% of plotted ions. That is why rhombus and square diagrams could be divided in 100 plots (1–100) and chemical types of groundwater are classified according to the plot number. In some diagrams could be expressed chemical types (also called hydrochemical facies) of groundwater defined in accordance with the dominant type of ions and plotted graphically as a part of the whole diagram (Back, 1966).

***Linear method*s** are suitable to present limited number of chemical analysis of groundwater in diagram on which variables are plotted on the vertical axes in meq/l or mg/l, using mostly logarithmic, scale. Groundwater chemistry is expressed on the diagram as a line connecting the values of variables on a particular vertical axis. Most widely used is semilogarithmic diagram of Schoeller (1935). Zima and Vrba (1960) completed diagram with the line expressing the values of variables conformed to a drinking water standards. From diagram is well visible whether the groundwater chemistry fulfills criteria required for drinking water.

Other type of linear diagram expresses cumulative percentage composition of mayor and selected variables. The shape of the line is characteristic for main chemical types of groundwater.

Numerical methods are widely applied in groundwater chemistry assessment and classification. The oldest and still used Palmer's classification (1911) is based on splitting up ions according to their contribution to salinity or alkalinity. Groundwater chemistry is classified in five groups. Three groups include different types of salinity and two groups primary and secondary alkalinity. Palmer's concept was developed in the form of graphical visualization by Rogers (1917), Langelier and Ludwig (1942) and others.

Widely used numerical method is also Kurlov formula, expressing (in meq/l or meq%) in form of fraction the relationship among major cations (numerator) and major anions (denominator). Concentration of TDS (in mg/l) or other parameters (SiO_2, temperature) could be added in front or behind the fraction.

4.3.3 Statistical methods of groundwater quality assessment

Statistical methods help elucidate the extent of natural processes and human impacts on groundwater quality. The representativity of statistical operations and the choice of statistical methods depend on:

- representativity of the groundwater data sets under study,
- relationship between data sets, and
- objectives of groundwater assessment.

From the selected data files, systematic errors must be eliminated, while they may contain random errors which do not affect the results in any significant way.

Relationship between variables are categorized as stochastic or deterministic. Deterministic relationships can be used rarely to describe natural processes, and thus also the groundwater system, because groundwater parameters are variable and random. Correlation and regression are stochastic relation, both of them are commonly used to analyse the groundwater quality

monitoring data. In view of the close mutual dependance among variables, correlation is of a special importance particularly when dealing with the anthropogeneous impacts on the groundwater system.

The statistical methods used should be matched with the purposes of groundwater quality assessment and include: correlation and regression analyses for selected physical and chemical parameters of groundwater trend analyses involving the calculation and graphic interpretation of the trends in evolution of the physical and chemical variables of groundwater in space and time spectral analyses giving expression of periodic changes of the physical and chemical composition of groundwater in time. Factor analysis also can be used to calculate statistically selected relations between chemical and hydraulic parameters of groundwater within the vegetation-soil-water system.

The purpose underlying the use of multivariate statistical methods is to optimize the density and location of groundwater quality monitoring points, sampling frequency and the number of parameters and variables to be monitored and analyzed, thereby reducing the costs of groundwater monitoring while preserving the value of the information obtained.

4.3.4 Groundwater chemistry presentation on maps and on cross-sections

The following methods are used to express groundwater chemistry on maps or cross-sections: pictorial diagrams, areal methods, numerical methods and iso-lines of equal concentration of variables or equal ionic ratios.

Quality of data available, density of sampling points, scale of the map and objective of groundwater quality assessment influence significantly the choice of method to present groundwater chemistry on the map or cross-section.

Pictorial diagrams. Different kinds of column, circle or radial diagrams are applied to express on the map chemical type of selected points of groundwater quality monitoring network. Individual characteristics of groundwater (TDS, SiO_2, temperature, etc.) could be also plotted on the map by different size or colour of the circle. Pictorial diagrams are applied on the maps of smaller scales (1:50 000 and less).

Areal methods are suitable to use on the maps of bigger scale (1:100 000 and more) and express groundwater chemistry in a generalized form. Areas of selected chemical types of groundwater are differentiated by colors or shadings, or by combination of both.

Numerical methods are applied in a similar way like pictorial diagrams, expressing chemical characteristics of individual groundwater monitoring points. Kurlov formula is the most suitable to express groundwater chemistry on maps.

Isolines methods are frequently applied on the map of different scales to present equal concentration of selected variables (iso-chlors, iso-sulfates, iso-TDS, etc.) or equal ionic ratios (sodium-chloride, alkalinity-sulfate, etc.). Color of lines could be used to differentiate chemical properties of individual aquifers. Hem (1959) in his concept of groundwater quality maps classification calls these maps as isogram maps.

Cross sections. Pictorial methods (particularly Stiff diagram), areal and numerical methods are widely applied to express groundwater chemistry in vertical profile of groundwater system (two or more aquifers or vertical profiling of one thick aquifer). Cross sections usually form a part of hydrochemical maps and help to visualize the complexity of groundwater system in a vertical scale. However both, the construction of hydrochemical maps or cross-sections, required good knowledge of hydrogeological conditions and some level of homogenity in groundwater chemistry of the mapped area.

Maps of groundwater chemistry are widely used and depicted in a different scales on the international, national, regional and local level in many countries.

4.4 Groundwater vulnerability, assessment and mapping

In many parts of the world groundwater is the most accessible, relatively the safest and often the only source of drinking water. Timely assessment of groundwater resources vulnerability prevents their qualitative alteration, deterioration or pollution. If groundwater vulnerability is not evaluated in time and groundwater protection strategy is not defined, the costs on groundwater remediation – when polluted – by far exceed those on its preventive protection. Groundwater vulnerability assessment must be interrelated with and integrated into master plans to support the planning, policy and strategy of groundwater resources protection and quality conservation.

4.4.1 Concept and definition of groundwater vulnerability

The formulation and definition of what is understood by ground water vulnerability and clarification of the concept of a vulnerability map is essential for the design, methods of cartographic representation, and compilation of vulnerability maps.

The concept of groundwater vulnerability is based on the assumption that the geological environment may provide some degree of protection to groundwater against the natural and human impacts, especially with regard to contaminants entering the soil-rock medium. The term 'vulnerability of groundwater to contamination' was introduced by French hydrogeologist J. Margat (1968) in the late 1960s. A synoptic map of aquifer vulnerability to pollution in France on a scale of 1 : 1 000 000 was published as early as 1970 (Albinet, 1970).

The idea of describing the degree of vulnerability of groundwater to contaminants as a function of hydrogeological conditions by means of maps was conceived to show that the protection provided by the natural environment varies at different locations and that it would be helpful to identify on maps areas where protection measures are most needed.

The fundamental concept of groundwater vulnerability is that some land areas easily contribute to groundwater contamination, and thus are more vulnerable, and others do not. Results of vulnerability assessment are portrayed on a map showing various homogeneous areas, sometimes called cells or polygons, which have different levels of vulnerability. The differentiation between the cells is, however, arbitrary because vulnerability maps only show relative vulnerability of certain areas to others, and do not represent absolute values.

Although the concept of groundwater vulnerability has been around for almost three decades, a generally recognized and accepted definition of vulnerability has not been developed yet. However the following definition is widely accepted: Groundwater vulnerability is a natural intrinsic property of the groundwater system that depends on the ability or sensitivity of this system to cope with natural processes and human impacts (Vrba et al., 1994).

The Committee on Techniques for Assessing Groundwater Vulnerability of the U.S. National Research Council (1993) defined groundwater vulnerability to contamination as 'the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer'. However later in the text, the Committee also differentiated two general types of vulnerability: specific vulnerability (referenced to a specific contaminant, contaminant class, or human activity) and intrinsic vulnerability, which does not consider the attributes and behaviour of specific contaminants.

The U.S. General Accounting Office (1991) used the term 'hydrogeological vulnerability' for

the instrinsic susceptibility of an aquifer to contamination and the term 'total vulnerability' for vulnerability that is a function of hydrogeological factors, as well as of the land-use practices and contaminant loading.

Development of a generally recognized and accepted definition of vulnerability does not imply a standardized approach to vulnerability mapping. Hydrogeological environments are much too diverse to be subjected to a standardized assessment. However, it is important to agree on a common base, i.e. definition of vulnerability, before we determine possible approaches to the assessment of these diversified conditions.

Groundwater vulnerability assessment

The assessment of groundwater vulnerability and methods and techniques of its graphical and numerical representation are essential in the compilation of vulnerability maps. All groundwater, with possible exception of fossil water that has not been new part of the hydrological cycle and deep-seated brines, is vulnerable to various degrees. Vulnerability of groundwater is a relative, non-measurable, dimensionless property. The accuracy of its assessment depends above all on the amount and quality of representative and reliable data.

Vulnerability map is based on the assessment and display of several parametres, which vary over regions as a function of the physical environment. The principal attributes used in groundwater vulnerability assessment (intrinsic and specific) are recharge, soil, properties, and the characteristics of the unsaturated and saturated zone (Table 4.4.1.1).

4.4.2 Intrinsic parameters of groundwater vulnerability

Recharge is the amount of water passing through the unsaturated zone into an aquifer during a specified period of time. Recharge is usually expressed as annual net recharge. The amount and mode of recharge significantly affect the physical and chemical processes in the soil-rock-ground water system, and ultimately the attenuation processes. Also needed are the climatic data, such as precipitation, air temperature, and evaporation that significantly influence the amount of recharge. However the importance of recharge varies with the change of climatic conditions. In arid zones recharge is very low and nil in hyperarid regions. In these regions groundwater vulnerability is very low because it is cut from present-day hydrologic cycle. In semi-arid zones low recharge implies very slow movement of contaminants. The result is delayed detection of groundwater contamination. Net recharge to groundwater body is more difficult to evaluate in case of bank river or stream infiltration.

Recharge is frequently used in the U.S. vulnerability maps and its importance is regarded rather highly (e.g., weight 4 in DRASTIC system, Aller et al., 1987). Andersen and Gosk (1987) used recharge in their concept of the 'restoration capability of an aquifer'. The capability is defined as the volume of water contained in the aquifer (m^3) divided by the rate of recharge (m^3/year). The potential annual recharge was used as one of the main attributes when the sensitivity of European shallow aquifers to acid deposition was assessed (Holmberg et al., 1987).

The ***soil***, the upper unconsolidated layer of the earth's crust, is commonly regarded as one of the principal natural factors in the assessment of groundwater vulnerability. The main soil parameters related to vulnerability include texture, structure, thickness and the content of organic matter and clay minerals (Table 4.4.1.1). If developed, the soil usually forms a continuous layer but the spatial variability of its physical, chemical, and biological properties, especially in the root zones, is great. Therefore, any generalization of soil parameters should be done with great care. The soil has an important attenuation function and represents the 'first line of defense' against contaminants

Table 4.4.1.1 Intrinsic and specific attributes of groundwater vulnerability and their parameters

Attribute/	*Intrinsic (Natural) Primary importance*			
Parameters	*Soil*	*Unsaturated (vadose) zone)*	*Aquifer (saturated zone)*	*Recharge*
Principal	Texture Structure Thickness Organic matter content Clay minerals content Permeability Soil pH Leaching potential	Thickness (related to groundwater table) Lithology (with regard to consolidation and stratification of rock) Geometry	Lithology (with regard to consolidation and stratification of rock) Thickness Geometry Effective porosity Hydraulic conductivity Groundwater flow direction and hydraulic gradient Age and residence time of groundwater in aquifer	Net annual recharge rate Annual precipitation
Supplemental	Moisture Cation exchange capacity Reduction and adsorption Carbonate content + Bulk density + Full soil water capacity + Organic carbon	Vertical permeability Weathering rate (index) Fracture rate (index) Karst rate (index) Boundary condition	Storativity Transmissivity Permeability (primary, secondary)	Evaporation Evapotranspiration Air temperature Humidity

+ Mostly assessed when groundwater vulnerability to diffuse contamination from agricultural activities is studied.

Attribute/	*Intrinsic (Natural) Secondary importance*			
Parameters	*Topography*	*Underlying geological unit of aquifer*	*Contact with surface and sea water*	*Specific*
Principal	Slope variability of land surface	Permeability Structure and tectonics Potential recharge/ discharge	Gaining/loosing stream in relation with underlying aquifer Bank infiltration Interface of salt/fresh water in coastal areas	Land use natural: forest, meadow, non-farm landman-made: farm land, land under industrial activities, rural or urban settlements Population density Travel time of contaminants in the unsaturated zone Attenuation capacity of the soil, unsaturated zone, and aquifer in relation to the specific contaminant
Supplemental	Ground elevation Vegetation cover	In case of confined aquifer the same parameters apply for the overlying unit of aquifer		Contaminant features Residence time of contaminant in aquifer Distribution coefficient (K_d) Persistence (half-life) Artificial recharge Irrigation Drainage

moving from the surface toward the groundwater. The soil is a critical attribute when groundwater vulnerability to diffuse contamination sources (fertilizers, pesticides, acid deposition) is assessed.

The soil has a specific position among the groundwater vulnerability attributes because it itself is very vulnerable. The soil's function as a natural protective filter in the retardation and degradation of contaminants can be damaged relatively easy. The damage may lead to the loss of control over groundwater quality. Therefore, the soil properties assessment should always take into consideration whether the soil in the area under study is in natural conditions or under the human stress.

The ***unsaturated zone's*** main feature is that it delays the arrival of contaminants to the groundwater table by a variety of chemical and physical processes. This zone is particularly important in areas where the soil column is not well developed. Then the character of the unsaturated zone (thickness, lithology, and vertical permeability) and its potential attenuation capacity decisively determine the degree of groundwater vulnerability. The thickness of the unsaturated zone depends on the position of the water table, which is not stable and fluctuates. For this reason, an analysis of groundwater level fluctuations should be included in vulnerability assessment and the highest elevation of the water table (the minimum thickness of the unsaturated zone) is used in vulnerability evaluation. If unsaturated zone is composed of low permeable rock, it creates a confining layer for the underlying aquifers and reduces significantly their vulnerability.

An ***aquifer*** (the saturated zone) is a heterogenous system and its influence on groundwater vulnerability varies spatially and with depth. The aquifer vulnerability should be differentiated according to the existing groundwater flow systems of varying geographical extent (local or regional) and depth (shallow or deep). The definition of recharge and discharge areas and determination of semiconfined, confined and unconfined aquifer conditions is quite important and must always be considered when assessing its vulnerability.

The main parameters for assessment of aquifer vulnerability include the aquifer nature and geometry, porosity, hydraulic conductivity, transmissivity, storage properties, and groundwater flow direction (Table 4.4.1.1). The importance of hydraulic conductivity is emphasized.

Fewer attenuation processes take place in the saturated zone where solution, dilution, and hydrodynamic dispersion would be the most important for the assessment of aquifer vulnerability.

From the attributes of secondary importance, *topography, groundwater/surface water relation, and the nature of the underlying unit of the aquifer* usually are included in vulnerability assessment. Their importance for vulnerability assessment varies with the area. Depending on the natural conditions, the importance may be greater in flat recharge areas, in the sector of surface stream bank infiltration into a shallow aquifer and in aquifer where groundwater has a contact with the underlying strata of high ion-exchange capacity; and smaller in steep-slope recharge areas, and in groundwater system with low level ion-exchange or sorption capacity of the underlying strata of the aquifer. An important attribute is particularly topography, which influences amount of recharge, soil development, and groundwater flow direction and velocity.

4.4.3 Assessment of groundwater specific vulnerability

Specific vulnerability of a groundwater system is mostly assessed in terms of the risk of the system becoming exposed to contaminant loading. In comparison with the assessment of intrinsic vulnerability, which is based mostly on the static natural parameters of the soil-rock-groundwater

system, the dynamic and variable parameters are included in the assessment of specific vulnerability (Table 4.4.1.1). The contaminant's travel time in the unsaturated zone and its residence time in an aquifer are often introduced.

The important parameter in the assessment of specific groundwater vulnerability is the attenuation capacity of the soil, of the unsaturated zone, and of the aquifer with respect to the properties of a particular contaminants. The attenuation capacity of these media can be exceeded or reduced over time, which results in a changed vulnerability of the groundwater system to that contaminant. A special approach is required for persistent and mobile contaminants. In their case the role of attenuation processes in the soil and the unsaturated zone is minimal. The aquifer has to cope with the persistent contamination on its own and its vulnerability depends mainly on the amount of water stored in the aquifer supported by the net recharge. Both of these parameters control the dilution of the contaminant in groundwater, which is the most important attenuation process in the aquifer.

Major attributes involved in assessing specific groundwater vulnerability include: land use and population density. There is a fundamental difference between areas with land under human stress (agriculture, industry, settlements, acid deposition) and areas where natural landscape with natural vegetation predominates (forests, uncultivated meadows, mountains regions). The more densely an area is populated, the greater the potential and real contaminant load on the groundwater system.

The single-purpose assessment is the simplest concept of the specific groundwater vulnerability assessment. The vulnerability is evaluated with respect to only one type of contaminant or one group of contaminants having similar properties. The attenuation capacity of the soil, unsaturated zone, and aquifer for a particular type of contaminant and its properties, travel time, and residence time are assessed and mapped. Usually a single map suffices for portraying single purpose specific groundwater vulnerability.

An example of the single purpose assessment at the international level is evaluation of the sensitivity of European shallow aquifers to acid deposition (Holmberg et al., 1987). Good example at the national and regional levels are the maps of vulnerability to nitrate leaching for selected major aquifers in the United Kingdom (Carter et al., 1987) and for southern Ontario aquifers in Canada (Ostry et al., 1987). The travel time of nitrate is not included in the assessment process in these maps.

Single-purpose specific vulnerability of groundwater is often assessed at the local scale with respect to point sources of contamination. Contaminants from point sources frequently enter the groundwater system under the soil profile (leaking underground tanks, no controlled landfills, etc.). In such cases the role of soil as an attenuation medium is nil, which considerably increases the aquifer's vulnerability.

Multi-purpose assessment of groundwater vulnerability includes an assessment of two or more contaminants or groups of contaminants and mapping at different scales. Recharge, time of travel, and contaminant movement through the underground system are widely used for assessing multi-purpose specific vulnerability in order to illustrate the diversity of contaminants and variety of their individual properties.

It is difficult to assess and portray varying contaminants on a single map as groundwater vulnerability differs for different kinds of contaminants. Specific multipurpose vulnerability of groundwater, therefore, can be portrayed on several map sheets using transparent overlays, superimposed maps, or atlases.

4.4.4 Methods and techniques of groundwater vulnerability assessment

There is a number of methods and techniques available for the assessment of groundwater vulner-

ability. They vary according to the physiography of the area under study, the purpose of the study, and the quantity and quality of data. Civita (1994) grouped the available methods into three basic categories: hydrogeological complex and setting methods, parametric system methods, and analogical relation and numerical model methods.

The hydrogeological setting methods primarily employ the overlay cartographical method and can be used for large areas with a variety of hydrogeological and morphological features. The methods involve the comparison of a subject area to criteria judged to represent vulnerable conditions.

The parametric methods include matrix systems, rating systems, and point count systems. The overall procedure for all of these systems is the same. It begins with the selection of parameters judged to be representative for vulnerability assessment. Each of the selected parameters has a given range, which is subdivided into discrete hierarchical intervals. Each interval is assigned a value reflecting the relative degree of vulnerability, and the rating points are summed. The final numerical score is divided into segments expressing a relative vulnerability degree.

The point count system models, also called the parametric weighting and rating methods, differ from the rating systems that in addition to a rating a multiplier (importance weight) is assigned to each parameter to reflect fairly the relationships among the parameters and their importance for vulnerability assessment. The point-count methods DRASTIC (Aller et al., 1987) and SINTACS (Civita et al., 1991) are the well known ones.

Analogical relations and numerical models are a narrowly defined category of methods generally applicable for the assessment of specific vulnerability only. These methods require contaminant specific and site-specific data. The application of models is useful for small areas where vulnerability to contamination shall be assessed.

Data presentation on vulnerability maps

Vulnerability assessment requires a thorough knowledge of local hydrogeological and hydrochemical data and location and properties of potential contamination sources.

The amount, distribution and quality of basic data determines the quality and accuracy of vulnerability assessment. A close correlation exists between the density of data points, amount of data obtained at any measured point, and the scale at which the map is to be constructed.

Also the reliability of basic data has to be considered before selecting a method for vulnerability assessment. For example, reliability of data varies with the elevation of the area under study, and it sharply decreases already at altitudes higher then 300-400 m above the sea level. Therefore, for mountainous regions, only the simplified vulnerability assessment can be used.

Vulnerability maps can be created manually or photographically, if the individual data layers are on transparencies; or by a computer, if the data are encoded into a geographical information system (GIS).

An important step in manual vulnerability mapping is the method of combining data that are being mapped. One of the most widely used approaches is the overlay method, which involves producing several maps of individual attributes or their parameters on scale-stable transparent material. A composite vulnerability map can be obtained by stacking all of the transparencies.

Stacking of the individual layers of data also can be done by computer. Data can be manipulated by any of the existing GIS, such as ARC/INFO, ERDAS, or GENE MAP. This approach requires that all attributes and their parameters are geographically referenced, digitized, and entered into a data base. Once in the data base, it is possible to register all data sets as data

layers with a common coordinate system and manipulate them to produce derived maps, and finally, a vulnerability map.

The design of groundwater vulnerability maps still lacks international coordination and standardization. An agreement should be reached on colours, patterns, and symbols to be used; a standard graphical design; and explanatory notes and text accompanying the map. All information should be presented on one map sheet.

4.4.5 Classification of groundwater vulnerability map

Groundwater vulnerability maps usually are classified as special purpose interpretive groundwater protection maps, derived from general hydrogeological maps. They differ from hydrological maps in that they do not show the elements of a groundwater system but the specific characteristics of these elements as they relate to vulnerability of groundwater, which vary over regions as a function of changing physical environment.

The groundwater vulnerability map is expressing a more or less subjective view of the capacity of the subsurface environment to protect groundwater, typically in terms of water quality. It is subjective because the contents of the map must meet requirements or criteria of the map user. The ultimate goal of the vulnerability map is a subdivision of an area into several units showing the differential potential for a specified purpose and use. The subdivision is achieved by combining several thematic maps of selected physical attributes and/or their parameters.

There are basically two approaches to vulnerability mapping, itrinair and specific. The intrinsic or natural vulnerability map is used to evaluate the natural vulnerability of groundwater, without context to a specific contaminant or a specific contamination source. The specific vulnerability map is used to evaluate the impact of a specific contaminant or contamination source on groundwater system.

Groundwater vulnerability maps can be classified according to their purpose, scale, and method of compilation. According to purpose, vulnerability maps are compiled to be used for groundwater protection planning, strategy and management, assessment of contamination potential and education purposes. The scale of maps depends on their objective, the character and complexity of natural conditions, and the accuracy required. Generally, four categories of map are distinguished (Table 4.4.5.1): small-scale (1:500 000 or more), medium-scale (1:500 to 1:100 000 and 1:100 000 to 1:25 000), and large-scale (1:25 000 or less). According to the method of compilation, vulnerability maps can be either analytical, focusing on a specific condition or specific contaminant (usually of larger scales) schematic and operational concern of regional groundwater vulnerability procedure and synthetical, offering a general overview of intrinsic vulnerability (usually of smaller scales).

For example, large-scale maps usually are special-purpose maps expressing contamination potential of a specific contaminant or a specific human activity. Such maps require representative, detailed data that are not always available, and therefore, a complementary field investigation is necessary. On the other hand, the need for detail is much lower for the general overview (synoptical) maps showing groundwater intrinsic vulnerability at a national or international scale.

The map scale also determines the graphic representation of vulnerability. The large scale specific maps, based on a large volume of data, increasingly are produced digitally or with the help of a geographical information system (GIS). Manual construction still is the preferred method for synoptical maps, however manual construction of synoptical maps is costly and time consuming.

Table 4.4.5.1 Classification of groundwater vulnerability maps

Type of map	*Scale*	*Purpose and content*	*Graphic representation*
Synoptical General overview	1:500 000 or more	General planning and setting policies in groundwater protection on national or international level; educational purposes. Synthetical maps showing intrinsic vulnerability of groundwater, local details are lost.	Mostly manually compiled maps or atlases computerized; synoptial maps are not frequent yet.
Schematic	1:500 000 to 1:100 000	Regional planning, groundwater protection strategy and management, vulnerability assessment related to diffuse pollution problems. Most of local details are still lost, need to be followed by specific mapping.	Mostly manually compiled maps or atlases, less frequent computerized maps (GIS).
Operational	1:100 000 to 1:25 000	District land-use planning and design of groundwater protection programs. Analytical maps depicting vulnerability of groundwater in areal extent in relation to the specific contaminant. Field survey usually desirable.	Computerized digital maps (GIS), less frequent manually compilled maps; cross sections and diagrams increase their usability.
Specific Special purpose	1:25 000 or less	Special purpose and site-specific maps for local or city planning, water supply system protection and point pollution problems clarification. Express local or site specific groundwater vulnerability. Require set of representative data; site specific investigation is necessary.	Computerized digital maps (GIS) or diagrams (surface charts) and grid maps.

4.4.6 Limitations in use of groundwater vulnerability maps

In order to have a broad range of uses and applications, vulnerability maps should be consistent, standardized in graphical and numerical expression, understandable, with a good synthetic visibility, and accompanied by expanded descriptive legend and comprehensive explanatory notes, thereby helping to overcome the gap that frequently exists between the scientific and lay communities. The risk must be minimized of producing too sophisticated maps overflowing with data, which might lead to their misinterpretation or misuse or, in case of low understandability, even to their non-use.

Groundwater vulnerability maps are used for three main purposes: 1) planning, policy and management, 2) contamination assessment, and 3) education.

The maps are particularly useful as an effective and valuable tool for the planning, policy, and operational levels of the decision-making process concerning groundwater protection strategy and management. Vulnerability maps can help planners and regulators make informed, environmentally sound decisions regarding land use and protection of groundwater quality. Vulnerability maps can be used also for the first-cut screening of an area, which would allow planners to focus

on the areas of highest priority. However, under no circumstances should the vulnerability maps be used as substitutes for site-specific studies.

Vulnerability maps also are a good tool for groundwater professionals to make local and regional assessment of vulnerability potential, to identify areas susceptible to contamination, and to indicate the relative concern and effort needed for more detailed assessment. The maps help to determine which areas may have groundwater vulnerability problems and what types of site-specific data or studies may be needed. Vulnerability maps also can help in the design of groundwater quality of monitoring networks and in the evaluation of contamination situations.

Vulnerability maps inform regulators, and decision-makers about the need of groundwater protection and contamination prevention. The maps also can be used to educate the public and policy makers about aquifers vulnerability being part of a larger, interconnected ecological system affected by human activities.

The limitations of vulnerability maps are mainly caused by the lack of representative data with relation to the scale of the map; inadequate knowledge of the soil-rock-groundwater system; lack of generally accepted methodology; and insufficient verification and control of the process of vulnerability assessment.

The use of vulnerability maps is predetermined by their inherent deficiency-generalization of multifactor data. The amount of data and the map scale are in a delicate balance. Any attempt to disturb this balance, for example by a common mistake of enlarging the general map and presenting it as detailed information, would lead to gross errors. The major potential misuse of vulnerability maps is in attempting to extract site-specific information from or in applying site-specific problems to a general vulnerability map.

Vulnerability maps should be carefully thought out and their meaning and degree of reliability fully explained. It is important that a disclaimer appears on a map informing the user about the map limitations and intended use. The map also should be accompanied by sufficient documentation to fully describe the assumptions and methodologies used and the level of accuracy of presented information. With a proper disclaimer, any vulnerability map can be used, even that one based on scanty data.

5 Fresh and brackish groundwater resources and their use on continents and in individual countries

5.1 Groundwater resources and their use in Europe

5.1.1 Groundwater discharge and natural fresh groundwater resources of Europe

In recent decades serious work has been carried out in different European countries for the regional assessment of groundwater discharge and natural groundwater resources. For the first time, quantitative characteristics of the natural productivity for the main aquifers and for groundwater's role in the water balance and total water resources can be obtained in separate regions.

A brief characteristic of groundwater discharge and natural groundwater resources is given below. The results have been widely used for assessing and mapping groundwater resources in the former USSR countries (Maps of groundwater discharge in the USSR at a scale of 1:1 500 000 and 1:2 500 000, published in 1965 and 1972 correspondingly), territories of the Central and Eastern Europe at a scale of 1:1 500 000 and a Monograph, prepared according to the Project of UNESCO International Hydrogeological program and published in 1982–3 and some other works. It should also be noted, that the *World Map of Hydrogeological Conditions and Groundwater Flow* has been compiled not long ago, at a scale of 1:10 000 000, also according to the project of the International Hydrogeological Program. Scientists of many European countries have actively participated in these studies.

The regional estimates of the groundwater runoff of West European countries given in the above works were analyzed and refined with consideration for more recent hydrogeological and hydrological information. The hydrometric data were updated (*Discharge of selected rivers*, 1985) and additional information on discharge of springs, groundwater development, aquifer parameters and water-balance computations (Streit, 1971; Nordberg and Persson, 1974; Reeves et al., 1978; Margat, 1979; Zektser et al., 1989) were analyzed.

5.1.1.1 Results of groundwater runoff studies

The analysis and generalization of all the above information resulted in compiling a map of groundwater flow of Europe on a 1:10 000 000 scale. The main data of the map – average long-term discharge values in liters per second per square kilometer – are shown by a color cartogram. The schematic map of groundwater runoff of Europe (*Groundwater Flow Map*..., 1983) shows the distribution of these values by hatched lines. This allows the map compilers to trace and visually represent on the map the role of geological, structural, hydrological, and hydrogeological factors in groundwater runoff generation and distribution. Groundwater runoff/precipitation ratios are shown on the original map by isolines, which fairly represent the nature of groundwater generation closely associated with the general physiographic zonality and altitudinal zoning.

The schematic map shows that the groundwater runoff in Europe is irregular. In keeping with the geostructural regional subdivision, let us follow the variation of groundwater discharge values and groundwater runoff/precipitation ratios from east to west. This will reveal the main groundwater runoff generation characteristics.

The Urals hydrogeological area extends from north to south for over 3,000 km, has a complicated geological structure, and is characterized by a sharp alternation of groundwater flow media both horizontally and vertically. This is indicative of diverse groundwater runoff generation conditions largely in fractured and fracture-karst media. Substantial groundwater resources are typical for highly dislocated karstified Paleozoic rocks where specific groundwater discharge values amount to 10–15 l/s.km^2 and up and groundwater runoff/precipitation ratios range from 10 to 40%. Minimal groundwater discharge values are characteristic of the volcanogenic and metamorphic formations of the spurs of the South Urals and the North Polar Urals. Thus, the distribution of groundwater runoff values in the Urals area definitely depends on general geo-structural, climatic and orographic conditions. Specific groundwater discharge values gradually increase from south to north from 0.1–1 to 1–3 l/s.km^2 that is characteristic of metamorphogenic and magmatogenic types of groundwater flow media. These values sharply increase on the contact with the karst type of groundwater flow medium as well as in the zone of influence of local geological and hydrogeological conditions.

The main groundwater runoff in the Timan hydrogeological massif is generated in Paleozoic carbonaceous and terrigenous deposits. Here, the distribution of groundwater discharge values is governed by the flow medium, ruggedness of the topography, and to a lesser degree by confining cover ice-laid deposits. Average groundwater discharge values increase from NW to SE from 0.1–1 (ice-laid deposits) to 1–3 (Paleozoic terrigenous rocks) and 3–5 l/s.km^2 (Paleozoic carbonaceous rocks). The groundwater runoff/precipitation ratios in this region do not exceed 20%.

Farther west, in the Severnaya Dvina artesian basin, the picture of groundwater runoff distribution is more varied. In the western edge of the basin, fractured and karstified limestones outcrop as vast plateau containing appreciable groundwater resources. The Lower Permian dolomite-gypsum and anhydrite strata have mineralized water with a total dissolved solids content of up to 10 g/l. The specific groundwater discharge values amount to 2–3 and locally up to 5 l/s.km^2. The Upper Permian terrigenous aquifer system is mainly within the Mezen and Vychegda depressions and is characterized by discharge values of 2–3 l/s.km^2. Quaternary aquifers play the principal role in the generation of groundwater runoff in the central and southern parts of the basin where discharge values are no more than 2 l/s.km^2.

In the area of the Volga-Kama basin, the groundwater runoff of the upper hydrodynamic zone is largely generated in three types of flow media: karst, porous-fractured, and porous. Specific groundwater discharge values in carbonaceous rock regions range from 1 to 5, in terrigenous rock regions from 0.1 to 3, and in loose alluvial and glacial rock regions from 1 to 2 and locally up to 5 l/s.km^2. The variation of groundwater discharge values within a flow medium depends primarily on the latitudinal variation of precipitation, river network density, and the degree of penetration of principal drains. The range of the variation of specific groundwater discharge values matches well that of groundwater runoff/precipitation ratios (3–20%).

The Caspian artesian basin is characterized by insignificant fresh groundwater resources. marine sandy and clayey sediments are noted for minimal discharge values (0.1–0.05 l/s.km^2 and smaller). Valleys of large and medium rivers with groundwater discharge values of 1–3 l/s.km^2 in alluvial formations are distinguished against the general background of small resources of groundwater with various dissolved solids content. Similar discharge values are also typical for fractured rocks of different origin and age in the north-eastern region of the basin. Consequently, in regions with an arid or semiarid climate, fresh groundwater resources are formed mainly in recent and buried river valleys, filled with sorted material, storing the water of perennial and ephemeral streams.

In the Moscow artesian basin, the most favorable conditions for groundwater runoff generation are observed within Valdai, Middle Russian and other uplands where principal groundwater flow is confined to karstified Devonian and Carboniferous limestones and upper

Cretaceous marl and chalk strata. Here, groundwater discharge values average 2.5–3 l/s.km^2 and the groundwater runoff/precipitation ratios amount up to 15%. Jurassic, Cretaceous and Quaternary sandy and clayey deposits composing lowlands are generally noted for insignificant groundwater resources. Here, discharge values commonly amount to 1–1.5 and locally 0.5 l/s.km^2, and groundwater runoff/precipitation ratios up to 5–10%. Fluvioglacial and ancient alluvial sands, covering large areas in the north and west of the basin, have much groundwater; the discharge values, here, locally amount to 3–5 l/s.km^2.

In the area of the Leningrad and Baltic artesian basins, principal groundwater resources occur in the intensively karstified limestones of the Silurian-Ordovician plateau where discharge values average 3–5 l/s.km^2 and groundwater runoff/precipitation ratios sometimes amount to 30% and up. To the south, Devonian carbonaceous, sandy and clayey deposits are water abundant with discharge values of 1–2 l/s.km^2. The resources of these water-bearing deposits substantially increase where they are hydraulically connected with overlying sandy glacial and lacustrine-alluvial aquifers. However, in waterlogged, poorly drained regions, discharge values decrease down to 1–1.5 l/s.km^2. In the Southwestern Baltic basin, Quaternary glacial deposits make a major contribution to groundwater storage. The diversity of the lithological composition of these rocks is responsible for the sharp variability of discharge values from 1.5–3 to 5–10 l/s.km^2. Thus, the groundwater runoff in the above basins is chiefly governed by the type of groundwater flow medium and depends, to a lesser extent, on physiographic factors and conditions.

In the hydrogeological region of the Voronezh antecline, the most favorable conditions for groundwater resources generation are observed in its northern and northwestern sections. Here, in the Don and Oskol river basins, main groundwater resources (discharge values of up to 3 l/s.km^2) are confined to Devonian and Carboniferous limestones, as well as to Cretaceous sand, marl, and chalk strata. To the south-east, such factors as removal of the topography, a decrease in precipitation, increase in evaporation, and reduction in the transmissivity of marl and chalk rocks deteriorate groundwater runoff generation conditions and, here, discharge values decrease down to 1–0.1 l/s.km^2 and smaller, while the groundwater runoff/precipitation ratio does not commonly exceed 10%.

In the neighboring Pripyat-Dnepr-Donets artesian basin, groundwater runoff generation conditions gradually deteriorate from north-west to south-east. Here, the decrease in discharge from 3 to 0.1 l/s.km^2 is due to the climate and to the replacement of highly permeable fluvioglacial sand of the Pripyat Polesye area by semipermeable fine-grained Paleogene and Neogene sands with clay and sandstone interlayers composing the Poltava plain and the southeastern margin of the basin.

Over most of the Ukranian hydrogeological massif, main groundwater resources are generated in the Pre-Cambrian crystalline rocks. As known, the water content of these rocks depends above all on the thickness of the fractured rock zone and the degree of structural disturbance, as well as on the permeability and occurrence conditions of overlying sediments. Because of this, relatively high discharge values (1–0.5 l/s.km^2) are characteristic for western and southwestern regions where crystalline rocks are overlain by Neogene fluvioglacial sands and limestone.

Within the Black Sea and Moldavian artesian basins, principal groundwater runoff is associated with porous and fractured-porous groundwater flow media. As compared to the relatively small discharge values of Neogene aquifers (0.1–0.5 l/s.km^2), valleys of large rivers (the Danube, Dnepr, Yuzhny Bug, Dnestr and Prut) with more favorable groundwater runoff generation conditions in alluvian, lacustrine and liman deposits have larger groundwater discharge (up to 1 and locally 3 l/s/km^2). The chemical composition of groundwater is closely connected with the distribution of discharge values. The dissolved solids content of groundwater in the coastal regions of artesian structures locally amount to 10–17 g/l.

Within the main artesian structures of the North Caucasus, its southern portion (piedmont area and foreranges) and the northern section (vast plain regions) are distinguished for their groundwater runoff generation conditions. The piedmont area is characterized by appreciable groundwater flow gradients, presence of V-shaped river valleys, the coarse-grained composition of loose sediments, fracturing and karstification of the bedrock, as well as by abundant precipitation. This creates favorable conditions for groundwater recharge and is the cause of intensive groundwater runoff whose discharge values amount to 5 l/s.km^2 and up. Northward the groundwater runoff gradually gets depleted as a result of its intense discharge. This explains the medium discharge (1–0.5 l/s.km^2) from the main sandy and clayey Neogene and Quaternary aquifer systems of the plain portion of the basins. The groundwater discharge values regularly decrease down to 0.1 l/s.km^2 toward the southern, western, and eastern margins of the artesian structures.

When considering conditions of groundwater runoff generation in the Crimea-Caucasus hydrogeological area it should be pointed out above all that the regional distribution of absolute and specific groundwater discharge values is governed by the geotectonic plane of mountain-fold structures, the nature of groundwater flow media, height and dissection of ridges, exposure of their slopes, and altitudinal zonality. The groundwater runoff generally decreases from north-west to south-east according to the increase in the continentally and aridity of the climate. Anomaliosly large discharge values (30–50 l/s.km^2) are typical for the intensely karstified Jurassic and Cretaceous limestone in the Black Sea zone. High discharge values (5–10 l/s.km^2 and up) are characteristic for the fractured rocks of the volcanic massifs of the Caucasus whose elevated position creates favorable conditions for groundwater recharge and discharge. The Paleogene-Neogene and Quaternary sandy and clayey deposits of the Kura lowland have smaller groundwater resources: discharge values rarely exceed 0.3–0.5 l/s.km^2.

Groundwater runoff generation conditions within the vast Baltic and Scandinavian hydrogeological areas depend to a lesser extent on the age and composition of rocks, and are mainly governed by the orographic and climatic features of the areas. Here, under conditions of occurrence of a practically single type of fractured volcanogenic-metamorphic flow medium, the areal distribution of absolute and specific groundwater discharge values are dependent on topographic elevations and annual precipitation. The coefficients of correlation between specific groundwater discharge values and precipitation amount to 0.43–0.80 and at higher elevations up to 0.75–0.85. The map of specific groundwater discharge values as a whole resembles the precipitation map of this region. Discharge values increase from north-east to south-west and west from 2–3 to 5–10 l/s.km^2. Groundwater runoff/precipitation ratios range from 10 to 30%, maximum ratios being in mountainous regions. The overall direct groundwater discharge to the seas from the hydrogeological areas under consideration is over 65 km^3/yr, 12 discharging to the Baltic Sea, 46 to the Norwegian Sea, 5 to the North Sea, and 3 to the Barents Sea.

Over most of the Polish artesian basin, groundwater resources are largely concentrated in Quaternary deposits. The diverse lithological composition of these deposits is responsible for the sharp groundwater discharge variability over the area, from 1–3 to 5–18 l/s.km^2. The largest discharge values are in the northern section of the structure with thick fluvioglacial formations. Here, Neogene and Paleogene sands make a small contribution, 10–20%, to groundwater discharge generation. To the south, in the Kelec-Sandomir range area, groundwater runoff is generated in Mesozoic limestones and sandstones, however, the groundwater discharge values are small on the whole (up to 3–5 l/s.km^2) as compared to those in northern regions. The groundwater runoff/precipitation ratios broadly vary and average 15–20%.

Farther to the west, in the Northern German, Danish and Netherlandish artesian basins, groundwater resource generation conditions are the same in many respects. There, groundwater chiefly occurs in sandy and clayey glacial formations covering large areas. Maximum discharge values (up to 5 l/s.km^2) are observed in outwash plains and the sandy deposits of ancient

terminal moraines in the southern and central portions of the basins. Main groundwater flows are confined to U-shaped ancient valleys of recent and ancient rivers filled with sorted coarse-grained rocks. The northern and coastal regions of the basins are chiefly composed of clayey morainic deposits of recent glaciations in the upper strata, and this is the cause of reduction of discharge values here down to 3–1 l/s.km^2. The exception is the narrow coastal regions covered by dune sand with favorable conditions for groundwater recharge.

The Carpathian fold system within the Pannonian-Carpathian hydrogeological area is distinguished by maximum specific groundwater discharge values. Here, intensive groundwater discharge is generated due to the favorable combination of permeable groundwater flow media, altitudinal climatic zonality, and substantial topographic slopes. The largest discharge values (up to 10 l/s.km^2 and up) are encountered in the karstified limestones of the high-mountain zone of the East and South Carpathians where groundwater runoff/precipitation ratios amount to 35%. At lower elevations, discharge values decrease down to 6–7 l/s.km^2 in similar permeable rocks primarily because of smaller annual precipitation.

The altitudinal zonality in groundwater discharge distribution is also observed in crystalline and volcanic rock areas, as well as in zones with thick flysh strata. Thus, the altitudinal climatic zonality determines the potential possibility of replenishment of groundwater resources, and the realization of this possibility depends on rock composition and permeability.

Similar characteristics of groundwater resources generation are observed within the Alpine fold system. Here, discharge values also gradually increase from the piedmont to middle-and high-mountain regions. Maximum discharge values (up to 20 l/s.km^2 and up) are encountered in massifs composed of karst Mesozoic limestones, as well as metamorphosed and highly dislocated Pre-Cambrian and Paleosoic rocks. Large groundwater discharge values (up to 10 l/s.km^2) are characteristic for the Provence, Jura, and Dauphin areas due to prevalence of karst media there. This general picture of the zonal distribution of groundwater discharge values in the Alpine fold regions may be disrupted in some areas by the azonal manifestation of individual factors of conditions such as alluvial deposits, regional structural disturbances, and the slope exposure effect.

Various groundwater flow media and diverse physiographic factors in the Pannonian artesian basin are responsible for the appreciable range of groundwater discharge values from 10 to 1–0.1 l/s.km^2. Here, the leading role of geological, lithological, and climatic features in groundwater runoff generation is complicated by the substantial manifestation of such subordinate factors as the variability of the granulometric composition of water-bearing rocks, the permeability of cover deposits, and depth to groundwater. The rate of evaporation from the water table depends on depth to groundwater. So, discharge values in the near-channel sections of river valleys decrease down to 1–0.5 l/s.km^2 due to intensive evapotranspiration.

The Thracian massif and the Dinarian system are the largest and most important hydrogeologically within the Balkan area. In Thracia, the main groundwater resources are formed in small intermountain artesian basins and in the weathered fractured zone of hard rock composing ridges and uplands. Despite the fact that metamorphosed and intrusive rocks cover most of the area they are poorly water-bearing on the whole (discharge values are equal to 0.1–1 l/s.km^2) and they hold up to 50% of replenished groundwater resources. Over 20% of the resources are generated in karstified Mesozoic and Proterozoic limestones extended over a restricted area. The ancient alluvial deposits of river systems are also noted for appreciable groundwater runoff: discharge values amount to 1–3 l/s.km^2 (*Groundwater flow ...*, 1982).

In Europe, the Dinarian hydrogeological fold system, and its western portion in particular, is characterized by the largest groundwater discharge values. Here the main groundwater runoff is concentrated in karst limestones extended over vast areas. In this system, the annual precipitation equals more than 1,500 mm and locally even 2,000–3,000 mm. The distinctive feature of the

Dinarian karst is the predominance of groundwater runoff over surface runoff in large areas since many rivers flowing from springs later submerge into karst rocks and flow underground, in caves. Because of this, groundwater discharge values amount to 50–75 l/s.km^2 and up and groundwater runoff/precipitation ratios are equal to 50–100%.

Another picture is observed in the neighboring Apenninian Peninsula. Here, groundwater discharge values are various due to the complicated geological structure and the existing clear-cut latitudinal climatic zonality. In the Padanian artesian basin, occurring in the vast lowland of the same name, groundwater runoff is confined to the thick loose strata of fluvial and glacial formations. However, the relatively poor ruggedness of this area does not contribute to the generation of appreciable groundwater resources. As compared to adjacent mountain regions, the basin is distinguished small discharge values (3–5 l/s.km^2). Farther south of the peninsula, groundwater resources are mainly generated in fractured and porous rocks, except for its central and eastern parts, where karst and porous groundwater flow media are developed, respectively. The groundwater discharge values increase up to 5–10 l/s.km^2 under the effect of this factor and also due to greater precipitation and substantial erosional dissection. Discharge values decrease down to 1–0.5 l/s.km^2 and lower in the eastern coast of the peninsula, in sandy-clayey aquifer systems. Discharge values are relatively smaller (2–1 l/s.km^2 and less) in the Southern Apenninian hydrogeological area.

The tectonic structure and the nature of groundwater flow media are the principal factors of groundwater runoff generation in the Bohemian hydrogeological massif. The fractured intrusive rocks of the basement usually do not contain appreciable groundwater resources, however, in its elevated portions and in faulted zones discharge values generally increase up to 5 l/s.km^2. The limestones of the Moravian and Czech karst have the same values of groundwater discharge. The Paleozoic terrigenous deposits are noted for low permeability and because of these discharge values, seldom exceed 2 l/s.km^2.

In the Southern German artesian basin, northern and southern parts are distinguished according to groundwater runoff generation conditions. The northern area is largely composed of sandstones, shales and more rarely of limestone and marls with gypsum interlayers. In the southern area, the main groundwater resources are encountered in karstified Jurassic limestones. In the north of the basin, groundwater runoff depends to a large extent on the degree of rock fracturing and the drainage effect of deeply incised river valleys. The groundwater discharge values, here, range from 1 to 3 l/s.km^2 and groundwater runoff/precipitation ratios from 5 to 15%. The change of the groundwater flow medium in the south of the basin from fractured and porous to karst and the gradual increase of annual precipitation of up to 1,000 mm results in sharp improvement of groundwater recharge conditions, up to 5–10 l/s.km^2. The cuesta topography of this area contributes to the formation of sinkholes and sinks of fairly wide leveled plateau where groundwater runoff/precipitation ratios are the greatest.

The Rhine-Ardennes hydrogeological system is chiefly composed of dislocated Devonian rocks (shales, sandstones, quartzites, and more rarely limestones). The principal structural elements are oriented from south-west to north-east and are alternations of low ridges and valley depressions, commonly occupied by river systems, lakes, and bogs. The sandstones and quartzites are permeable and this factor together with favorable climatic conditions (the annual precipitation equals 1,000–1,400 mm) contributes to active groundwater runoff/precipitation ratios amount of 10–20%.

The Upper Rhine and Rhone artesian basins, located in the valleys of rivers of the same names, are highly peculiar as to their geological and hydrogeological conditions. These valleys inherit grabens, which are similar to continental rifts in their history of geological development, character of deposits and thickness. The thick sandy and clayey deposits with persistent conglomerate layers are good storage media for groundwater whose resources are appreciable

here. Intensive under-channel flow is generated in the deeply incised valleys of the Rhine and Rhone. In addition, the lithified sedimentary and volcanic rocks composing valley slopes are broken by tectonic disturbances and are noted for intensive fracturing with discharges of some tens of litres per second and larger. The specific discharge values increase from 5–7 l/s.km^2 in the Upper Rhine basin to 10 l/s.km^2 and up in the Rhone basin due to the active effect of the Mediterranean air masses.

In the Paris artesian basin, groundwater runoff is mainly confined to karstified Jurassic and Cretaceous limestones occurring over vast areas along the periphery of the synclinal structure. Here, these rocks outcrop or are overlain by an insignificant cover of Quaternary sediments which creates favorable conditions for groundwater recharge (discharge values are equal to 5 l/s.km^2 and up). In the direction of the centre, groundwater discharge values (3.5–4 l/s.km^2) gradually decrease as a result of covering of limestones by younger sediments and diminishing of fracturing and karstification. In the central area of the basin, the main aquifers are composed of Paleogene and Neogene sands, sandstones, and thin limesones. The permeability of the latter is much smaller. Here, groundwater discharge values do not practically exceed 3 l/s.km^2 and average 1–1.25 l/s.km^2.

In the Aquitaine artesian basin, the principal aquifer systems in the north are composed of lithified, fractured and karstified Jurassic and Paleogene sediments. In the south, they submerge under thick Neogene and Quaternary molassa strata. Here, groundwater runoff is mainly generated in gravel and sand beds which account for 20–80% of the total thickness of the upper hydrodynamic zone (Astie and Marionnaud, 1969). In the extreme south of the basin, sand and coarse gravel deposits form vast detrival cones with highly favorable conditions for groundwater recharge. Here, discharge values amount to 5 l/s.km^2 and up, decreasing to the north down to 3 l/s.km^2 due to the lower permeability of sandy and clayey deposits and the smaller thickness of the water-bearing rocks.

The groundwater resources of the Armorician and Central hydrogeological massifs depend on the tectonic structure, the degree of crushing, and exogenic fracturing of hard metamorphosed and volcanic rocks. In these massifs, the distinctive block structure governs groundwater runoff generation and areal distribution. Graben-like depressions are generally inherited by river systems and filled with Mesozoic and Kainozoic deposits of various origins where the main groundwater resources are stored. Because of this, maximum discharge values in the Central massif are equal to 10 l/s.km^2. In other localities, they range from 3 to 5 l/s.km^2 and groundwater runoff/precipitation ratios vary from 15 to 30%. The total direct groundwater discharge to the Atlantic Ocean from the French coast exceeds 10 km^3/yr.

The hydrogeological structures of Great Britain and Ireland are composed of all types of groundwater flow media. This creates a fairly complicated distribution of groundwater runoff. In Great Britain, the gradual increase of discharge values from south-east to north-west, from 1 to 10 l/s.km^2, is observed. Limestones and sandstones, as well as metamorphic and intrusive rocks have the largest groundwater resources due to their intensive structural disturbance and exogenous fracturing.

Iceland is a peculiar, hydrogeologically. The thick lava sheets with high permeability and faulted zones may have abundant groundwater resources under favorable climatic conditions. Depending on these conditions, discharge values in this country range predominantly from 1–3 to 10–20 l/s.km^2 and up, with a maximum in the rift zone (Kononov, 1983).

The Pyrenean hydrogeological area is subdivided into the Pyrenean fold system proper and the Aragonese artesian basin appreciably differing in groundwater generation conditions. In the West Pyrenees, the main water-bearing rocks are fractured and karstified Mesozoic limestone. Here, under humid climatic conditions (the annual precipitation is 1,500 mm), the groundwater discharge equals up to 10 l/s.km^2 and larger. In the Central (high-mountain) section, groundwater

is also confined to the metamorphic and intrusive rocks of the basement whose water yield is insignificant. To the east, Paleozoic and Mesozoic limestone with distinctive karst features again occur. However, due to a drier climate here, groundwater discharge values decrease down to 5 l/s.km^2. It should be pointed out that the inter-mountain areas and the southern foredeep are composed of Paleogene flysh deposits and thin conglomerate and sandstone water-bearing interlayers. The main fresh groundwater resources in the Aragonese artesian basin are confined to Paleogene limestone and sandstone in the area of their outcrop, as well as to sandy and clayey, chiefly alluvial Neogene and Quaternary deposits. The discharge values in these porous and fractured media amount to 2–3 l/s.km^2.

The hydrogeological massifs of the Pyrenean Peninsula are characterized by diverse groundwater runoff generation conditions. Within the Iberian fold system, discharge values increase from north-west to south-east from 0.1–1 to 1–3 l/s.km^2 which is due to precipitation and the gradual predominance of Mesozoic karstified limestones and fractured sandstones. The distribution of discharge values over the Mesetian massif is primarily governed by precipitation. According to this distribution, groundwater resources gradually decrease from north to south (from 5–3 to 1–0.1 l/s.km^2). The prevailing climatic factor effect, here, is explained by the predominance of one type of groundwater flow media, fractured metamorphic and intrusive rocks.

The Castilian artesian basin, situated between hydrogeological massifs, is distinguished by the broad occurrence of porous and porous-fractured media, whose water conducting properties depend on the total thickness of water-bearing interlayers and the total clay content of the deposits. More permeable and relatively thick water-bearing deposits are encountered in the northern depression of the basin which together with high precipitation leads to groundwater discharge amounting to 1–3 l/s.km^2. In the southern depression, average discharge values usually do not exceed 1 l/s.km^2 and they are larger only in valleys of some rivers.

A peculiarity of groundwater generation conditions in the Western Portuguese basin is that groundwater flow media sharply change along the Tajo valley. The groundwater of the Mesozoic karstified limestone in the north has favorable recharge conditions, above all, high precipitation whose annual total equals 2,000 mm. In the south, in sandy and clayey media, discharge values decrease down to 1–2 l/s.km^2 owing to slower groundwater circulation and smaller precipitation (500 mm/yr).

The total direct groundwater discharge to the Atlantic Ocean and the Mediterranean Sea from the Pyrenean Peninsula is over 9 cu km/yr, i.e. about 10% of the total river runoff (*Water Resources...*, 1975).

In conclusion, the principal characteristics of groundwater generation within the area of Europe should be pointed out.

The character of specific groundwater discharge values is primarily governed by the type of hydrogeologic structure. Artesian basins of platforms, hydrogeological massifs, old and young mountain-fold areas are characterized by different conditions for groundwater resource generation, groundwater storage, specific discharge values and distribution, and the effect of groundwater runoff generation factors. At the same time, in all hydrogeological structural elements, over 90% of the total runoff is generated in the upper hydrodynamic zone.

The most substantial groundwater runoff variations are observed in artesian basins where zones of excessive and moderate moistening are replaced by the zone of insufficient moistening (it is the manifestation of the latitudinal climatic zonality). Within each zone, the specific discharge values depends on the type of groundwater flow medium, rock composition, vadose zone thickness, and the effect of local and regional bases of drainage. Azonal groundwater discharge values are characteristic for areas with karst rocks, large river valleys, and regional tectonic disturbances.

In mountain-fold areas, groundwater discharge values range on an appreciably larger scale and they are subject to altitudinal zonality that defines the gradient character of the variation of

discharge values and their dependence on the average altitude of the terrain. These variations are complicated by the geostructural plane of the highland, the nature of water-bearing rocks, topographic features, slope exposure, etc.

As groundwater flows away from regional or local areas of recharge groundwater runoff is redistributed between hydrodynamic zones and is gradually depleted by leakage and discharge. That is why about 10% of the groundwater runoff of hydrogeological structures reaches regional bases of drainage (seas or large lakes).

5.1.2 General characteristics of fresh and brackish water use

The rapid growth of the population and towns, improved living conditions and industrial and rural development lead to substantial augmentation of water use. So, if a total withdrawal in Europe at the beginning of the twentieth century by the available data (Ali-Zade et al., 1990) was about 40 km^3/yr. By the middle of the century it attained 120 km^3/yr, and in the 1970s it exceeded 300 km^3/yr (Table 5.1.2.1).

Water withdrawal considerably increased for domestic and drinking water supply. Population growth and specific rising water use (daily amount of withdrawing water in liters per inhabitant) has caused demand. In Europe specific water consumption was augmented to more than two times at the beginning of the century.

The results of estimated changes in water use for the period from 1900 in Europe and forecast data obtained by Sokolov and Shiklomanov (1977) are given in Table 5.1.2.1.

Table 5.1.2.1 Evaluation of water consumption changes in Europe

	Water withdrawal (km^3/year)				
Water consumers	*1900*	*1950*	*1960*	*1970*	*2000*
Population	9	14	14	30	77
Industry	9	43	90	160	320
Irrigation	23	60	95	125	320
Total (rounded)	40	120	205	315	720

As was pointed out above the water use for the subcontinent in 2000 as compared to 1970 has a tendency to increase to more than 2 times.

The comparison of water demands with total water resources shows that in many European countries the opportunity to satisfy these needs has become a serious problem. The situation is aggravated by irregular distribution of fresh surface and groundwater resources and contamination of water bodies by industrial and rural waste water. In this connection, the public need to satisfy domestic and drinking water with high quality water represents a particularly complex problem. In solving this problem, the rational use of fresh groundwater plays an important role. Its attraction as a source of water supply is described in Chapter 2. These advantages essentially have predetermined the total amount of groundwater use for public water supply in a number of Europe countries. At the same time, in some countries due to inadequate and irregular distribution of surface and groundwater resources, the groundwater is widely used for industrial water supply and irrigation.

In Table 5.1.2.2 general data on groundwater use in different countries of Europe is provided. The above tables are made on generalized data edited in state or intergovernmental publications as well as for individual contributions by some authors (Vartanyan et al., 1993;

Table 5.1.2.2 Groundwater and use, and percentage of total or sectoral water demands supplied by groundwater

Country	Year	Total withdrawal (hm^3 per year)	%	Sectoral withdrawals (hm^3 per year): Communities water supply	%	Agriculture irrigation and livestock	%	Self-supplied industries	%	Energy	%	Others	References
Albania													
Austria	1985 1993	1,120 1,430	52.7 60.6	525	99	95	–	500	33	–	–		UN-ECE 1989 OCDE 1995
Belarus	1988	1,150	41.3										Goscomstat USSR 1989
Belgium	1980 1986	778	8.6	435 442	64 66.5	– –	30 –	170	2.7	–	–		UN-ECE 1981, 1989 OCDE 1987
Bosnia and Herzegovina													
Bulgaria	1989	1,520	15.2										Galabov 1993
Croatia													
Czech Rep.	1990 1993	850 530	23.5 19.3										Conf. Dublin 1992 OCDE 1995
Czechoslovakia (former)	1990	1,597	27.6										OCDE 1993
Denmark	1985 1989	1,100 1,200	~92.0 99.0	385 700	100 100	340	100						UN-ECE 1992 Tage Selchau 1991
Estonia	1988	160	5.5										Goscomstat USSR 1989
Finland	1984 1993	285 239	4.5 10.8	167 (87) 217	45	100	56.5	18	~1	–	–		UN-ECE 1989 OCDE 1995
France	1990	6,210	16.5	3487	57	1,009	20.5	1,700	38	14	Σ		Minist.Envir. 1992 OCDE 1993
Germany	1993	7,766	16.8	3,679 (90)	73								OCDE 1995
Greece	~1990	~2,000	28.0	740	64	1,160	20	100	71	0	–		Rep. Conf. Roma 1992
Hungary	1985 1993	1,765 983	30.0 14.4	807	88.5	190	27.5	450	11		–	–	UN-ECE 1989 OCDE 1995
Iceland	1993	150	91.5										OCDE 1995
Ireland	1980	174	16.0	61	17		28	64	12	–	–		UN-ECE 1989
Italy	1990	13,900	31.0	5,400	91	8,000	29	500	7	0	–		Rep. Conf. Dublin 1992 INVED 1992
Latvia	1988	310	45.6										Goscomstat US SR 1989
Lithuania	1988	500	14.0										Goscomstat USSR 1989

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Table 5.1.2.2 (continued)

Country	Year	Total withdrawal (hm^3 per year)	%	Sectoral withdrawals (hm^3 per year): Communities water supply	%	Agriculture irrigation and livestock	%	Self-supplied industries	%	Energy	%	Others	References
Luxembourg	1989	27	45.8	(86) 31	70								UN-ECE 1989 OCDE 1993
Macedonia													
Malta	1990	20.9	53.5	17.8	50	2.8	100	0.3	100	0	–		Wat. Aerv. Corp. 1993
Moldova	1988	290	7.9										Goscomstat USSR 1989
Netherlands	1993	1,049	13.4	77.4 (90)	70								UN-ECE 1989, 1992 OCDE 1995
Norway	1985	110	4.8	(87) 135	15								UN-ECE 1989 OCDE 1987, 1989
Poland	~1985 1993	5,200 2,053	~33.0 16.7	2,080	72	1,820	~100	1,300	12	–	–		UN-DTCD 1990 OCDE 1995
Portugal	1989	3,065	42.0										OCDE 1993
Romania	1993	3,630	22.4										Conf.CCE/Balkans,
Russian Fed.	1988	12,550	11.8										Goscomstat USSR 1989
Slovak Rep.	1990	730	39.4										Conf.Dublin 1992
Slovenia													
Spain	1992 1993	5,428 5,600	16.0 18.2	961	22	4,364	18	103	5	0			MOPU/Ham. hidro. nac. 1993 OCDE 1995
Sweden	1993	612	20.7	1,983:443	47	1983:35							OCDE 1995
Switzerland	1993	980	82.2										OCDE 1995
United Kingdom													
Ukraine	1988	4,220	13.8										Goscomstat USSR 1989
USSR (former)	1985 1988	237,000* 31,397	10.4 9.5	10,670	43	10,920	~5	6,360	~7	–	–		UN-ECE 1989:*Σ? Goscomstat USSR 1989
Yugoslavia (former)	1990	~2,250	13.0	~1,150	~66	~100	~10	~1	~17	0	–		Sém.CCE Alger 1990 NU Bmijatovic 1986
Yugoslavia Fed. Rep.	1993	2,352	20.0										
UK/England and Wales													OCDE 1995

Guide on water resources..., 1987; Ali-Zade et al., 1990; Juodcasis and Klimas, 1991; *Water Economy Prospects...*, 1990, 2000; Altshul et al., 1986; *Base principles of hydrogeology...*, 1983; Bodelle and Margat, 1980; *Perspectives of water consumption...*, 1983). The summary papers of Yazvin, 1989, and Borevsky et al., 1989, were also used.

As correctly noted in many works, statistical data on water resource use, in general, and groundwater, in particular, are not sufficiently available for accurate water use characteristics. In contrast to recent decades some progress has been made in this field. Currently, the data on potable water from sources of centralized water supply system are available in most countries. Data on the water use by dispersed water consumers are mostly incomplete. Moreover, the data on groundwater use in some countries are non homogeneous. In some countries, groundwater use for population includes only its use for drinking and domestic purposes, and in others, also for vegetation, fire fighting, etc. In a number of countries the water supply for a rural population is taken into account together with irrigation. Sometimes, groundwater use for public water supply and industries are both estimated together, especially when industrial enterprises use water from municipal water supply systems. All this predetermines the approximation values given in the table. In some countries, based on various publications, the available data are contradictory. Nevertheless, in total, the given data rightly reflect the existing tendencies of groundwater use in variable fields of national economy and total weight of groundwater for general water resources use.

In some countries (e.g. Albania, Ireland, Cyprus and others) there are no data in the published literature. However, due to insignificant groundwater use in the above countries, the general situation is actually similar.

In recent years, the world political map was subjected to notable changes (territorial subdivision into some independent states, such as USSR, Yugoslavia, Czechoslovakia, and reunification of FRG and GDR). Data on individual countries such as the former states of USSR, FRG and GDR are provided separately, Yugoslavia and Czechoslovakia data are given together.

The data considered in Table 5.1.2.2 and additional available information relating to the groundwater use allows us to draw the following conclusions:

- On the whole, groundwater use in the countries of a subcontinent is approximately assessed to be 80 km^3/yr, which is about 21% of the total water consumption. In most countries groundwater amounts to 10–25% in the total water balance (Belgium, Great Britain, Lithuania, Poland, Russia, Romania, Federal Republic of Germany, Finland, Ukraine, France and others). However, in some countries the percentage of groundwater use has been increased from 30 to 60% (Austria, Armenia, Byelorussia, Hungary, Greece, Latvia, the Netherlands and others), and in some cases amounting to 90–100% (Denmark, Iceland, Malta).
- The total amount of groundwater use depends on different factors such as population, climatic and hydrogeological conditions, availability of surface water resources and their degree of contamination. So, the maximum volume of groundwater use is characteristic for big countries, such as Italy, Russia, Federal Republic of Germany, Spain, France, Ukraine, and in a number of countries groundwater withdrawal for irrigation purposes plays an important role. In these countries groundwater use ranges from 4.5 to 12 km^3/yr.
- The urban and rural population is the highest groundwater user. Its share is about 44 km^3/yr, that is equal to 56% of the total water use for this purpose. It should be noted that in such countries as Austria, Belgium, Great Britain, Hungary, Georgia, Italy, Latvia, Lithuania, Moldova, the Netherlands, Poland, Russia, Romania, FRG, Finland, Ukraine, France, Switzerland, Sweden and Estonia, a part of groundwater for public water supply exceeds 50% of the total water use.

Analysis of the available data allows us to affirm that groundwater is the main source for public water supply in the European countries accounting to more than 70% of the total water resources

used for this purpose. In Austria, Armenia, Byelorussia, Hungary, Georgia, Denmark, Italy, Latvia, Lithuania, Luxembourg, Malta, FRG, Switzerland, Estonia, Yugoslavia the percentage of groundwater in public water supplies amounts to 70–100%. In Bulgaria, Moldova, the Netherlands, Poland, Russia, Romania, Ukraine, France, Czechia and Slovakia groundwater use ranges from 50% to 70%. Rural populations and small and medium towns rely mainly on drinking groundwater. However, in some countries groundwater plays an essential role for water supply of large cities and towns (with populations of more than 0.5 millions (Vartanyan et al., 1993; Shevelev and Orlov, 1987). In general, more than 90% of big cities and towns are supplied exclusively by groundwater. Among them are such major cities as Vienna, Hamburg, Munich, Berlin, Rome, Budapest, Yerevan, Voronezh, Krasnodar, Lvov, Vilnius and Tula. Public water supply for cities such as Brussels, Copenhagen, Paris, Minsk, Tbilisi, Ufa, Riga use groundwater for more than 60%. Groundwater is vital (more than 20%) for water supplies of such cities as Lisbon, Zurich, Kharkov, Kiev, Baku, and others.

- A large amount of groundwater used for rural water supply is mainly for irrigation. The total withdrawal for these purposes accounts for more than 17 km^3/yr. Groundwater is widely used for irrigation in countries of South Europe and Transcaucasia (e.g., Spain, Italy, France, Greece, Portugal, Azerbaijan, Armenia). In the above countries groundwater withdrawal for irrigation ranges from 0.7 to 5 km^3/yr. Nevertheless, groundwater is used for irrigation not only in countries with arid climate but in those of more favorable hydrogeological conditions. For example in the Netherlands during dry years, groundwater withdrawal for irrigation purposes has increased up to 0.3 km^3/yr.
- Groundwater use for industrial water supply accounts to 17.4 km^3/yr (about 22% of the total withdrawal) including mine-water drainage in some countries (e.g., Germany, France). Moreover, in a number of countries (Armenia, Russia, former GDR, Ukraine, Estonia) groundwater use for mine-water drainage and vertical drainage of irrigated lands accounts approximately to 5.5 km^3/yr, of which only about 0.6 km^3/yr (this value is given in Table 5.1.2.2) is used in national economy. The extensive groundwater use in industries is characteristic for such countries as FRG, Russia, France, and Great Britain.
- Hydrogeological conditions for groundwater exploitation in the European countries vary greatly. The upper unconfined aquifers (including underflow) are operated as well as deep (up to several hundred meters) confined aquifers of artesian basins of a platform type.

On the whole, on the territory of the European countries all types of groundwater reservoirs are exploited in the valley rivers, artesian basins of platform type, stream flows and groundwater basins, alluvial cones and intermountain depressions, lava flows, basins of subconfined intermoraine deposits, fissured water flows.

Large well fields are operated in artesian basins of a platform type (e.g., basins of Moscow, Dneprov-Donetsk, Baltic, Volga-Kamsk, Azov-Kuban, London, Paris, Aquitain and others).

As a rule, the aquifers of the above basins are protected against surface contamination. At the same time, their exploitation is accompanied by formation of large and deep cones of depression. A maximum depth to the confining bed of operating aquifers amounts to 500–600 m and up (Lower Cretaceous aquifer in eastern areas of Ukraine).

Groundwater is also widely used in the river valleys. When exploiting the groundwater, surface water of rivers is induced to the well fields, which are intensively exploited in Russia (in the areas of Urals, Volga region, Northern Caucasus), Ukraine (Donbass, Carpathians), Hungary, Bulgaria, Lithuania, Latvia, Germany, France, and in some other countries. In Germany (Mathness, 1979) groundwater use produced by coastal infiltration of surface water, accounted to 0.3 km^3/yr (7% of the total water supply by municipal pumping stations). In France, groundwater in alluvial river valleys (valleys of Rhine, Rhone, Seine) amounted to 46% of the groundwater withdrawal (Bodelle znd Margat, 1980). In Hungary, predictive induced resources, generated due to the coastal

infiltration, are equal to 2.85 km^3/yr (Altreder, 1984). At present, an important well field is exploited for water supplying the Budapest where water withdrawing by radial wells in the well fields in the valley of Danube amounts to 0.3 km^3/yr. A weak point of groundwater basins in river valleys is their low vulnerability to surface contamination.

In Azerbaijan, Georgia, Northern Caucasus and in some other regions of Europe groundwater of debris cones and intermountain depressions, where water-enclosing rocks composed of thick layer graveled deposits, are of practical importance. The availability of great regulating capacity and favorable conditions of the recharge contributes to constructing of large well fields. In mountain and submontane regions of Europe (e.g., Austria, Italy, France, Switzerland, the Crimea) the capture of source run-off is widely used. In a number of European countries the artificial recharge of the groundwater springs has been essentially developed. So, in 1975, on the territory of FRG (a former GDR is not taken into account) artificial groundwater resources withdrawing by public water supplying systems amounted to 0.45 km^3/yr or 11.3% of the total water volume (Mathness, 1979). A total water withdrawal including artificial recharge in the former GDR accounts to 0.1–0.15 km^3/yr (*Base principles in hydrogeology...*, 1983). Large systems of artificial recharge are exploited in Switzerland, France, Czech, Georgia, Latvia, Lithuania, the Netherlands, and some other countries. Water supply of Amsterdam (Shevelev and Orlov, 1987) is provided by artificially groundwater recharge equaling to 74%.

As noted earlier in a number of countries of Europe, an essential portion of groundwater withdrawal is derived from water-mine and open pit drainage, and also drainage of irrigating and waterlogged lands. However, limited pumping water in small amounts is generally used for industries and, rarely, for public and drinking water supply (some regions in Russia, France, FRG). Nevertheless, a great amount of pumped water flows to river networks or directly to the land without depletion of the groundwater and its safe yield.

The depletion of groundwater safe yield is observed at a number of well fields where water withdrawal substantially exceeds its fixed value. Traditional examples of such well fields are those of Catalonia and Canaries (Custodio, 1982). In the Canary Islands the groundwater that occurs in semipermeable volcanic rocks, the rate of water level decrease amounted to 10 m/yr with withdrawal only equaling 0.1 km^3/yr. After 12 years of pumping in a karst aquifer the water level was reduced to 200 m in Jurassic and Cretaceous deposits in the province of Amiksite located in the south-east of Spain where water withdrawal was equal to 40 mln. m^3/yr.

5.1.3 Brief characteristics of fresh groundwater resources in some countries in Europe

As indicated in Section 2.1, the potential for practical groundwater use can be defined more appropriately only on the basis of quantitative data of its safe yield. Besides, in many countries the assessment of potential regional reserves, traditionally, is not carried out. Here the potentials for groundwater operations are estimated with allowance given to the value of natural dynamic resources.

The notion of 'groundwater potential reserves' is widely used in hydrogeological practice of such countries as Azerbaijan, Armenia, Bulgaria, Hungary, former GDR, Georgia, Latvia, Lithuania, Moldova, Poland, Russia, Romania, Ukraine, Czechia and Slovakia, Estonia. The above countries implemented a regional estimation of predictive reserves, which determined the potential productivity of well fields allowing for hydrogeological, technical-economic and nature protection limitations. Various countries used distinct approaches to the definition of potential reserves under specific hydrogeological conditions, technical facilities of capture, economic and social factors. In a number of countries the value of groundwater potential reserves corresponds completely to reserves compensated by recharge resources (natural dynamic resources and

induced resources of surface water). In other countries complete reduction of water storage occurred within a certain period ranging from 20 to 50 years.

In the majority of cases, groundwater natural dynamic resources are estimated based on the average long-term groundwater runoff to rivers and seas. When analyzing the estimated results, one should take into account, that using this approach, the value of groundwater recharge even in regions with humid climate is rather underestimated due to partial groundwater discharge caused by evaporation from the water table.

The data available on natural dynamic resources and potential reserves in some countries are given in Table 5.1.3.3 and based on published papers. It should be noted that in some papers substantially distinct estimates of groundwater runoff (natural resources) are given. In these cases the recent data estimates are used. Since the reduction of water storage can provide groundwater withdrawal only for a limited period of time, the table gives the value of potential reserves. The table also cites the values of the use of natural resources and their potential reserves which are understood to be the ratio of groundwater withdrawal (including water-mine drainage) to its resources.

Data analysis given in Table 5.1.3.2 show that the intensity of groundwater withdrawal in different countries is distinguishable. In countries such as Byelorussia, Great Britain, Greece, Georgia, Spain, Poland, Portugal, Russia, Romania, FRG, Finland, France, Switzerland, Sweden, Yugoslavia the present withdrawal does not exceed 30–35% of the natural resources or potential reserves and there are tendencies for a considerable increase in groundwater withdrawal. Groundwater in Azerbaijan, Armenia, Bulgaria, Denmark, Lithuania, Moldova, the Netherlands, Ukraine, FRG, Czechia and Slovakia are being intensively exploited. However, in the above countries the potential of increasing groundwater use exists. The data given in the table are characteristic of the countries considered on the whole. However, in most countries, due to the irregular distribution of natural and potential reserves over separate regions, public water supply problems should be solved using surface water even in the case when the situation in the country on the whole is favorable. Although in most countries of Europe groundwater is the main source of domestic and drinking water supply in the future. In some countries, referring to the paper (6), the total weight of groundwater use will be decreased (Belgium, Greece, Poland, Czechia and Slovakia).

At the same time, it should be noted that in most countries of Europe groundwater resources studies are not sufficient and future hydrogeological investigations will allow us to estimate the perspectives of groundwater use more reliably.

5.2 Groundwater resources and their use in selected countries in Asia

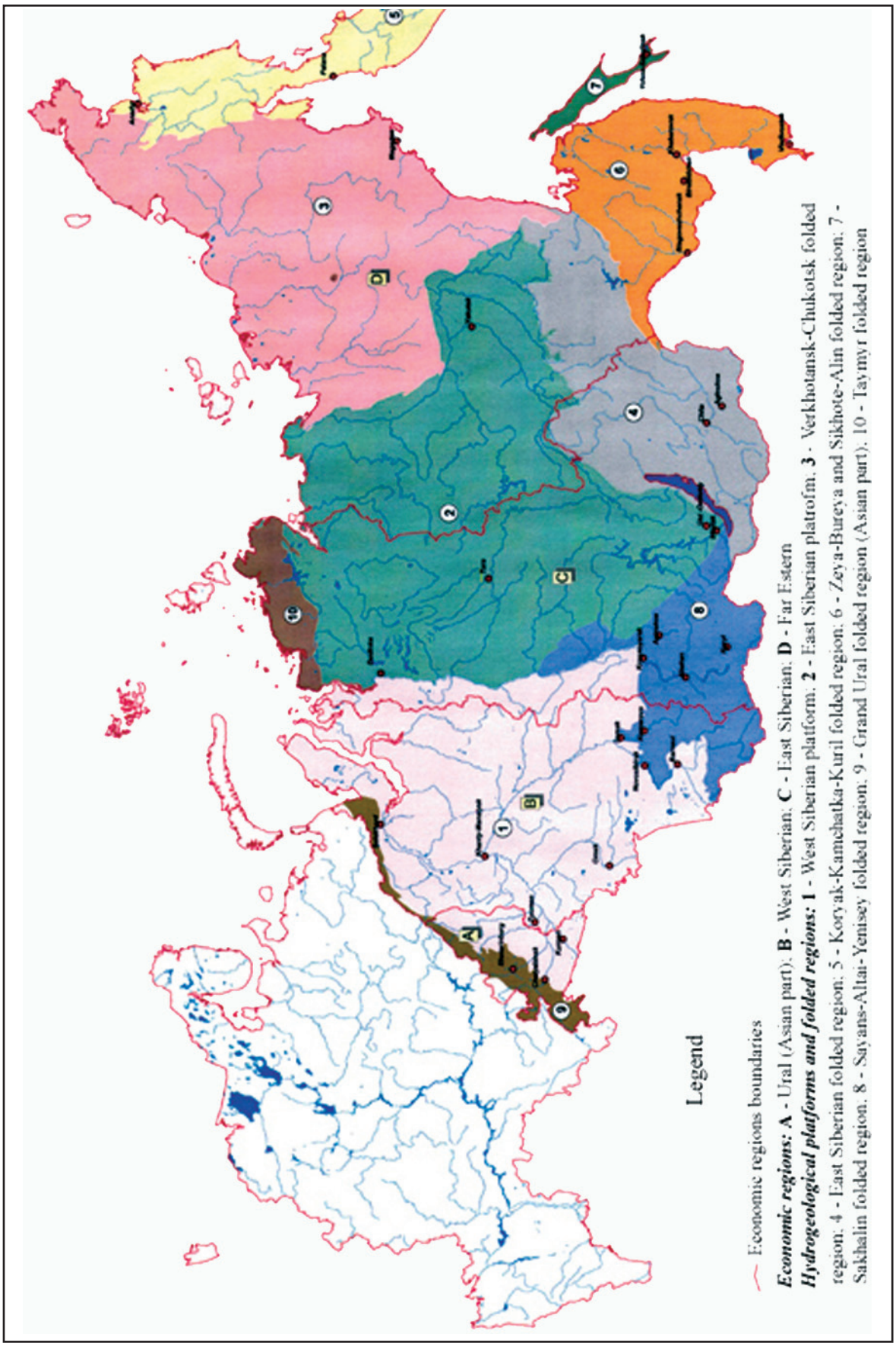
5.2.1 The resources of fresh groundwater and their utilization in the Asia Part of the Russian Federation

5.2.1.1 General overview and hydrogeological zoning

The Asian part of the Russian Federation represents a vast region, stretching over 13 mln. km^2 and contributing more than 75% to the total area of Russia and about 30% of the sub-continent area. This great area, where 32 subjects of Russian Federation are located, includes three important Russian economical regions (West Siberian, East Siberian and Far Eastern) and part of Ural economic region (see Fig. 5.2.1.1.1).

The population of the investigated region is about 41 mln, with 75% classified as urban. In

Figure 5.2.1.1. Map of hydrogeological zoning within Asian part of Russian Federation



the whole, the population distributes over the territory very irregularly, with the most part concentrated in the southern sectors (southward of Ekaterinburg-Chelyabinsk-Tomsk-Irkutsk-Chita-Khabarovsk line). The average density of the population is 3.2 persons per square kilometer, varying among the entities of the Russian Federation from 0.03–0.4 persons (northern areas – Evenkiya, Chukotka, Koryak, Taymyr autonomous districts and Republic of Yakutia) to 25–40 people (Sverdlovsk, Kemerovo, Chelyabinsk provinces).

There are about 900 cities and urban villages in the Asian part of the Russian Federation, including 35 communities with population from 100,000 to 500,000, seven cities – from 500,000 to 1,000,000, and four cities (Ekaterinburg, Chelyabinsk, Novosibirsk, Omsk) with a population of more than 1,000,000.

In compliance with hydrogeological zoning adopted in Russia, the Asian part of Russian Federation exhibits the following superordered units: hydrogeological platform domains and hydrogeological folded regions. Hydrogeological platform domains link the various types of subsurface water basins (artesian basins of stratal undergroundwater and basins of fracture and fracture-vein water) with dominance of the artesian basins. Two large platform domains can be identified in this area: West Siberian platform, which occupies about 2.6 mln. km^2 within the Russian borders, and the East Siberian platform with a total area of 3.6 mln. km^2.

The hydrogeological folded regions are the regions with prevailing occurrence of fracture and fracture-vein water basins, confined to the mountain formations, and stratal water basins in submontane troughs, intermountain and intramountain depressions. The Verkhoyansk-Chukotka folding has an area of 2.5 mln. km^2. The east Siberian folding has an area 1.3 mln. km^2, the Koryak-Kamchatka-Kuryl folding area is 1.0 mln. km^2 as well as the Zeya-Bureya, Sikhote-Alin', Sayans-Altai-Yenisey, Sakhalin, Taymyr and most parts of the Grand Urals foldings were identified in the Asian part of the Russian Federation. The locations of hydrogeological platforms and folded regions are presented in Fig. 5.2.1.1.1.

5.2.1.2 The predictive resources of fresh groundwater

The following study presents the characteristics of predictive groundwater yields, which in Russia imply the quantity of subsurface water with specific quality and targeted use, that can be produced within the boundaries of hydrogeological region, basin or administrative entity, thus reflecting the potential for water use. Accordingly, the yield forecasts represent the potential withdrawal of groundwater, which can be realized within the boundaries of the area under consideration, i.e. the overall output of water removal facilities, evaluated with due regard to the specified hydrogeological, environmental, technical and economic limitations.

To assess the predictive water yields within the above named superordered hydrogeological platforms and foldings, the various hydrogeological formations of first and second order was identified: artesian basins, fracture and fracture -vein water basins; the latter were the principal objects of the assessment. The evaluation was performed for major aquifers and systems. At the same time, it was assumed that total value of predictive groundwater yield could not exceed its natural resources, i.e. the recharge of subsurface water to the particular basin in natural conditions. Within the boundaries of the investigated territory the areas were identified, where the production of groundwater was impossible or unpractical due to various limitations (very low water carrying capacity of water-bearing rocks; absence of fresh and low brackish water; virtual absence of groundwater recharge; mining fields; the areas where the groundwater abstraction is prevented by orohydrographic conditions, etc.).

The estimation of resource forecasts in the explored territory where water-removal wells operation is possible, was performed in reference to selected water well fields. The latter were assumed with due regard to the location density of the principal distributed consumers.

In mountain regions, where the utilization of groundwater is possible only by capping springs, the resource forecasts were estimated by the annual low-water spring runoff providing 95% of the supply; only those springs which can be used for water supply, were considered. In addition, in some regions the predicted fresh groundwater yields, which corresponded to the total potential discharge of waterside the watershed infiltration removal, provided by surface run-off recharge, were evaluated.

Thus, the predictive fresh groundwater yields, in contrast to their natural resources, take into account the withdrawal of subsurface water at water removal facilities, including capping springs. As a result, the value of predicted resources is determined not only by the volume of subsurface water recharge (which, in turn, depends on topography, climate – overall area watering –, geostructural features, geologic characteristics and hydrogeological conditions), but from a number of other factors as well. These factors include: aquifer hydraulic properties, the conditions of the interaction of a particular aquifer with adjacent aquifers, the water carrying capacity of water-bearing rocks, acceptable water table drop, well fields location and, conditions of surface and groundwater interaction.

One of the principal factors, which determine groundwater recharge and, consequently, generation of groundwater safe yields in the vast Asian region, is the widespread occurrence of permafrost rocks.

In the territory explored, the occurrence of permafrost rocks and the variation of their thickness depend, in large part, on latitudinal zoning, which is upset only in mountain regions. Against the general background of zonal permafrost rocks, some places reveal their zonal differences in the thickness, occurrence entirety and temperature of permafrost rocks, associated with topography features, geology tectonics and other factors.

Near the southern border the thickness of the permafrost zone does not exceed 10–20 m in average, while in the central and northern parts of the region investigated and in the mountain range it reaches 600–700 m or more, irrespective of their geographic location.

When considering the permafrost rocks occurrence and their area, the regions of continuous, interrupted and echelon-type occurrence can be identified. Generally, the continuous permafrost rocks implies their presence in all relief units within the given region if the area of thawed rocks, formed at the bottom of river valleys, under deep lakes and in the places of deep groundwater discharge, does not exceed 5%. In the zone of interrupted occurrence of permafrost rocks the total area of thawed rocks rarely exceeds 50% of overall the region area. In the zone of echelon-type occurrence of permafrost rocks their total area rarely exceeds 20–40%, and these rocks are generally confined to the boggy floor of river valleys, peat hillocks and lower slopes of northern exposition.

The specific features of formation for natural and production resources of fresh groundwater were recorded only in the first zone, i.e. the continuous permafrost rocks. In this zone only subsurface water from through-carrying and non-through thawed zones, particularly, in the valleys of large rivers, can have any practical importance to the supply of drinking water. The reason is that subsurface water in these zones is linked hydraulically with surface water. Since the indicated thawed zones have a fragmentary pattern, the estimation of predictive fresh groundwater yields in the boundaries of continuous occurrence zone were not attempted. The only exception were the isolated regions where the available hydrogeological data has allowed the identification of a large number of thawed zones. As a result, the total predicted resources of these regions were adopted as an estimated value for this zone.

The presence of permafrost rocks in the interrupted and echelon-type zones does not have any particular impact upon the formation of groundwater safe yields.

Following is the brief overview of predictive fresh groundwater yields within the principal hydrogeological regions.

West Siberian platform

With respect to geomorphologic features the West Siberian platform artesian area relates to the West Siberian Plain. The zone of continuous permafrost rocks is located in the northern part of this territory its area accounts for 6% of the total area. Within its boundaries two large artesian basins can be identified, with sandy aquifers of Paleogenic, Neogenic and Quaternary periods, containing fresh groundwater under pressure, which is of greatest interest for use as a water supply. On the contrary, in southward regions (Kurgan, Omsk, southern parts of Novosibirsk and Tyumen provinces and some other) the groundwater, with a mineralization of about 1 g/dm^3, was not recorded. The microelements requiring attention included increased iron and manganese levels were found almost everywhere. In northern parts the strong coloration of groundwater was observed necessitating special measures for treatment.

The source of fresh groundwater formation in the major aquifers is, typically, the subsurface water of upper groundwater horizons, which, in turn, is supplied with atmospheric precipitation.

The overall predictive fresh groundwater yield, was performed on an area of 2.5 mln. km^2, averages 225 mln. m^3/day with a yield rate forecast mean value of about 1.0 l/sec . km^2.(1)

East Siberian platform

The East Siberian platform artesian area occupies a vast territory, stretching over the Lena and Yenisey river basins. Most of its territory is related to the Central Siberian plateau, the Central Yakut lowland, located in the east, and the Khatanga (North Siberian) lowland in the north. Within these area boundaries, 7 major artesian basins and fracture water basins, confined to the Anabar Shield, were identified.

Almost 70% of the territory considered is located within a continuous permafrost rocks zone where the predictive fresh groundwater yield was not estimated. At the same time, as was indicated above, this area reveals large-sized thawed zones in the valleys of large rivers, where the groundwater can be the source of water supply, (in some cases a large-scale supply). They are exemplified by Talnakh and Ergalakh groundwater reservoirs in the valleys of the same-name rivers in the Norilsk mining region. The reservoirs are confined in the deep river valleys, formed by boulder-gravel-pebble sediments, where subsurface water links with river water in periods of surface run-off. When surface run off is absent, the groundwater safe yield accumulates at the expense of drainage of water-bearing rocks, which are completely saturated with water during river discharge. The estimation of predictive resources of fresh water was performed for the southern part of the East Siberian platform within the boundaries of Angara-Lena artesian basin and for the southern parts of Yakut and Tungus artesian basins. The major fresh water aquifers in the assessed regions are confined to terrigenous deposits (sandstone, siltstone) and, occasionally, to carbonaceous deposits of Cambrian, Ordovician, Triassic and Jurassic periods.

The predictive fresh groundwater yields of the East Siberian platform amount to about 115 mln. m^3/day, of which about 15 mln. m^3/day are related to predicted resources, corresponding to the infiltration of water removal discharge. The yield rate mean value in the assessed area (the waterside wells are not included) is 0.9 l/s . km^2, and for total area is 0.3 l/s . km^2.

Verkhoyansk-Chukotka folded region

The Verkhoyansk-Chukotka folded hydrogeological region lies at the North-East of the Russian Federation. It covers Verkhoyansk mountain ridge, Kolyma and Chukchi tablelands, Kolyma lowland, and a number of smaller mountainous and lowland regions.

Within the boundaries of the territory investigated the large number of fracture and

1. The term 'yield rate forecast' implies the consumption of groundwater in l/s, which can be produced from assessed aquifers with water removal wells or from capped springs at an area of 1 km^2.

fracture-vein water basins, assigned to hydrogeological ranges, superimposed volcanogenic superbasins and stratal artesian basins in the intermountain depressions, were identified. The greatest part of the Verkhoyansk-Chukotka folding is located in the zone of continuous permafrost rocks. Due to this factor as well as to lack of hydrogeological data the groundwater safe yield was estimated only for 50% of the area, mostly in the southern and south-eastern parts. In Magadan province the resources forecast was assessed by the potential discharge of water removal in thawed riverside zones, taking into account the possible depletion of groundwater in alluvial deposits during critical no-flow periods followed by recharge with surface flood water.

The overall predictive fresh groundwater yield averages 65 mln. m^3/day with a yield rate forecast mean value for the assessed area of about 0.47 l/s . km^2 and for the total area of about 0.3 l/s . km^2.

East Siberian folded region

The East Siberian hydrogeological folded region is located in the southern sector of the territory and includes the mountain formations and intermountain depressions of pre-Baikal Upland, Transbaikalia, Baikal-Patol plateau of Stanovoy ridge and the Aldan Shield. Within the boundaries of the East Siberian folded region we can identify six large hydrogeological folded areas of first order, each including several basins of fracture water and artesian basins of groundwater in the intermountain depressions. The East Siberian fold hydrogeological region is characterized by difficult occurrence of permafrost rocks. Common to the whole Asian part of the Russian Federation, the reduction in thickness and increased interruption of frozen rocks in the north to south direction, were observed. However, the frosted rock with several hundred meters in thickness were found in mountain ranges, located at the south of the area studied.

The estimation of predictive fresh groundwater yield was performed for 88% of the total area in the region.

Within the boundaries of the territory assessed the fracture water from metamorphic and magmatic associations of Paleozoic and earlier origin is predominant, but the main resources of groundwater are accumulated in the Mesozoic and Cainozoic sediments in the intermountain artesian basins.

The predicted groundwater yield is about 125 mln. m^3/day, of which more than 20 mln. m^3/day are related to waterside (infiltration) take-offs. The yield rate forecast mean value for assessed area (the waterside (infiltration) take-off not included) is 0.9 l/s . km^2.

The Koryak-Kamchatka-Kuril folded region

The Koryak-Kamchatka-Kuril folded region lies to the east of the Asian part of the Russian Federation, covering the Koryak upland, Kamchatka peninsula, Kuril islands and including the Koryak and Kamchatka hydrogeological fold regions and the Kuril artesian basin of the first order.

The greatest part of the Koryak hydrogeological fold region is located in the zone of continuous permafrost rocks. Here the predicted resources were assessed only for 10% of the total area, in thawed zones, and found to be 2 mln. m^3/day, on the average.

The groundwater safe yields at the Kamchatka hydrogeological folded region are concentrated mostly in the artesian basins of stratal confined water, located in sedimentary and effusive deposits of Paleogenic, Neogenic and Quaternary ages. The basins of fracture and fracture-vein water in mountain formations are of secondary importance. The significant reservoirs of groundwater in the alluvial sediments, located in the river valleys, form the basis of water supply for the city of Petropavlovsk-na-Kamchatka.

The water yield of the Kamchatka hydrogeological fold region was investigated for about 25% of the total area (the northern part of the peninsula, located in the continuous permafrost zone, and some mountain regions were excluded). The predicted resources amount to a little more

than 25 mln. m^3/day, of which 12 mln. m^3/day are related to waterside (infiltration) take-off. The yield rate forecast mean value, without accounting for the waterside take-off in the assessed area, was equal to 2.6 l/s.km^2, and for the total area was 0.63 l/s.km^2.

The Kuril artesian basin incorporates the stratal water basins of the Kuril islands. Water-bearing sediments includes the volcanogenic, volcanogenic-sedimentary and intrusive rocks of Paleogenic, Neogenic and Quaternary ages. The predicted resources within the Kuril artesian basin were not assessed.

Zeya-Bureya and Sikhote-Alin' folded regions

The Zeya-Bureya and Sikhote-Alin' hydrogeological folded regions are located south of the Far East. They include the basins of fracture and fracture-karstic water of Minor Khingan, Bureya, Sikhote-Alin' and other mountain formations as well as intermountain artesian basins. The Amur-Zeya and Central Amur basins are the largest basins.

In mountain regions the groundwater is confined in zones of erosion, tectonic breakings and karstic formation in the intrusive metamorphic and sedimentary rocks (the age varies from the Archeic to the Kainozoic periods). In the intermountain artesian basins the major aquifers are confined to Quaternary and Neogenic loose deposits.

The predicted fresh groundwater yields of the Zeya-Bureya and Sikhote-Alin' regions were estimated at about 45 mln. m^3/day with a yield rate forecast mean value of 0.6 l/s.km^2.

Sakhalin folded region

The Sakhalin folded region lies within Sakhalin island borders and includes, similarly to other folded regions, the fracture water basins and artesian basins. The fracture water basins are mostly confined to strongly separated West Sakhalin, East Sakhalin, Suskan, Tonino-Aniv and other mountain ranges. They are composed of metamorphized, strongly dislocated rocks of Mesozoic and Paleozoic periods, where groundwater is formed in the zones of erosion, tectonic breaking and, occasionally, karstic cavities.

The major fresh water aquifers in the artesian basins are confined in the loose sandy and sand-gravel sediments of Quaternary, Neogenic and Paleogenic ages.

The predicted groundwater yields are concentrated, chiefly, in the artesian basins with a total area exceeding 60% of the overall Sakhalin area. The cumulative water yield averages 35 mln. m^3/day with a yield rate forecast mean value of 5.1 l/s.km^2.

Sayans-Altai-Yenisey folded region

The Sayans-Altai-Yenisey hydrogeological folded region is located in the south of the Russian Federation and includes the fracture water basins in the mountain formations of the Yenisey mountain ridge, Altai, Sayans, Salair, Kuznetsk Ala-Tau, Kolyvan-Tomsk highland and numerous intermountain artesian basins, among which the Kuznetsk, Rybinsk and array of Tuva and Minusinsk basins are the largest.

The basins of fracture water, which constitute a significant part of area investigated, are confined to the intermountain artesian basins in the metamorphic, sedimentary and magmatic rocks of the Paleozoic, Proterozoic and Archeic periods. The major aquifers were formed in Quaternary, Mesozoic and Upper- and Middle-Paleozoic sediments. The predicted water yield was assessed at 80 mln. m^3/day with a yield rate forecast mean value of 1 l/s.km^2.

Grand Ural folded region (Asian part)

For the purpose of this study, the Asian part of the Grand Ural hydrogeological folded region covers the basins of fracture and fracture-karstic water on the eastern slope of Ural mountains, and are confined to the effusive, intrusive, metamorphic and sedimentary deposits of Paleozoic

age. As water supply sources the most important is the limited strip region of carbonaceous rocks, which have been subjected to karstic formation, especially, in the presence of surface discharge in this region.

The predicted water yield of this territory is assessed at 20 mln. m^3/day with a yield rate forecast mean value of 1.0 l/s.km^2.

Taymyr folded region

The Taymyr hydrogeological folded region is located in the northern part of the sub-continent and composed of Proterozoic, Paleozoic, Mesozoic and Quaternary sediments. The territory under consideration is entirely enclosed in the zone of continuous permafrost rocks. The predicted water yield of fresh groundwater, which can be found in the thawed zones, was not estimated.

The reported brief overview of predicted groundwater yield within the principal hydrogeological platforms and foldings in the Asian part of Russian Federation allows the making of the following conclusions:

The explored territory holds huge predicted resources of fresh groundwater. The total amount of groundwater is about 740 mln. m^3/day with a yield rate forecast mean value of 0.65 l/s.km^2. The distribution of predicted water resources over economic regions is presented in Table 5.2.1.2.1.

Water yields are distributed over the Asian part of the Russian Federation very irregularly. This irregularity can be explained, primarily, by the enormous impact of continuous permafrost zones on the formation of groundwater resources. For this reason, as well as because of the limited of hydrogeologic research in the northern and north-eastern parts of the area involved, an assessment of predicted the water yield in the area of more than 4.2 mln. km^2, was not performed. Over most of this area, fresh water can be found only in thawed zones.

In areas where permafrost rocks are either absent or their occurrence reveals interrupted and echelon-type nature, the irregularity of the predicted resource distribution is related to other factors. In hydrogeological folding regions where the assessment of resources was performed both

Table 5.2.1.2.1 Predictive resources of fresh ground water, certified ground water safe yield and their use over economic regions (mln. m^3/day)

Economic region	*Predictive resources of fresh ground water*	*Certified ground water safe yield*	*Scope of knowledge about water yield forecasts (%)*	*Ground water withdrawal*		*Use of ground water for public water supply*			*Share of ground water in balance of drinking public water supply (%)*	*Use of groundwater*		*Total use of ground water*
				Total	*Including mine and open pit drainage*	*Total*	*Including*			*For industrial water supply*	*For irrigation and pasture watering*	
							Surface water	*Ground water*				
1	2	3	4	5	6	7	8	9	10	11	12	13
Ural* (Asian part)	25.0	2.2	8.8	2.7	1.0	3.2	2.1	1.1	34.4	0.2	—	1.3
West Siberian	225.0	10.0	4.4	4.9	1.0	5.8	2.9	2.9	50.0	0.6	0.6	4.1
East Siberian	280.0	6.0	2.0	3.1	0.6	3.1	1.0	2.1	68.7	0.5	—	2.6
Far Eastern	250.0	6.3	2.5	1.7	0.3	1.8	0.9	0.9	50.0	0.5	—	1.4
Total	780.0	24.5	3.1	12.4	2.9	13.9	6.9	7.0	50.4	1.8	0.6	9.4

* Ural economic region include the data within Sverdlovsk and Chelyabinsk provinces including the hydrogeological regions located in the European part of Russian Federation.

for the fracture basins, fracture-vein and fracture-karstic water, confined to mountain formations, and for the artesian basins of intermountain depressions and submontane troughs, the major resources are concentrated in the artesian basins. As indicated above, the value of water yield depends largely on the conditions and size of recharge, water-carrying properties of water-bearing rocks, conditions of groundwater interaction in different aquifers, and some other factors. At the same time, the arrangement of water well fields with reference to which the predicted resources were estimated. The distance between water well fields corresponds, primarily, to the density of distributed water consumers. Thus, in various regions with similar hydrogeological conditions but with a different density of population, the resulting water yield forecasts differed very much.

The assessment of groundwater yield forecasts was performed for fresh water with mineralization under 1 g/dm^3. However, in some regions (Omsk, Kurgan, southern part of Tyumen and Novosibirsk provinces, a number of Central Yakutia regions, etc.), where fresh groundwater is absent, groundwater resources with a mineralization of 1–3 g/dm^3, which can be used for potable water supply after adequate treatment, were assessed.

5.2.1.3 Developed resources of fresh groundwater

In this study the term 'developed resources of fresh groundwater' implies the subsurface water discharge, averaged for the period of estimation, which can be achieved at a specific part of the aquifer with the use of geologically and economically proved water removal facilities. The specified operational regime, conditions and quality of groundwater, must meet the requirements of the intended utilization of the groundwater with due consideration for environmental regulations. The assessment of water yield is performed from the results of special exploratory and, especially, field data from operating wells. The results of this assessment are certified by a competent state authority, whose decision is to justify the possible exploitation of the subsurface water source. After approval, the areas with an estimated water yield are considered as 'groundwater reservoirs'. The latter, consequently, represent the space-confined part of aquifer, where the complex of economic-geological factors contributes to favorable conditions for groundwater removal in an amount, adequate for the intended use.

The water safe yield for more than 1,400 fresh groundwater reservoirs were certified on for the Asian part of the Russian Federation. The water yield resources, estimated for these reservoirs, amount to about 24.5 mln. m^3/day. The distribution pattern of certified water yield resources over economic regions is presented in Table 5.2.1.2.1.

The majority of fresh groundwater reservoirs (about 60%) are small reservoirs with water safe yields not exceeding 10,000 m^3/day. At the same time a number of large reservoirs with water yields over 100,000 m^3/day are developed.

In column 4 of Table 5.2.1.2.1 data is given, which characterize the scope of knowledge about water yield forecasts (defined as the ratio of certified safe yield to estimated predicted resources). The data in Table 5.2.1.2.1 implies that certified water yields are only 3% of the estimated predictive resources. This value varies from 2% (East Siberian economic region) to 8% (Ural economic region).

5.2.1.4 Groundwater withdrawal and utilization

The data, reported in this section on the current status of groundwater withdrawal and utilization as well as for surface water supply for household purposes, were valid for the late 1990s. They were founded on government water records, based upon water consumer accounting data and periodic surveys of water well fields, and performed by a Governmental Geologic Monitoring Service. In the whole, this data can be considered as somewhat conservative because of the

incomplete data coverage of groundwater consumers in rural areas. The summary data for withdrawal and utilization of fresh groundwater over economic regions in the Asian part of the Russian Federation, are presented in Table 5.2.1.2.1.

The data implies that overall groundwater withdrawal is 12.4 mln. m^3/day, of which 2.9 mln. m^3/day accounts for drainage during mining operations. The major groundwater withdrawal, over 1 mln. m^3/day, falls on the Sverdlovsk and Chelyabinsk provinces (Ural economic region), Altai Territory and Kemerovo province (West Siberian economic region) and Krasnoyarsk Territory (East Siberian economic region). The largest drainages were recorded in the province of Kemerovo (about 1 mln. m^3/day), Sverdlovsk (0.6 mln. m^3/day) and Chelyabinsk (0.5 mln. m^3/day).

The total utilization of groundwater in the explored territory was estimated at 9.4 mln. m^3/day, of which about 7.0 mln. m^3/day (75%) accounts for household and drinking water supply to an urban and rural population, 1.8 mln. m^3/day for an industrial water supply, and 0.6 mln. m^3/day for irrigation and watering pastures. The difference between groundwater withdrawal and utilization (3.0 mln. m^3/day) accounts, primarily, for mine and open pit drainage and, partially, for water losses during its production and delivery.

At present, household and drinking water supply is obtained from both surface and groundwater. The share of groundwater in thetotal inventory of this kind of water supply is a little more than 50%. The share for an urban population is 40% and that of rural areas is 83%.

In the Asian part of the Russian Federation groundwater is used quite irregularly. It is used most extensively in Tomsk province, Yamal-Nenetsk autonomous district (West Siberian economic region), Republics of Buryatia and Khakasia, Chita region, Ust'-Ordynsk Buryatsky and Achinsk Buryatsky autonomous districts (East Siberian economic region), where the share of groundwater exceeds 90%. In Altai Territory and Khanty-Mansy autonomous district (West Siberian economic region), Tuva Republic, Krasnoyarsk Territory (East Siberian economic region), Kamchatka province and Jewish autonomous district (Far East economic region) this share varies from 70 to 90%.

Less extensive is the utilization of groundwater in Kurgan and Sverdlovsk provinces (Ural economic region), Omsk and Kemerovo provinces (West Siberian economic region), Sakha Republic (Yakutia), Khabarovsk Territory, Chukotka autonomous district (Far East economic region), with the groundwater contribution varying from 24 to 35%.

While surface water prevail in household drinking water supply, cities and urban villages, supplied from groundwater, head the list of communities. Thus, about 65% of cities and urban villages are provided, chiefly, with groundwater, 17% with surface water and 18% have multiple supplies.

In total, the number of cities, supplied predominantly with groundwater, decreases with increasing population. Among communities, which rely on groundwater, their share reaches 70% in the category of cities with population under 25 thousand, about 53% in the cities with a population from 25 to 100 thousand, and only 26% of the cities with a population over 100 thousand.

The evaluation of data for groundwater use in the Asian part of the Russian Federation demonstrates that they are used, primarily, for household and drinking water supply for urban and rural communities. This fact is secured in Russian legislation, which regulates the priority of groundwater use as the source of household and drinking water.

Groundwater as the source of water supply to communities, located in the Asian part of Russia, is used in about the same quantity as surface water. However, due to better protection of groundwater from contamination, it tends to increase its share in household and drinking water supplies. It can be expected that this tendency will progress in the future.

The comparison of the current status of groundwater utilization (with water yield forecasts

and developed groundwater safe yields) reveals a broad potential for significant upgrowth. However, it must be noted that due to irregular distribution of groundwater resources some regions and large cities consuming much water, in particular, can be in a very unfavorable position.

5.2.2 Groundwater use in India

5.2.2.1 Introduction – Hydrogeological regions

Groundwater is being used in India since the Vedic times, for over 6,000 years. In the Holy Scriptures there are references to dug wells and even the guidelines have been given for locating well sites, based on certain types of trees, anthills and nature of the soil. However, in those days the Indo-Aryan civilization was mainly in the Indo-Gangetic alluvial terrain and these guidelines are not normally useful for the hard rock areas.

Today, the main problem for India is that it has 15% of world's population, which has to be sustained with only 6% of world's water resources and 2.5% of world's land. Both land and water resources must, therefore, be carefully managed in a sustainable manner.

About two-thirds of India is occupied by hard rocks and the remaining portion by unconsolidated and semi-consolidated sediments. The average annual precipitation is 4,000 billion cubic metres (BCM). Average surface water resources are estimated at 1,869 BCM per year, of which 690 BCM can be stored. In addition, the groundwater potential is estimated at 432 BCM. Against this water availability of 2,301 BCM, the population of the country would be between 1.5 to 1.8 billion in 2050. The per capita water availability will then be around 1,400 m^3/yr, making India a water-stressed country.

The groundwater potential of about 432 BCM is dispersed over the country in the wide spectrum of soft and hard strata having different characteristics viz. grain size, compaction, texture, structure, weathering and fracturing. The groundwater scenario is also complicated by varied physiographic and hydrometeorological conditions in landscapes ranging from snow clad mountains in the north to arid region in the north-west, to the coastline of over 7,000 kms in the west, south and east. There is continuous stress on groundwater resources due to increasing water demands. The number of groundwater abstraction structures has increased from merely 4 million in 1951 to 17 million in 1997. Consequently, irrigation potential created from groundwater has increased from 6.0 Million hectares (Mha) in 1951 to 36.0 Mha in 1997. Stress on groundwater resources has caused problems related to over-exploitation, such as declining groundwater levels, sea-water intrusion, quality deterioration, etc. in some watersheds covering an area of about 0.2 million km^2. Augmentation of groundwater resources in such watersheds through activities for recharge promotion has become necessary.

Groundwater utilization has increased over the past 50 years, in view of the following objectives: (1) Increased crop production. Compared to surface water, groundwater produces more agro-output per cubic meter of water, due to efficient use of water; (2) Drought proofing of agriculture. During long breaks in Monsoon rains, groundwater can provide supplementary irrigation to crops. Most of the dug wells also support winter season crop on small plots of land; (3) Providing safe drinking water supply to villages. Groundwater quality is usually better than that of the surface water. Availability of safe drinking water in villages is the foundation for rural development programs; (4) Alleviation of rural poverty: Using groundwater for irrigation gives a better income to the farmers and also provides employment of land-less laborers. Development of rural, agro-based industries is an additional step towards poverty alleviation. Increase in agro-inputs and use of farm implements gives rise to rural service centers and workshops for repairs;

(5) Providing drinking water supply to peri-urban slums, not connected to the urban water supply network, is an important use of groundwater; (6) Industrial development around urban centers often depends upon groundwater as the source of water supply for industrial and domestic use.

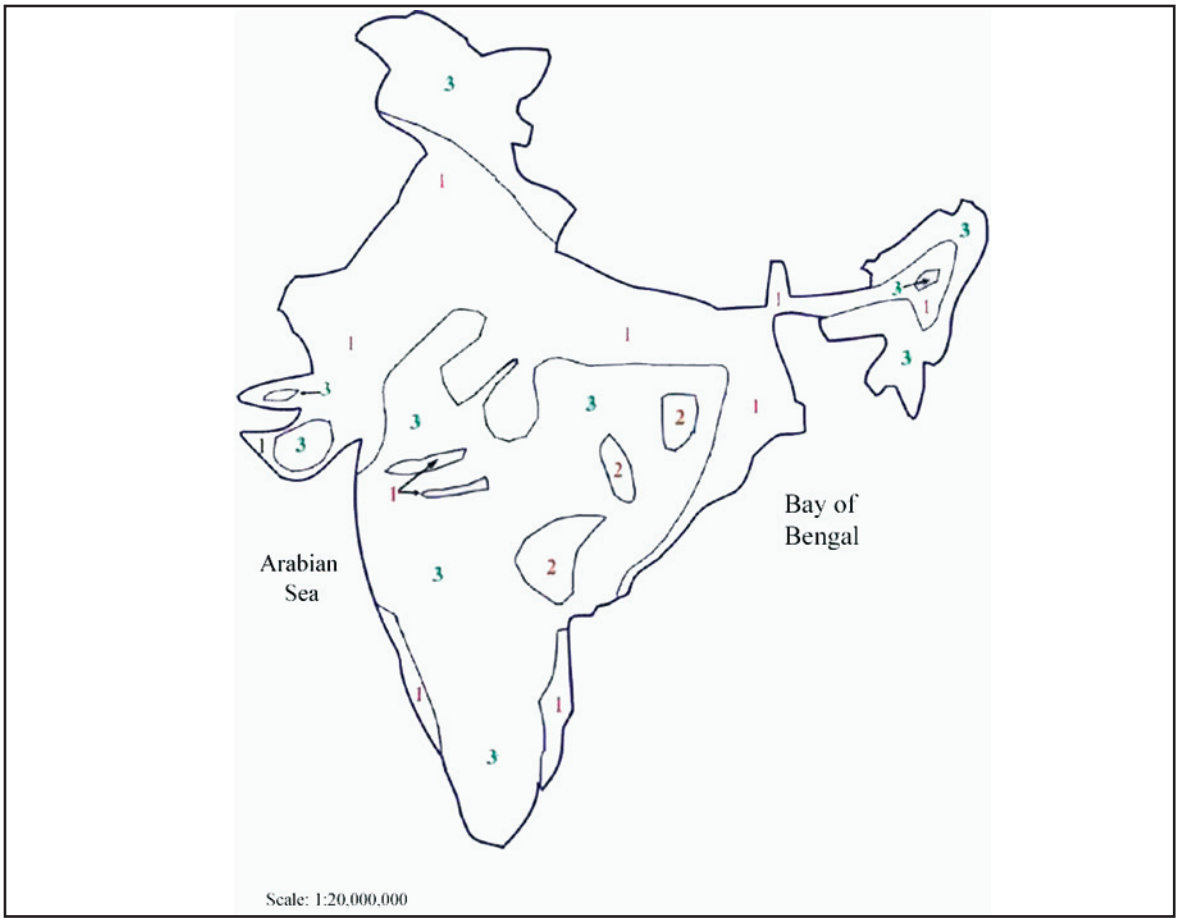
The National Water Policy in India gives drinking water supply the first priority, followed by irrigation use and industrial use. Out of the groundwater potential of 432 BCM, leaving a provision of about 71 BCM for drinking water and industries, about 361 BCM can be developed for irrigational use, which is the most consumptive use.

Figure 5.2.2.1.1 is a map of India showing aquifer zones 1 to 3 described below:

1. Prolific alluvial aquifers of Indo-Gangetic plains in the northern and eastern India. Also, Narmada and Tapi river alluvium, coastal alluvium, coastal sand dunes and coastal limestone aquifers.
2. Aquifers in the alluvium, limestone, sandstone etc. in the inland sedimentary basins of central and southern India.
3. Hard rock aquifers in the Basalt (Deccan Traps), Metamorphic rocks and Basement complex (granite and gneiss).
4. Aquifers in soft strata like laterite and alluvium overlying the hard rock, in the hard rock terrain. (Not shown separately in the Map.)

In India, about 76% landholders are small and marginal farmers, having less than 2 ha of land per family. The area owned by them is about 29% of the total cultivated area in the country. However, they irrigate about 38% of the area irrigated by wells and account for 35% of wells fitted with electric pumpsets (GOI, 1992). There is thus a sizable contribution from small scale irrigation to the national agricultural produce.

Figure 5.2.2.1.1 A map of aquifer zones in India (1,2, 3: aquifer zones)



5.2.2.2 Groundwater development

5.2.2.2.1 Background

Development of a natural resource such as groundwater can be defined as a concerted activity towards its optimum and sustainable use for the benefit of human beings. The concept of optimum use depends upon the known reserves, rate of annual recharge, rate of annual pumpage and the benefit: cost ratio of its use.

After gaining independence in 1947, the planners in India initially concentrated on surface water projects. During the severe droughts of 1951, 1952, 1962, 1965 to 1967 and of 1972, the limitations of surface water development became evident and more attention was focussed on groundwater development. Groundwater development received further boost from the following factors:

Central Government and State Government departments and institutions employed more hydrogelogists and engineers for scientific groundwater studies, taking watershed as a basic unit.

Farmers had access to Institutional finance for well digging/drilling, at low rates of interests, in schemes financed by Commercial Banks under refinance from Agricultural Refinance Corporation (ARC). Nationalization of major commercial banks accelerated the dispersion of Bank Branches in rural sector. International finance from World Bank – IDA was available for groundwater development in many States. Bilateral aid projects were also taken up by Government Departments, NGOs and Charitable Trusts, for groundwater development for irrigational and domestic use.

Initially, pumping of groundwater was done with diesel engine pump-sets. Then many States took up the Rural Electrification Program and even the remote villages got connected to the national or regional electric grid. Farmers were given electric connections at their wells, with a concession in the Electric Tariff.

In early days, bore well drilling in hard rocks was carried out with a calyx rotary rig using 5 H.P. diesel engine. In basaltic or granitic terrain, drilling upto 30 metres depth with this rig often took upto a month. In granitic areas, more time was required. Since 1972, down-the-hole hammer (DTH) rigs became popular. With these high power rigs using compressed air, drilling a bore of 150 mm diameter in hard rocks upto 60 metres depth, was possible within one day. This enabled the farmers to tap groundwater in deeper fractures and fissures. Usually, drilling up to 100 metres depth was taken as the limit for tapping useful supplies of groundwater. In Government's programs for rural drinking water supply, 60 meter deep boring installed with a hand-pump, became a standard norm.

Improvements in pumping technology resulted in marketing of low cost jet (ejecto) type pumps and submersible pumps for deep bores.

The 'Green Revolution' in India was based not only on surface and groundwater resources development but also on the development of rural infrastructure. This included long term credit for well digging/drilling and for purchasing farm equipment, establishment of farmers co-operative societies for agro-inputs, short-term credit for agro-inputs, availability of fertilizers, pesticides and high yielding varieties of seeds, improvement in network of roads and transportation, rural electrification, and warehousing and marketing facilities.

Projects for harnessing surface water are Government projects and farmers get surface water from canals for irrigation at highly subsidized rates. Wastage of surface water, over-irrigation in command area and the resulting water-logging and salinization of low lying farms are the commonly found features in surface water projects. As against this, groundwater development takes place under motivation of the individual farmer and is carried out with his private funds or institutional loans. Whatever supply of groundwater available from the well is fully under the

control of the farmer. The farmer is, therefore, very careful in using groundwater and tries to get maximum production per cubic meter of groundwater pumped from dug well or bore well. Groundwater development has also a few additional advantages, over surface water projects.

A mistake in site selection or in the design of surface water projects, could lead to considerable financial loss and threat to the life of thousands of people. In groundwater development, a mistake in selection of an area could be corrected after digging or drilling the first few wells. If the selected area is not found to be promising, the whole project can be shifted to other suitable area. Surface water irrigation is available only for a maximum of about 12% to 30% of the cultivated area in a watershed. Groundwater development schemes cater to the needs of the majority of farmlands distributed all over the watershed. Unlike surface water, the use of groundwater is fully within the control of the farmer. Even in the command area of canals, farmers prefer to have their own wells so that if the rotation of irrigation from canal is delayed, water from the well could be used. Temperature and chemical composition of groundwater is fairly constant, which is very useful in poultry and fishpond industries. In consideration of all these advantages of development of groundwater resources, D. G. Limaye (1908–1990), one of the pioneering hydrogeologists in India used to say: 'Sustainable development of groundwater is the lifeline for rural India.'

In watersheds or sub-basins in which around 50% of the available groundwater resources are being utilized, the emphasis is now shifting from groundwater development to sustainable groundwater management. Providing an institutional, legal and socially acceptable mechanism for such management is the challenge of the coming decades.

5.2.2.2.2 Hard rock terrain

Groundwater development in fractured hard rock aquifers, like Granite, Gneiss, Metamorphic rocks and Basaltic lava flows or Deccan Traps, which occupy 67% area in the country, has assumed a secondary role compared to that in the unconsolidated alluvial aquifers or in the soluble limestone-dolomite aquifers. This is because of the non-extensive, irregular, non-isotropic and inhomogeneous nature of the hard rock aquifer and the relatively small yields of water available from dug-wells or drilled bores. However, many of the highly populated areas in the country are underlain by hard, fractured rock aquifers. The Basalts cover an area of about 500,000 km^2 in Maharashtra, Karnatak, Gujarat and Madhya Pradesh (MP) States and form the largest exposure of volcanic rocks in the world. The basement complex of granite, gneiss and metamorphic rocks together covers about 800,000 km^2. In hand specimen these rocks may not have any connected porosity but on a macroscopic scale the storage coefficient is about 0.03% to 0.3% (Limaye, 1940). Whatever small supply of groundwater available from these rocks is the only source for the millions of people to obtain drinking water supply for the family and cattle, and to irrigate their small plots of farms. During the past few decades, institutional finance at low rates of interest was provided to farmers, for well digging/drilling for irrigation use. This resulted in over-development in some sub-basins, thereby stressing the need to adopt the principles of Integrated Water Resources Management (IWRM). For sustainable development, it is necessary to follow soil and water conservation techniques in each watershed, taking a sub-basin as the unit for planning.

The most significant features of these hard rock aquifers are as follows:

1 A topographical basin or a sub-basin generally coincides with groundwater basin. Thus, the flow of groundwater across a prominent surface water divide is very rarely observed. In a basin, the groundwater resources tend to concentrate towards the valley center, closer to the main stream and its tributaries. The profile of hard rock underlying the weathered zone plays an important role in directing the flow of phreatic water body. Occasionally, dikes, fracture zones and shear zones also modify the flow of groundwater.

2 The depth of groundwater occurrence, in useful quantities, is usually limited to about one hundred metres or so.

3 The aquifer parameters like Storativity or Storage Coefficient (S) and Transmissivity (T) often show erratic variations within small distances. The annual fluctuation in the value of T is considerable due to the change in saturated thickness of the aquifer from wet season to dry season. When different formulae are applied to data from a pump-test, a wide range of S and T values is obtained. The applicability of mathematical modeling is, therefore, limited to only a few simpler cases.

4 The saturated portion of the mantle of weathered rock or alluvium or laterite, overlying the hard fractured rock, provides the main storage for groundwater and often makes a significant contribution to the yield obtained from a dug well or bore well.

5 Only a modest quantity of groundwater, in the range of one cu.m. to about a hundred cu.m. per day, is available at one spot. Drawdown in a pumping dug well or bore well is often almost equal to the total saturated thickness of the aquifer.

5.2.2.2.3 Alluvial terrain

Although alluvial terrain covers less area of the country, major prolific aquifers lie in this zone. Investment on groundwater schemes is, therefore, much more in the States underlain by alluvial aquifers, than in those having hard rock aquifers. Table 5.2.2.2.3.1 shows outlay on groundwater schemes in some of the states in hard rock and in alluvial category.

Table 5.2.2.2.3.1 Outlay of groundwater schemes (Vora, 1975)

Name of the State	*Outlay on groundwater schemes till 5 September 1969*
Maharashtra (Hard Rock)	Rs. 3.24 million
Tamil Nadu (Hard Rock)	Rs. 2.34 million
Punjab (Alluvial)	Rs. 54.99 million
Haryana (Alluvial)	Rs. 28.28 million
Gujarath (Alluvial)	Rs. 23.04 million

The Indo-Gangetic alluvial belt, comprising intercalated beds of gravel, sand and clay, has thickness ranging from a few hundred to a few thousand metres. Both dug-wells and tube wells are used for domestic and irrigational water supply. Deep tube wells, over 200 m depth, cost around US$6,000 to 8,000 depending upon depth and diameter. They are expensive and are often State owned and maintained. Farmers' Cooperative Societies also drill deep tube wells and distribute water to their members. Dug wells of 2 to 4 m diameter and 10 to 15 m depth have retaining wall of brick masonry. They pass through the upper clayey strata and tap water from the shallow sandy aquifer. Horizontal and vertical bores are sometimes drilled in the bottom of a dug well to increase its yield. Dug wells cost around US$500. The cost of a shallow tube well up to 60 to 100 m depth is in between the dug wells and deep tube wells. Rich farmers afford to have their own, private shallow tube well.

5.2.2.3 Exploration of groundwater and resource assessment

Hydrogeological Survey, Geophysical Survey and Remote Sensing are the common methods of groundwater exploration. Remote Sensing is used as a tool for reconnaissance survey for delineating promising areas for conducting detailed hydrogeological and geophysical surveys. Old

river channels, lineaments and fracture orientations observed from satellite imageries or air photographs are also useful for this purpose. Electrical resistivity sounding and profiling are the most frequently applied geophysical techniques. Sounding is more applicable in alluvial terrain having thick extensive aquifers, while profiling is more useful in hard rock areas with undulating hard rock profile under a thin cover of soft and weathered strata. Instruments for resistivity survey, incorporating integrated transistorized circuitry are manufactured indigenously and cost around US$ 300 to 500. Resource assessment in a sub-basin can be done at the input side, by estimating the recharge from rainfall or at the output side, by estimating the dry season flow and underflow of the stream draining the sub-basin. The more the quantity of this outflow, better are the prospects for digging/drilling additional wells.

However, in hard rock areas, as the number of additional wells increases, this outflow gets reduced due to additional pumpage from the new wells. Such reduction of outflow from several sub-basins affects the dry-season flow of the river draining the main basin. This adversely affects the downstream schemes using surface water in the river as the source for domestic supply or irrigation. 'It is, therefore, necessary to adopt recharge augmentation schemes or water conservation techniques in all the sub-basins in which the drilling/digging of additional wells is taking place on a large scale, in order to minimize the adverse effect on the dry season flow of the river' (Limaye et al., 1974).

The ratio of (recharge or infiltration to groundwater/rainfall) in hard rock terrain is customarily estimated between 9% to 13%. However, in high rainfall Basaltic area of Konkan and Western Ghat region, the phreatic aquifer is often too thin to absorb even 9% of the rainfall of about 2,000 to 4,000 mm. Also, due to the rugged topography, most of the infiltration flows out as rejected recharge during Monsoon and immediately afterwards. The effective recharge is often below 3%. Only the areas having thick lateritic and forest cover can retain appreciable quantity of recharge. On the other hand, in drought prone basaltic areas of central India, the cover of weathered rock is thick and the topography is mild. Under such conditions it is possible to have recharge to the extent of 25% to 30% of the rainfall of about 500 mm. This gives rise to the paradox of having 'more recharge' in low rainfall areas and 'less recharge' in high rainfall areas, in the basaltic terrain. However, in the high rainfall areas that 'less recharge' is always assured, even in a drought year, while in the low rainfall areas that 'more recharge' is a function of the precipitation in Monsoon season. In a drought year, the recharge may be negligible.

The post-Monsoon, high water levels in the wells gradually deplete to a minimum position by the end of summer season. During Monsoons they recoup to their initial position. As long as the recuperation is full, the groundwater in the sub-basin is not being over-exploited. But if the post-Monsoon recuperated water levels show a declining trend over a couple of years, then over-exploitation is taking place.

In alluvial terrain, the ratio of recharge to rainfall is from 15% to 25% depending upon the nature of topsoil. Groundwater development in a new area, causes decline in piezometric levels for a few years after which they stabilize. Here also, a continuous decline in post-Monsoon levels would indicate over-exploitation. The main difference between hard rock and alluvial areas is that for the former, the annual pumpage of groundwater is a major part of the total water storage in the aquifer, while for the later, the annual pumpage is just a small fraction of the total storage. In the Indo-Gangetic alluvial belt, the Transmissivity values are over 3,000 m^2/day and the Storativity values are between 0.001 to 0.00001.

Exploration for locating sites for well digging and drilling is vitally important for successful completion of irrigation or drinking water supply projects. In alluvial aquifers exploration is relatively easy because of the extensive nature of the aquifer. But hard rock aquifers are not extensive and their properties vary in short distances. During the field work for exploration it is important to pay attention to the following factors:

1. Inventory of existing wells. Their depth, diameter and yield and type of strata met with. Level of water table. Area irrigated by each well. Type of pump and pumping schedule. Seasonal fluctuation in water table.
2. Rainfall and drainage pattern.
3. Lithological units met with in wells. Their strike and dip in sedimentary strata. Thickness of soft overburden and its relation to topography. The extent of fissuring in hard rock and its relation to topography.
4. The sandy or rocky nature of the stream or river bed. Whether the stream is seasonal or perennial. The prospects of attracting influent seepage from the stream to a pumping well on the bank.
5. Shifting and meandering of river. Erosional or depositional features on river bank. Evidence, if any, of rejuvenation.
6. Locations and discharge of natural springs, if any, in the area.
7. Locations of surface water reservoirs, if any in the area. Possibility of receiving recharge during the dry season from surface water reservoirs and/or the irrigational canals shooting off from the reservoir. If the canals are lined, the possibility of getting recharge from deep percolation below root zone, in the irrigated area.
8. The occurrence of dykes, pegmatite veins etc. in the area and their nature as groundwater conduits or barriers. Whether there are any good wells upstream from the dyke. Any preferred direction of fracture orientation in the area as observed from rock exposures and strata met with in dug wells.
9. Correlation, if any, between the lineaments observed in air photos or satellite imageries and the locations of successful wells in the area or patches of dense natural vegetation in an otherwise sparsely vegetated landscape.
10. Variations, if any, in the quality of groundwater along its general flow direction. Whether there are any erratically successful or erratically failed wells, which do not fit into the conceptual model of groundwater occurrence in the area. Such wells indicate discontinuity and lateral variation in the aquifer.

5.2.2.4 Well digging/drilling, pumpage and revitalization

Dug wells of 2 to 6 m in diameter and 8 to 12 m depth are commonly found in India. Masonry retaining wall is necessary to support the excavation in alluvial areas. Soft, weathered strata, overlying the fractured hard rock has also to be supported by a retaining wall. Horizontal bores of 50 to 75 mm diameter and up to 10 m length are drilled below water table, to increase the effective diameter of well and obtain more supply, from the weathered strata and also from fractured hard rock. Vertical bores of 100 mm to 150 mm diameter are drilled in the well bottom up to 10 to 50 m depth, to tap water under semi-confined condition, from the underlying fractured zones or flow junctions. This water often rises and gets collected in the bottom of the well. In alluvial terrain, the horizontal and vertical bores tap sand lenses in vicinity of the dug well and give additional supply into the well.

Centrifugal pumps are commonly used on dug wells. Bore wells are installed with Jet Type or Submersible Pumps depending upon the yield. Submersible pumps are much more efficient than Jet type pumps. Single-phase submersible pumps cost a little more than the three-phase submersible pumps. But they are popular because getting all the three phases live for working of a three-phase pump, could be a problem in some areas. Drinking water supply is mainly obtained by drilling bores of 150 mm diameter up to 60 m depth or so and installing hand pumps on these bores.

In the villages in hard rock terrain, many failed wells and bores exist. Bores can be

revitalized by blasting or by hydro-fracturing. Experimentation and guidelines for blasting are not available. The main aim of blasting is not to create a big volume of fractured rock for water storage around the bore but to connect the bore to an existing, saturated, fractured zone in the vicinity. In the bottom of failed wells, it is possible drill 2 or 3 vertical bores, fill them with sand and blast the bores, so as to use the wells as recharge wells in the monsoon season. Such experiments have to be carried out and their success rate recorded.

In the villages in alluvial terrain, drinking water wells are either dug wells or shallow bore wells. Towns and urban areas depend on deep bore wells. Development of a well after drilling is important to ensure long life. Otherwise, find sand gets into the bore and also in the water pumped from the bore. Clogging of screen due to encrustation is also a common problem.

Table 5.2.2.4.1 gives the data on the number of wells in some of the major States in India.

Table 5.2.2.4.1 Statewise groundwater abstraction wells in some of the major States in India (data till 1999)

Name of State	*Dug wells*	*Shallow tubewells*	*Deep tubewells*
Andhra Pradesh	1,075,860	97,560	13,421
Bihar	417,770	705,830	12,779
Gujarat	709,070	8,300	22,939
Haryana	42,420	434,980	2,677
Karnataka	512,650	35,020	7139
Kerala	169,010	2,590	
Madhya Pradesh	1,307,070	19,220	2,484
Maharashtra	1,116,020	100	4,168
Orissa	543,750	14,200	2,325
Punjab	93,470	622,600	1,532
Rajasthan	835,250	18,940	–
Tamilnadu	1,446,630	134,970	5,152
Uttar Pradesh	11,456,670	2,343,520	25,198
West Bengal	43,180	262,970	3,122

5.2.2.5 Recharge augmentation

Recharge augmentation can be done in two ways, by promoting natural infiltration of rainwater or by artificial recharge techniques. Increasing the cover of grass, bushes and trees through afforestation programs in a watershed promotes natural infiltration of rainfall. So also soil and water conservation techniques like hill-slope trenching, contour bunding, gully plugging, stream bunds, underground bunds across streams, farm ponds and percolation tanks, increase the residence time of water in the watershed. The shape of stream hydrograph, after a rainstorm event in a degraded, barren watershed, has a sharp peak and a narrow time base. When afforestation and soil and water conservation techniques mentioned above, are adopted in the watershed, the hydrograph gets a broader peak and a wider base. If the area under the hydrograph remains unchanged, it means that the afforestation and soil conservation works have not adversely affected the volume of runoff available from the watershed, but just moderated and delayed the availability. Any increase or decrease in the area would mean positive or negative effect from afforestation and soil conservation works, on the availability of runoff. These effects are site specific and also depend on the species of trees used in afforestation. Shallow rooted grasses and bushes should be preferred in low rainfall areas, due to their small rates of transpiration. Long term, quantitative studies are necessary on this subject, by taking baseline data from a degraded

mini-watershed and then converting the watershed into a well managed and afforested watershed. National policy for afforestation in different climatic regions can then be evolved.

Artificial recharge techniques usually include recharging of wells and bores with good quality, silt-free surface water from farm-ponds or streams. Rainwater collected from roofs in Monsoon season is also used for this purpose in urban areas facing the problem of declining water table. The basic rule in artificial recharge is that the surface water being introduced into the aquifer must be of equal or better quality than the quality of native water in the aquifer. Thus a brackish water bearing aquifer may even be charged with treated sewage water, to be recovered afterwards for irrigation.

In semi-arid hard rock areas, construction of Percolation Tanks has been found to be very useful in recharge augmentation. A percolation tank is constructed by putting an earthen bund with side waste weir across a stream. Runoff water stored behind the bund during rainy season gradually percolates during the dry season to recharge the groundwater body. A typical percolation tank has a bund of 8 to 10 m height and a catchment area of about 20 to 50 km^2. Ideally, the water stored in the tank should percolate within first 3 to 4 months of the dry season so that the shallow water body is not exposed to excessive evaporation rates in summer months. In the semi-arid area in India, thousands of percolation tanks have been constructed for recharge augmentation. In this drought prone area, construction of a percolation tank is also a preferred drought-relief measure by the Government authorities, because it provides employment to about 2,000 people for 3 to 4 months in a drought year. The percolation tank becomes operative from the next year's rainy season.

The storage efficiency of a percolation tank is the ratio of the volume of water stored in the tank at the end of rainy season to the volume of runoff water available from the catchment. The percolation efficiency is the ratio of the volume of water percolated to the volume of water stored. The overall efficiency is the product of the above two efficiencies and is around 40 to 70% for percolation tanks constructed at technically suitable locations. Occurrence of exposed hard rock in the tank bed impedes percolation. So also, silting in the tank bed over the years, reduces both storage and percolation efficiencies. Regular desilting is therefore necessary. A percolation tank and a couple of smaller stream bunds and underground bunds is an ideal combination for recharge augmentation in a sub-basin. In areas where regional groundwater has high salinity, or contains arsenic or fluorides, dug wells excavated on the down-gradient side of percolation tanks give better quality of groundwater. This is due to the dilution of regional groundwater by percolation from good quality runoff water collected in the tank.

Recently, a novel experiment in recharge augmentation was taken up in semi-arid, basaltic terrain in western India, by a voluntary organization. In this experiment, surface water flowing in effluent streams during the early post-rainy season, was lifted by the farmers, using their pumpsets and was delivered into several dug wells in each stream basin. About 100,000 dug wells were thus charged with water that would have flown out of the area as surface flow in a few days and its residence time was prolonged to more than a few months. The local farmers realized the beneficial effects of this experiment during the following summer season.

5.2.2.6 Groundwater quality

Quality of groundwater is suitable for agricultural and also for irrigation in most of the cases. Only in certain regions in hard rock terrain and in alluvial aquifers, the quality problem arises. A few typical cases are mentioned below:

1. In semi-arid areas where more than 15 to 20 metres thickness of heavy black soil overlies the hard rock, the quality of water is sometimes brackish. If used for irrigation, the soil gets

hard and unproductive within a few years. People may however, drink the water if there is no alternative.

2. In granitic terrain fluoride in groundwater is as high as 10 ppm in some villages. The fluoride content is often related to residence time of infiltrated rainwater in the fractured rock aquifer. Wells downstream from the bund of a village water tank storing Monsoon runoff indicate reduced fluoride due to infiltration of good quality runoff water from the tank.
3. In alluvial areas, arsenic is present in groundwater in some villages. This problem has started due to lowering of piezometric head and water table in the unconsolidated alluvial aquifer in the state of West Bengal. Previously, when Monsoon runoff storage tanks in villages were used to provide drinking water, this problem was minimal.
4. Groundwater in isolated lenses of sand in alluvial strata, has impaired water quality due to its sluggish movement and long residence time.
5. Seawater intrusion in the coastal alluvial and limestone aquifer in the state of Gujarat in western India has taken place up to 10 km from the seashore. Extensive pumping for agricultural and industrial purpose from a sensitive system has caused this problem. Recharge augmentation is a solution to this problem.
6. Urban groundwater is polluted in all small and large cities. Leakages from industrial chemicals and effluents, from sewers and waste water lines, from septic tanks and landfills, and influent seepage from streams and rivers, are the main sources of pollution. There is no easy solution to this problem. Urban residents who augment their Municipal water supply by drilling bore wells prefer to install UV water purifiers in their houses.

5.2.2.7 Groundwater legislation and pumpage control

Recharge augmentation is a positive way of resource management, while pumpage control is a negative way. However, in overexploited watersheds it is sometimes necessary to impose pumpage control and apply the provisions of groundwater legislation. The change in over-exploited and critical areas between 1984–85 to 1992–93 represents a growth of 5.5% per year. If this rate continues, such areas would double after every 12.5 years (World Bank, 1998).

However, the basic right of any farmer to dig or drill a well in his farm and improve his living standard, by using an equitable share of groundwater for irrigation, must be recognized and honored. A farmer should not be prevented from well digging or drilling, just because his neighbors have already dug their wells and a new well would reduce the yield of the existing wells. Even if the existing wells are affected, this should be looked upon as an equitable distribution of a scarce resource. Whenever pumpage control is to be imposed, the power of restricting pumpage from high yielding wells should be vested with Village Authorities.

In a drought year, if the drinking water well or bore in a village goes dry, it is possible under current legislation to acquire temporarily a neighboring private well with adequate yield, by giving due compensation to the owner. This provision is being used rather than imposing a blanket restriction on well digging or drilling within 500 m of the village drinking water well or bore.

Many States in India have passed groundwater protection act, controlling well digging by farmers in overexploited watersheds. The provisions of the act are, however, not strictly followed because of political fear that such actions would surely be 'vote losers'. The farmers have a strong sense of ownership of the groundwater underlying their farm. At the same time, if the yield of a well owned by a farmer suddenly reduces due to digging/drilling of new wells by neighboring farmers in their farms, the farmer accepts this as his fate and does not enter into a court battle.

Pumpage control is a negative way of management but when it has to be imposed, it should

only be through mutual monitoring by farmers or by local council at the village level. The concept of sustainability in such a case may imply only a period of about 7 to 9 years in which a farmer usually recovers his investment made in constructing the well. The owners of high yielding wells should be the first ones to cut down on their pumpage. They should only pump an equitable share, as approved by the Village Council, so that other farmers may also dig/drill new wells. This is better done through persuasion and social pressure rather than through any rigid legislation. In the complex, non-isotropic and discontinuous hard rock aquifers, any rigid legislation on a hidden resource like groundwater is technically unsound and socially unjust.

5.2.2.8 Research areas or gaps in existing technology

Research areas or the gaps in the existing technology are discussed below, from the viewpoint of promoting Integrated Water Resources Management (IWRM) in hard rock terrain. Most of this research work is field based and not laboratory based. Ideally, a few sub-basins in different climatic zones should be selected as pilot projects for conducting the research work and promoting IWRM, hand-in-hand. Guidelines for IWRM in hard rock terrain in general and basaltic terrain in particular can be developed through the research work.

1. The ratio of (groundwater recharge to rainfall) needs better estimation. Estimations have been made from input side, using soil moisture balance or tracer techniques. It is necessary to confirm them on output side by measuring the dry season stream flow and underflow, which is a measure of excess of recharge over the pumpage in the sub-basin.
2. The role of afforestation and soil and water conservation techniques in a sub-basin needs a careful study. The Report of World Commission on Dams (WCD) has recommended these techniques in flood management (page 161) but has indicated their possible negative role in availability of dry season stream flow (page 139). On the other hand, the Center for Science and Environment, New Delhi has recorded a few cases in which a seasonal river has become perennial after afforestation and water conservation techniques were applied in its watershed. After a rainstorm event in a watershed, the increase in groundwater recharge due to afforestation and water conservation techniques, is on the positive side but the increase in evaporation from small water storages and transpiration by more vegetation is on the negative side. Their relative quantities are very much site-specific. A national afforestation policy has therefore, to be formulated, so that in low rainfall areas, trees of high transpiration capacity like Eucalyptus are not planted in afforestation programs. In these areas, soil and water conservation with grass and hardy bushes would be better. Long-term pilot studies in selected sub-basins are necessary for determining the net effect of afforestation and soil and water conservation techniques on the dry season stream-flow.

   Climatologists have indicated that in future the climatic pattern will be more harsh, causing flash floods in some areas and severe droughts in other areas. Under these circumstances, afforestation and soil and water conservation programs in a sub-basin assume a special importance, because the resilient interface or the buffer between a rainstorm and the runoff is offered through these programs.
3. Percolation tanks store runoff water from mini-catchment in Monsoon season and provide recharge to groundwater during winter season, thereby playing a valuable role in water conservation. Over the years these tanks get silted. This reduces their storage capacity and also the rate of vertical infiltration. Studies are required to measure the efficiency of percolation tanks and the effects of desilting. In some cases, when a tank has exposures of hard rock in its bed, percolation does not take place and most of the water is exposed to high rates of evaporation in summer. Research regarding the feasibility of revitalization of these tanks by drilling bores or excavating wells in their beds is necessary.

4. Exploration by Electrical Resistivity Method is useful for well siting and for locating suitable sites for percolation tanks in hard rock areas. Research in low cost instrumentation is necessary so that even the smaller NGOs could purchase these units. NGO staff should be trained in operating the instruments and in qualitative interpretation.
5. In command areas of irrigation canals, the low lying farms near the stream or river get water-logged due to over-irrigation in the higher lands. It may be possible to control this problem of water logging by conjunctive use of surface water and groundwater. In such a pilot scheme, surface water irrigation from canal is restricted to about 50% to 60% of the command area in the upper reaches near the canal, while in low lying areas irrigation is exclusively from groundwater available in wells and bores.
6. Drinking water supply in villages is mostly through bore wells installed with hand pumps. It is necessary to train local people, if possible the local women, in hand pump repairs, so as to maintain the continuity of supply from this source. Revitalization of some of the old and abandoned bores in villages is also necessary.
7. In another 25 years, over 50% of the population in developing countries in Asia, Africa and Latin America, will live in urban and peri-urban areas and about 60% of these people will live in slums, without any facility of sanitation and piped water supply for domestic use. Providing this vast population with safe quality drinking water and with in-situ sanitation, without causing groundwater pollution is a big technical challenge. Equally big financial challenge is to find funds for this task in Public or Private sector. Protecting the quality of urban groundwater and urban surface water is an important component of urban environment. To start with, baseline data collection through Government Agencies, institutions, NGOs and university departments has to be encouraged.

5.2.2.9 Tenets of groundwater policy for sustainable development

The groundwater policy for the future should have the following tenets for achieving sustainable development:

1. economical and efficient use of the water pumped from the aquifers;
2. watershed development through soil and water conservation programs. Recharge augmentation;
3. conjunctive use of surface water and groundwater;
4. prevention of pollution of surface water and groundwater;
5. irrigation of food crops giving more calories per cubic meter of water;
6. use of aquifers having marginal quality of groundwater;
7. creating a public awareness about the true economic value of water;
8. involvement of women in management of village drinking water supply;
9. pumpage control in overexploited watersheds, only through village councils;
10. and building the bridges of understanding and co-operative action between the various stakeholders in water resources.

Government of India has now formed the Central Groundwater Authority. With the co-operation of groundwater organizations in various States and the NGOs, the Authority should promote the following activities.

1. Preparing a database of NGOs and institutions active in water resources sector.
2. Compilation of case histories of experiments in watershed development, afforestation, soil and water conservation, artificial recharge and other research work carried out by various Agencies.
3. Organizing workshops/conferences for providing a platform for discussion and dissemination of ideas and experiences.

4. Organizing training courses in watershed management, afforestation, repairs of hand pumps installed on drinking water bore wells, irrigation management in small farmers, for rural women so as to foster their active participation in water related issues.
5. Create 'water awareness' or 'water culture' in the society through audio-visual media, as a foundation for integrated water resources management.

5.2.3 Groundwater resources of China and their use

5.2.3.1 General features

5.2.3.1.1 Topography and morphology

The territory of China offers sharp contrasts in topography. From the Tibet plateau in the west to the coastal areas in the east, the average altitude decreases from 4,000m (locally over 5,000m) to less than 50 m above sea level. Areas with altitude less than 500 m account for only 16% of territory (Table 5.2.3.1.1.1).

Table 5.2.3.1.1.1 Areas with different range of altitude in China

Altitude above sea-level (m)	<500	500–1,000	1,000–2,000	2,000–5,000	>5,000
Percentage of total area (%)	16	19	28	18	19

The main morphologic features are as follows (Table 5.2.3.1.1.2).

Table 5.2.3.1.1.2 Characteristics of main morphologic features in China

Name	*Percentage of total inland territory*	*Altitude above sea level (m)*	*Height difference (m)*
Plain	12	< 200	50
Basin	19	Various	500 or more
Plateau	26	>1,000	> 500 above nearby plains
Hill	10	< 500	50–450
Mountain	33	500–3,000 or more	generally > 500

China has 18,000 km coastline and more than 6,000 islands. The two biggest islands, Taiwan island and Hainan island, are located in SE part of China. Two largest peninsulas, Liaodong peninsula and Shandong peninsula, are located in northern part of coastal zone.

5.2.3.1.2 Climate

Rainfall decreases from SE China to NW China. Annual average precipitation of China accounts for 650 mm. Most of precipitation is concentrated in summer months. Variation of precipitation for stations at different latitudes and different longitudes are as follows (Table 5.2.3.1.2.1, Table 5.2.3.1.2.2).

Table 5.2.3.1.2.1 Variation of precipitation for stations at different latitudes

Station name	*Latitude*	*Observation duration (years)*	*Precipitation (mm)*
Harbin	45°40'	32	701
Jinan	36°42'	64	603
Zhenjiang	32°13'	83	1,036
Guangzhou	23°08'	69	1,036

Table 5.2.3.1.2.2 Variation of precipitation for stations at different longitudes

Station name	*Latitude*	*Observation duration (years)*	*Precipitation (mm)*
Shangqui	115°40'	32	701
Xian	108°56'	48	576
Lanzhou	103°53'	46	331
Hetain	79°56'	37	34

Perennial variation of precipitation differs for different parts of China. Ratio Ka (Ka=Maximum annual rainfall/Minimum annual rainfall) is as follows: for NW China Ka > 8, for North China Ka = 4–6, for NE China Ka = 3–4, for SE China Ka. = 2–3, for SW China Ka < 2.

5.2.3.1.3 Hydrographic networks

Outwards drainage systems, running over a total area about two third of China, occur mainly in eastern and southern parts of China, with *most* rivers flowing eastwards into the Pacific ocean, whereas the internal river systems drain the NW part of China, forming lakes in their lower reaches or depressions, or disappearing in the deserts. Characteristics of main rivers of China are as follows (Table 5.2.3.1.3.1).

Table 5.2.3.1.3.1 Characteristics of main rivers in China

River name	*Drainage area (km^2)*	*Annual rainfall (mm)*	*Runoff depth (mm)*	*Runoff ratio (%)*
Songhua river	545,665	525	145	27.6
Yellow river	752,443	492	76	15.4
Huai river	261,504	929	191	20.6
Yantze river	1,807,199	1,055	542	51.4
Pearl river	452,616	1,438	772	53.7

Note: Runoff depth = total runoff/drainage area ; runoff ratio = runoff depth/annual rainfall.

Rivers with catchment area > 100 km^2 account for 50,000, and rivers with catchment area >1,000 km^2 account for 1,500. Areas without runoff account for 160 x 10^4 km^2 (desert and similar land).

Glacier covers area 5.86 x 10 km^2. Annual average melting water from glacier is estimated as 560 x 10^8 m^3, which is a very important source of groundwater, recharge in NW arid zone of China.

5.2.3.1.4 Geology

On the basis of the regional geologic and tectonic features, the whole country can be divided into three major regions with the Tianshan-Yinshan and Kunlun-Qinling latitudinal structural zones as boundaries: the northern, the central and the southern regions. These three major regions have respectively gone through different geologic histories, hence they have different geologic features.

As result of significant subsidence and strong Variscan movement in the region north of the Tianshan-Yinshan mountains, a thick sequence of Paleozoic marine formations were tightly folded and intensely metamorphosed, and covered by part of alternately marine and continental Mesozoic strata. The Variscan granites and the late Paleozoic volcanic rocks are relatively common, especially in the Greater and Lesser Hinggans and Altai mountains, where granites cover 1/5 –1/4 of the region's total area.

In most parts of the region between Tianshan-Yinshan mountains and the Kunlun-Qinling mountains, the crustal movement was relatively moderate in Paleozoic period. This is mainly marked by: (a) uplifts and subsidences en masse, (b) relatively weak magmatic activity, (c) limited regional metamorphism, (d) gently folded strata, (e) fracture large in size, but moderate in number. About 2/3 of the region is occupied by a series of large-size or medium-size Mesozoic and Cenezoic structural basins with sediments in substantial thickness (Mz - Tr - Q, mainly continental origin). In the other 1/3 of this region, exist mainly tightly folded and metamorphosed Archean rocks and less tightly folded, essentially un-metamorphosed or slightly metamorphosed rocks of Sinian period and partly of Paleozoic and Mesozoic era.

To the south of the Kunlun-Qinling mountains, there is a region which has experienced the longest duration of transgressions since the Sinian period, and during which marine formations have been developed the most. It is also a region where the orogenic movement has been relatively intense since the Mesozoic era. The structural basins of the Mesozoic and Cenezoic eras are small in extent (except Sichuan basin) and also few in number. Karst area of SW China accounts for 50 x10^4 km^2 with various well-developed karst landscape. Quaternary sediments are developed along main rivers or around large lakes.

5.2.3.2 Groundwater resources of China

5.2.3.2.1 An outline of regional hydrogeology

China is a country with vast inland territory of 9.6 x 10^6 km^2. The various regions differ greatly in climate, geomorphology and geology (lithology and structure). The whole country not only embraces various climatic zones at different latitudes, but also features varied geomorphology, ranging from coastal plains to uplands and the Tibet plateau – the 'roof of the world'. Therefore, China is characterized by great complexity of regional hydrogeologic settings and by differing hydrogeologic patterns within various regions. Here is some more information about pore water and karst water distribution in China.

Distribution of pore water in unconsolidated sediments: Large-sized and middle-sized basins are mostly concentrated in the vast areas north of Kunlung-Qinling mountains, such as Song-Liao plain in NE China, North China plain (Huang-Huai-Hai plain), interior basins in NW China, including Tarim basin, Chaidamu basin and Hexi corridor. In the middle reach of Yellow river, the distinctive Loessal plateau lies between the interior basins and the North China plain, and has complicated hydrogeologic characteristics in vertical profile, Mesozoic sandstone aquifers of Ordos artesian basin and Paleozoic carbonate aquifers lie underneath the Loessal plateau. Piedmont plains have the most productive aquifers within the above-mentioned basins. However, in piedmont plains within different climatic zone, main recharging sources of shallow

groundwater vary greatly. In interior basins within arid zone of NW China, river water, running from mountainous areas, accounts for 70–80% of total groundwater recharge, while in piedmont part of the North China plain with semi-humid climate, precipitation accounts for 50–60% of total groundwater recharge. In southern China, mountains and hills are the dominant morphologic features. Lei-Qiong basin (10 x 10^4 km^2) and Chengdu plain (0.64x10^4 km^2) may serve as examples of groundwater basins with good perspective for water supply.

Distribution of karst water in carbonate rocks

Carbonate rocks are widely distributed in China. Hydrogeologic characteristics of karts water are quite different in southern China and in northern China (Table 5.2.3.2.1.1). In southern China, the climate is rather humid, the surface and underground features of karst are well developed. In northern China, at present time the climate is arid, semi-arid and semi-humid. But in the geologic past (middle of Paleozoic era), the hot and humid climate provided favorable conditions for paleo-karst development.

Table 5.2.3..2.1.1 Comparative characteristics of karst of water between southern China and northern China

Characteristics of karst water	*Northern China*	*Southern China*
Water-bearing formation	mostly Cm–O	Zn–T
Continuity of media	continuous	continuous or uncontinuous
Water-collecting area (km^2)	n x100–n x1,000	n–n x100
Underground flow modulus (l/s. km^2)	3–5	3–8
Variation of spring discharge (Q_{max}/Q_{min})	1.2–5.8	> (10–100)

In mountainous and hilly areas with widely distributed carbonate rocks of SW China, karst water mainly is unconfined water. Here exist numerous karst springs and underground karst rivers. In North China Platform, paleo-karst formed during O_2–C periods, has significant role for accumulation of karst water with good quality. Buried confined karst aquifers in Ordovician carbonate rocks not only serve as important water supply source, but also is a unfavorable condition for coal mines, extracting overlying coal deposits in C-P formations.

5.2.3.2.2 Groundwater resources evaluation and their distribution in China

During the period of 1981–5, regional groundwater resources evaluation was conducted through three steps: (1) for each province, (2) for large hydrogeologic regions, (3) for whole China. In the successive years, some new data were added to results of groundwater resources evaluation for several provinces, but the general picture of groundwater resources evaluation and their distribution has no change. The total amount of annual precipitation is about 6 x 10^{12} m^3/yr for inland territory of China, while the total amount of natural resources of groundwater is around 8,700 x 10^8 m^3/yr. According to the principle of water balance, the so-called natural groundwater resources are represented by the total amount of average recharge of groundwater under natural conditions. Therefore, it is also known as the recovery or reproductive resources of groundwater. Different methods are used: method of groundwater balance, hydrograph separation, mathematic statistics, etc. The regional exploitable groundwater resources are around 2,900 x 10^8 m^3/yr, which was calculated mainly for pore-water in plains and basins, as well as for karst water. Detail prospecting results and groundwater monitoring data are used for calculation (Figure 5.2.3.2.2.1, Table 5.2.3.2.2.1, Table 5.2.3.2.2.2, Table 5.2.3.2.2.3).

Figure 5.2.3.2.2.1 Sketch map, showing large hydrogeologic units in China

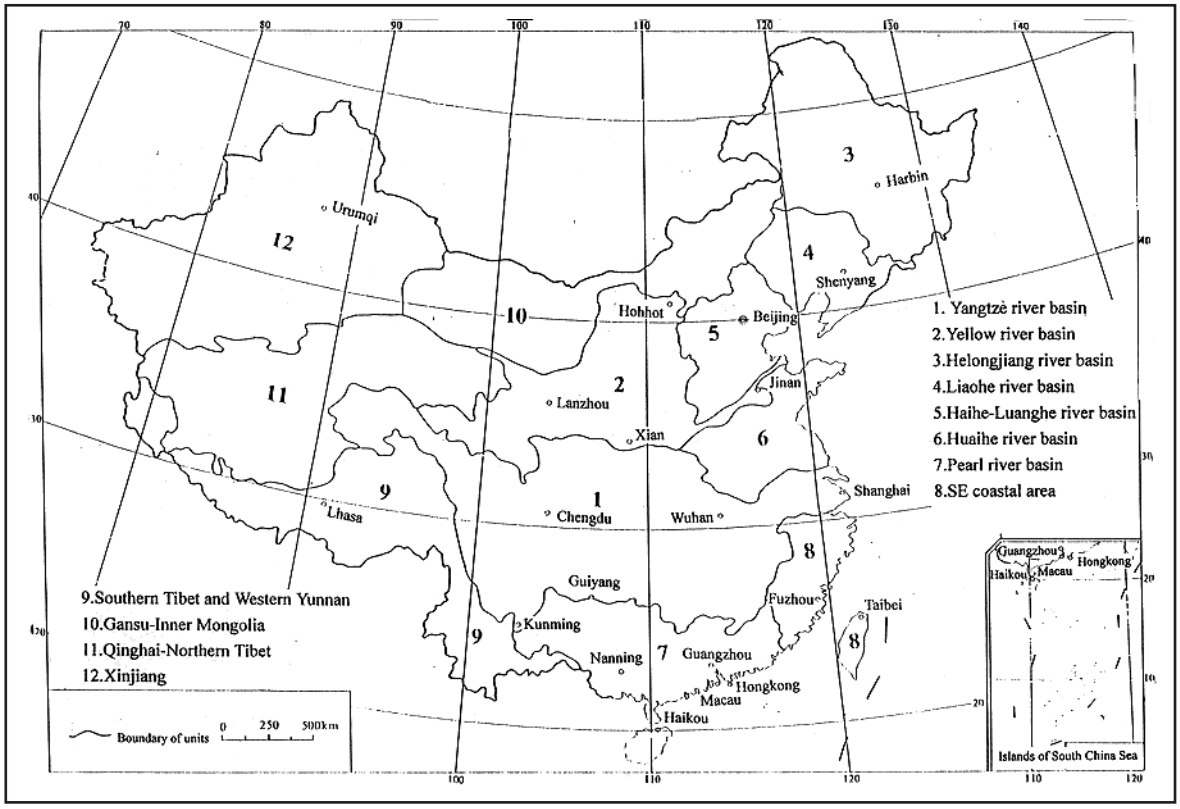


Table 5.2.3.2.2.1 Groundwater resources for large hydrogeologic units (10^8 m^3/yr)

Order of unit	*Name of hydrogeological unit*	*Natural resources*	*Exploitable resources*
1	Yantze river basin	2,662	870
2	Yellow river basin	458	261
3	Heilongjiand river basin	459	258
4	Liaohe river basin	242	136
5	Haihe-luanghe river basin	287	218
6	Haihe river basin	364	355
7	Pearl river basin	1,548	302
8	SE coastal area	827	101
9	Southern Tibet and western Yunnan	1,017	95
10	Gansu-Inner Mongolia	140	29
11	Qinghai-Tibet	163	18
12	Xinjiang	570	251
	Total	8,742	2,902

Table 5.2.3.2.2.2 Groundwater resources in some plain areas

Plain name	*Area* ($x\ 10^4\ km^2$)	*Natural resources* ($x\ 10^8\ m^3/yr$)	*Exploitable resources* ($x\ 10^8\ m^3/yr$)
North China plain	32.0	492	481
Songlaio plain	31.1	334	238
Sanjiang plain	4.30	50	39
Guangzhong plain	1.86	33	25
Chengdu plain	0.65	34	26

Table 5.2.3.2.2.3 Karst water resources in northern China Region

Refion name	*Carbonated rocks* ($x\ 10^4\ km^2$) *Total*	*Exposed on surface*	*Natural resources* ($x\ 10^8\ m^3/a$)	*Exploitable resources* ($x\ 10^8\ m^3/a$)
Shanxi plateau	6.90	2.20	36.5	32.9
Easterflank of Taihang mountain	2.47	1.52	31.7	24.1
Central and Southern Shangdon	2.22	1.52	31.0	29.0
Other regions	4.37	1.99	29.2	17.6
TOTAL	15.96	7.26	127.4	103.6

Beside regional evaluation of groundwater resources, detail hydrogeologic prospecting works have been made for more than 1,200 water-well fields, in which pore-water well fields account for 846 (68%), kart-water well fields account for 315 (25%), fissure-water well fields account for 82 (7%). Their regional distribution is as follows: 72% of pore-water well fields are in northern China, while 28% of pore-water well fields are in southern China. 62% of karst-water well fields (big springs, underground karst river, buried confined karst water) are in southern China, while 38% of karst-water well fields are in northern China (Figure 5.2.3.2.2.2).

5.2.3.2.3 Groundwater resources of some typical regions in China

Some more information about three regions, where groundwater resources play important role for water supply, is presented below. There are: (1) Huang-Huai-Hai plain (North China plain), (2) Loessal plateau, (3) Karst area in SW China.

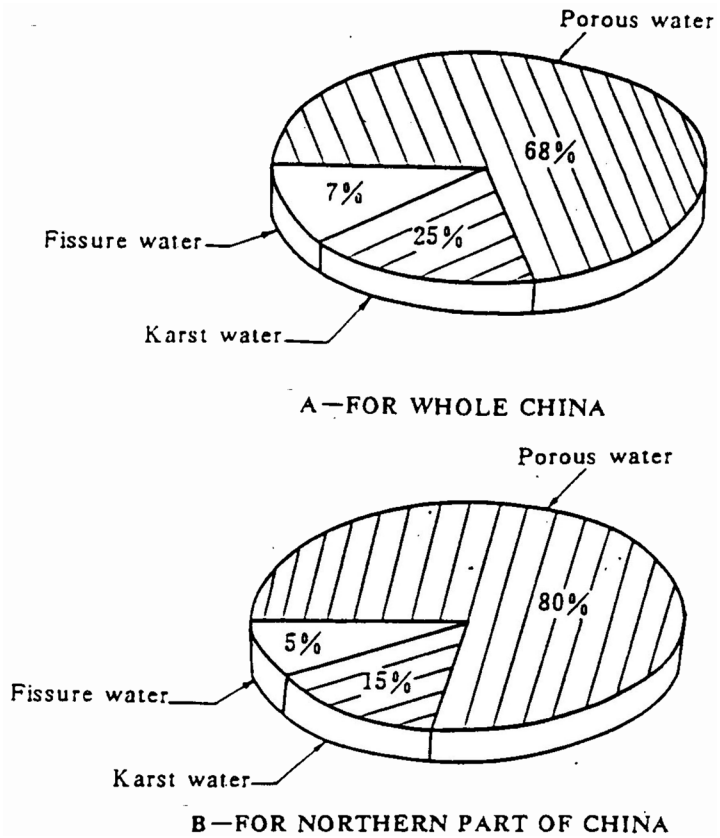
Huang-Huai-Hai plain

This alluvial plain has an annual average precipitation of about 500–1,000 mm concentrated mostly in the summer months. Rivers, with sources in adjacent mountain areas, flow through plain and finally into Bohai Sea, some being seasonal due to construction of reservoirs within mountains and hills. Underground salty water in coastal plain has a genetic connection with the transgression of the Bohai sea and surface evaporation during Quaternary period. The present salty soil has developed against this background.

The region, north from Yellow river, can be divided into two parts: an entire fresh groundwater zone in the west, and inter-layered fresh and saline groundwater zone in the east. Within the second zone there is a sequence of shallow fresh water, intermediate saline water, and deep fresh water in the vertical direction. The region south from Yellow river has no saline water and the groundwater quality is rather good.

Thickness of Quaternary deposits may reach as much as 600 m in northern part. There are

Figure 5.2.3.2.2.2 Percentage of vaious types of water well fields



four water-bearing units vertically. Borehole depth is no more than 150–200 m in entire fresh groundwater zone and may reach 300–500 m to exploit deep fresh groundwater beneath saline water. Thickness of Quaternary deposits is less than 200 m in southern part, and borehole depth is usually less than 100 m.

Total annual recharge of groundwater accounts for 492 x 10^8 m^3/yr. Recharge components are as follows: rainfall infiltration 79.7%, penetration of surface irrigated water 6.0%, lateral inflow from rivers and canals 6.87%, lateral underground flow 5.98%, seepage through aquitards 1.42%. Exploitable shallow groundwater resources account for 481 x 10^8 m^3/yr.

Groundwater withdrawal in North China plain accounts for 1/3 of that figure for whole China. Shallow aquifers are the most productive aquifers for urban and rural water supply. Experiences show that shallow aquifers are being used for regulating surface runoff and store more infiltrating rainwater for utilization in the coming years. To control optimal groundwater level in irrigated farmlands and to promote combined well-ditch irrigation-drainage technique is a best way to prevent and control drought, water-logging and soil salinization in wide spread plain with semi-arid or semi-humid climate.

Loessal Plateau

It is located in the middle reach of Yellow river. Total area accounts for 62 x 10^4 km^2. Annual rainfall decreases from 700 mm in SE to 120 mm in NW. Plateau surface is at the altitude 2,000–1,000 m, declining toward the east. Some alluvial plains along the Yellow river and it's tributaries are at lower altitudes. There are five types of aquifers: (1) Porous aquifers in plains along rivers (Yinchuan plain, Hetao plain, Guangzhong plain), (2) Karst aquifers (mainly

Cambrian-Ordovician carbonate rocks), (3) Mesozoic sandstone aquifers with pore-fissure water in Ordos basin, which is located in western part of Loessal plateau; (4) Water in loessal layers, which cover karst aquifers and Mesozoic sandstone aquifers in many places; (5) Fissure water in metamorphic and intrusive rocks, which are exposed in mountainous and hilly areas (Table 5.2.3.2.3.1).

Table 5.2.3.2.3.1 Natural groundwater resources in Loessal plateau

Water type	*Area* ($x\ 10^4 km^2$)	*Groundwater resources* ($x\ 10^8 m^3/yr$)	*Modulus of groundwater resources* ($x\ 10^4\ m^3/yr.km^2$)
Porous water	16.97	196.33	11.57
Karst water	4.55	44098	9.89
Pore-fissure water	10.00	21.75	2.18
Water in loess	20.00	22.46	1.12
Fissure water	10.82	50.46	4.66
TOTAL	62.34	335.98	–

Karst area in SW China

Total area accounts for 50 x 10^4 km^2. Annual precipitation is more than 1,000 mm/yr. Altitude decreases from 2,500 m in NW to less than 200 m in SE. Mountains and hills are dominant morphologic features. Carbonate rocks (from Sinian to Trias age) are wide spread and comprise one-third of total area. Karst features are extensively developed and the ratio of penetration of rainfall is generally about 30% to 70%. Thus karst water resources accounts for 40% to 70% of total groundwater resources in this area (Tables 5.2.3.2.3.2 and 5.2.3.2.3.3).

Table 5.2.3.2.3.2 Karst water resources in four provinces of SW China (x 10^8 m^3/yr)

Province	*Karst water resources*	*Total groundwater resources*	*R (%)*
Yunnan	325	742	43.7
Guizhou	168	229	73.2
Guangxi	484	776	62.3
Sichuan	294	630	46.6

Note: R = karst water resources/total groundwater resources.

Table 5.2.3.2.3.3 Number of big karst springs with different flow rates range for three provinces

Flow rate range (l/s)	*50–500*	*500–1,000*	*1,000–2,000*	*>2,000*	*Total number*
Yunnan province	648	45	35	3	731
Guizhou province	231	20	11	1	263
Guangxi province	284	13	2	0	229
TOTAL	1,163	78	48	4	1,293

5.2.3.3 Groundwater development and utilization

Total groundwater withdrawal in 1997 accounts for 968 x 10^8 m^3/yr. Distribution of groundwater use by sectors is as follows: urban residential use 7.4%, urban industrial use 17.5%, rural residential use 12.8%, farmland irrigation 54.3%, rural enterprises and others 8.0%

5.2.3.3.1 Urban water supply

Since 1980s, number of cities is increasing, urban territory is expanding and urban population is also increasing in China. At present time, this trend is continuing (Tables 5.2.3.3.1.1 and 5.2.3.3.1.2).

Table 5.2.3.3.1.1 Urban development in China

Year	*1980*	*1985*	*1989*	*1995*	*1999*
Number of cities	223	324	447	640	666

Table 5.2.3.3.1.2 Cities with different range of population at the end of 1999 in China

Population	*<200,000*	*200,000–500,000*	*500,000–1,00,000*	*>1,000,000*
Number of cities	399	192	43	32

Because many industrial enterprises are located in cities, industrial use occupies the leading place among all sectors of water use in urban areas.

Water supply sources for main cities in China are as follows: (a) mainly groundwater (35% of total number of cities), (b) conjunctive use of groundwater and surface water (21%), (c) mainly surface water (44%). Groundwater resources play significant role for urban water supply, especially in northern China. In the middle of 1990s, total exploited water-well fields account for 900, two-thirds of which are located in northern China. The total amount of extracted groundwater is about 3,055 x 10^4 m^3/a. Besides, there are self-served water wells for factories and other units in cities.

The most important types of water-well field in northern China are as follows:

Type 1. Water-well fields in piedmont plains

Subtype l a. With semi-humid climate (Yongding river's al-pl fan near Beijing city);
Subtype 1 b. With arid climate (Manasi river's al-pl fan in Xinjiang of NW China);

Type 2. Water-well fields in valleys

Subtype 2a. Located in narrow valleys, and with closer hydraulic connection with river water (Tar water-well field in Xining city);
Subtype 2b. Located in wide valleys, and with less connection with river water (NW suburb water-well field in Xian city);

Type 3. Water-well fields in carbonate rocks

Subtype 3a. Big karst springs, as water supply source (karst springs in Shanxi province);
Subtype 3b. Buried confined karst aquifers (Baodi water-well field in northern suburb of Tainjin city).

Some more information of above-mentioned types of water-well fields is presented below (Tables 5.2.3.3.1.3, 5.2.3.3.1.4 and 5.2.3.3.1.5).

Table 5.2.3.3.1.3 Comparison of recharge components for groundwater in alluvial-proluvial fans with different climate conditions

Name of plains	*Al-pl fan Yongding river near Beijing*	*Al-pl fan of Manasi river in Xinjiang*
Precipitation (mm)	635	173
Annual recharge (x10 ^{8} m^3/yr)	6.12	3.03
Recharge components (%):		
From precipitation :		
Rainfall	49.02	–
Melting snow	–	10.89
From river water:		81.52
River water	16.34	–
Irrigation water	15.85	–
Lateral flow:		
From bedrock	18.79	–
From alluviam	–	7.59
TOTAL (%)	100.00	100.00

Table 5.2.3.3.1.4 Characteristics of two subtypes of water-well fields (WWF)

Name of subtype	*WWF in narrow valley*	*WWF in wide valley*
Morphology	V-profile valley	U-profile valley
Quaternary deposits	Gravel, coarse sand	Various-sized clay with clay layers
Permeability	High	Moderate
Aquifer type	Unconfined	Multi-layer
Connection with river water	Close	Less direct connection
Water-well yield	High	Moderate

Table 5.2.3.3.1.5 Karst springs from various formations in Shanxi province

Water bearing formation	*Number of big springs*	*Total discharge*	
		m^3/s	*%*
Middle Ordovician	50	70.6	66
Middle Cambrian	42	29.4	27
Upper Cambrian, Lower Ordavician	18	7.8	7
TOTAL	110	107.8	100

In southern China with humid climate and abundant surface water, groundwater is being used for urban water supply in some specific circumstances, for examples: (a) Middle-size and small-size

basins, such as Lei-Qiong basin in south China, Chengdu plain in Sichuan province, some inter-mountainous basins in Yunnan province, (b) Karst water as urban water supply for provincial capitals Kunming and Guiyang.

Over-pumpage has caused some negative environmental effects, such as groundwater table depletion, land subsidence, sea-water intrusion, etc. (Table 5.2.3.3.1.6).

Table 5.2.3.3.1.6 Main geo-environmental problems in areas of urban groundwater development

Geo-environmental problems	*Main aquifer*	*Example city*
Constant depletion of groundwater level	Deep confined aquifer	Cangzhou
Partial drainage of aquifer	Shallow aquifer	Shijiazhuang
Reduction of spring discharge	Karst aquifer	Jinan
Land subsidence	Confined aquifer	Tianjin
Land collapse	Overlain karst aquifer	Taian
Seawater intrusion	Shallow aquifer	Dalian

The following countermeasures have been undertaken to deal with over-pumpage:

- To develop water-well fields in suburb and to divert surface water at long distance. For example, in Tianjin city, water-shortage problem was serious since the 1970s. For the last 30 years, several big karst water-well fields in northern suburb have been put into use, and water-diverting project from Luan river through tunnel and canal has been completed, which bring great benefits to Tainjin city.
- To develop underground storage of surface flow. Some experiences have been accumulated in Beijing, Qingdao and other cities. In Beijing, at the end of rainy season of wet 1994 year, 1×10^8 m^3 water from Miyun reservoir has been put into Chaobai river channel, 0.7×10^8 m^3 water has infiltrated into underground. As the result, groundwater got quick recovery from artificial recharge sources.

It can be seen from the above-mentioned examples that conjunctive use of groundwater and surface water, and development of underground storage of surface flow are effective measures for dealing with over-pumpage problems in urban areas, especially for big cities.

For newly developing cities, we should take into account the following points during city planning: (a) to define city size in accordance with it's water supply potential; (b) to develop 'Satellite towns', because direct expansion of urban territory may cause significant decrease of groundwater recharge; (c) to supply drinking water by separated systems, which is easy to be realized in newly developing cities; (d) to protect water supply sources from contamination and to establish sanitation zone strictly.

5.2.3.3.2 Irrigation and reclamation

In northern China, total groundwater extraction accounts for 80% of that figure for whole China. Here, farmland irrigated by groundwater, accounts for 1×10^8 mu (note: 1 hectare=15 mu).

The distribution of groundwater extraction for farmland irrigation within northern China is also uneven; in North China plain groundwater development intensity occupies the leading place in whole China (Table 5.2.3.3.2.1).

Table 5.2.3.3.2.1 Distribution (%) of extracted groundwater in northern China

Region	*North China*	*NE China*	*NW China*	*Total*
1977	78	5	17	100
1993	67	17	16	100

The amount of extracted groundwater for irrigation in northern China has increased by about 30% from 1977 to 1993. It can be seen from Table 5.2.3.3.2.1, that: (1) North China has the greatest groundwater extraction intensity; (2) during the 16 years period, NE China has the greatest growth rate; (3) groundwater extraction in NW China is also increasing, but the growth rate is less than the average growth rate for whole northern China.

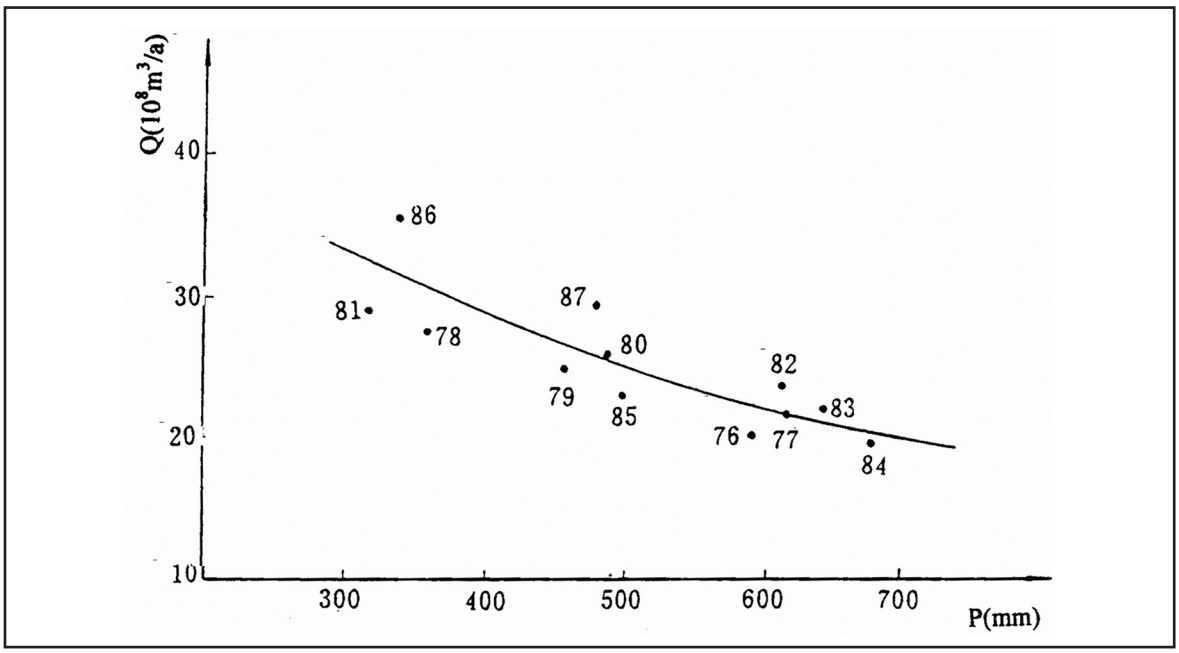
Time variation of extracted groundwater for irrigation is caused by great variation of precipitation during dry year, normal year and wet year (Table 5.2.3.3.2.2).

Table 5.2.3.3.2.2 Characteristic values of precipitation in northern China

Observation station	*Xining*	*Yinchuan*	*Tongguan*	*Daxing*	*Jinan*
Average precipitation (mm)	354	195	562	547	664
P_{max}/P_{min}	2.53	7.72	2.58	4.01	3.08
Observation period	1956-90	1956–190	1956–90	1959–93	1983–5

Detail investigation of correlation of extracted groundwater and annual precipitation has been made for northern plain of Henan province with total area 2 x 10^4 km^2. Observation data during 1976–87 show that the modulus of extracted groundwater is reducing from 15 x 10^4 $m^3/yr.\ km^2$ to 10 x 10^4 $m^3/yr.km^2$, while average annual precipitation is rising from 350 mm to 700 mm (Figure 5.2.3.3.2.1).

Figure 5.2.3.3.2.1 Correlation between annual precipitation (P) and extracted groundwater (Q) for farmland irrigation (Northern plain of Henan Province, 1976–87)



According to main recharge source, four genetic types of groundwater regime have been identified. Each type has certain geographic distribution in specific hydrogeologic situation (Table 5.2.3.3.2.3).

Table 5.2.3.3.2.3 Types of groundwater regime for irrigated farmland

Name of type	*Main recharge source*	*Example*
1. Dominating vertical water exchange type	Precipitation	North China plain
2. Dominating horizontal water exchange type	River water from surrounding mountain area	NW piedmont plains
3. Irrigation water feeding type	Irrigation water	Yinchuan plain, Hetao plain
4. Artificial recharge type	Artificial diverted water	Local areas at present time

1. *Dominating vertical water exchange type*

In alluvial or alluvial-lacustrine plains within semi-humid or humid zone, groundwater is mainly recharged by rainfall infiltration and lost through evapotranspiration. This type is characterized by active water exchange among meteoric water, water of aeration and groundwater in vertical direction. Huang-Huai alluvial plain in semi-humid zone may serve as an example. Quantitative relationship of groundwater balance of Huang-Huai plain within Henan province is as follows: groundwater recharge (100%) consists of rainfall infiltration (81%) and other sources (19%); groundwater discharge (100%) consists of withdrawal (58%) and evaporation from water table (42%).

Within a meteorological cycle, if the total amount of extraction does not exceed that of recharge, the amount of replenishment in a humid year can be used in the next dry or normal year. According to statistic data, the frequencies of humid, normal and dry years in North China plain are 30%, 40% and 30% respectively, that is three humid years, four normal years and three dry years appear alternatively within ten years cycle. Experiences in Shangqiu county of Henan province and other experimental sites show that to rationally develop shallow groundwater and to control water level seasonal and perennial fluctuation around optimal depth (3.5–4.0 m) may make sufficient use of water resources in plain areas with greatly varied precipitation.

2. *Dominating horizontal water exchange type*

The aquifers receive main recharge source from rivers, originated from adjacent mountain areas and flowing into the piedmont plains. It is very typical in NW China with arid climate, where precipitation in plains is especially small. While flowing into the piedmont plains, river water loses greatly into underground space. Underground flow forms a large number of springs in middle and lower parts of piedmont plain. 'Springs' rivers' become one of the important component of the stream flow in the surface flow and underground flow are consumed in depression or seasonally dried lakes through evaporation. This type is characterized by intensive reciprocal transformation between surface water and groundwater, which form an integrated water resources system.

Groundwater resources in plain areas in Xinjiang, NW China, have the following recharge components: (a) river water (flowing out from mountains) infiltration: 30.38%; (b) irrigation canal infiltration: 33.67%; (c) farmland infiltration: 9.11%; (d) lateral underground inflow:

17.97%; (e) local rainwater infiltration: 3.54%; (f) piedmont storm infiltration: 3.03%; (g) reservoir seepage: 2.37%.

These data prove that river water from surrounding mountain areas (partially through irrigation system) is the main recharge source for groundwater in plain area. Unified planning of water resources development for upper and lower parts of piedmont plains is a very important principle to avoid ignoring water demand of lower part of plain, which often leads to serious ecological consequences.

3. *Irrigation-water-feeding type*

This specific type exists in Yinchuan plain and Hetao plain in the middle reach of Yellow river. Both plains are basin with thick deposits of Cenezoic age, and have long history of irrigation by using water from Yellow river (Table 5.2.3.3.2.4). Due to inadequate drainage system, groundwater table has been rising and secondary soil salinization has been expanding.

During the last two decades, pilot projects have been implemented for promotion of well-irrigation and well-drainage technique to control optimal groundwater table. But it has not been popularized due to social-economic reasons.

Table 5.2.3.3.2.4 Examples for groundwater regime type with dominating irrigation water recharge

Name of plain	*Yinchuan plain*	*Hetao plain*
Area (km^2)	6,700	13,000
Annual precipitation (mm)	175	140–225
Average flow rate of transit Yellow River ($10^8 m^3/yr$)	around 250	around 200
Groundwater recharge (%):		
Infiltration of irrigation water	87.8	51.5
Rainfall infiltration	8.2	32.6
Others	4.0	16.3
Groundwater discharge (%):		
Evaporation	68.2	90.7
Pumpage	11.9	8.0
Others	19.9	1.3

4. *Artificial recharge type*

At present time, this type has limited distribution. For the last years, water-diverting project from Yellow River to Tainjin city have practiced several times. In the future, after implementation of ware-diverting project from Yantze River, more territory of North China plain will get considerable supplementary groundwater recharge. This type of groundwater regime will become more important for optimal water resources utilization. And groundwater monitoring will be an important task for hydrogeologists in the future.

Positive effects of groundwater development for agriculture in northern China can be summarized as follows:

- Well-irrigated farmland accounts for 40% of total irrigated farmland in northern China. More than 1,000 x 10^4 rural population has got safe drinking groundwater supply sources in severe water-shortage areas.

- Reduction of salinized soil farmland. Since late 1950s, when groundwater utilization was widely spreading, half of salinized soil has been reclamated in North China plain.
- Enlargement of underground regulatory reservoir, increment of infiltration and reduction of water logging. Local surface runoff in 1987 in North China plain is 30% less than that in 1957 due to intensive groundwater development and increment of infiltration.

However over-pumpage also causes some negative effects in rural areas. For example, in the dry season of 1992 in Hebei province, shallow fresh water, with water table depth more than 10 m accounts for 35% of total plain. In the meantime, deep fresh water, with water table depth more than 30 m, accounts for 40% of total area of its occurrence. Annual rate of water table depletion for deeper aquifer is much more than those for shallow aquifer, even if the intensity of groundwater extraction of the former is much less than that of the later (Table 5.2.3.3.2.5).

Table 5.2.3.3.2.5 Intensity of groundwater extraction and annual rate of water table depletion (Canzhou district, Hebei province, 1986 – 90)

Aquifer	*1*	*2*	*3*	*4*
Intensity of groundwater extraction ($x10^4 m^3/yr.km^2$)	2.88	0.71	0.51	0.17
Annual rate of water table depletion (m)	0.15	0.37	0.86	2.44

For further rational groundwater development for agriculture, we recommend the following points:

1. *For North China plain and Songliao plain*
   - Water demand management.
   - Reduction of water consumption by using new irrigation techniques (Sprinkling irrigation, drip irrigation, etc.).
   - To keep optimal groundwater level for dealing with drought, water-logging and soil salinization.
   - Utilization of slightly saline water (up to 4,000 ppm) for certain kinds of crops.
   - Artificial recharge and use of trans-basin 'quest water'.
2. *For Ymchuan plain and Hetao plain*
   - Promotion of well-irrigation and well-drainage technique in whole irrigation-drainage system to reduce salinized farmland.
3. *For NW arid zone*
   - Enhancement of hydrogeologic investigation and evaluation by using new techniques.
   - Promotion of new water-saving irrigation techniques.
   - Groundwater development strictly in accordance with hydrogeologic conclusions in order to avoid over-pumpage, which may cause serious ecological consequences.
   - Overall planning of water development and utilization; conjunctive use of surface water and groundwater, proportional utilization for upper reach and lower reach, etc.

5.2.3.4 Mineral water and thermal water

In part two and part three, we have discussed problems about evaluation and utilization of fresh groundwater. This part will present materials about mineral water and thermal water in China.

5.2.3.4.1 *Mineral water*

Up to the middle of 1990s, 3,500 mineral water springs (as well as some boreholes) have been investigated and chemical analysis has been made. About 900 plants, producing bottled drinking mineral water, have put into operation.

Correlation of mineral water springs and rock types is as follows: mineral water springs in intrusive rocks: 34%, clastic rocks: 24%, carbonate rocks: 17%, unconsolidated rocks: 17%, metamorphic rocks: 8%.

Based on materials of 407 mineral water springs or water-wells, we made statistics of percentage of various types of mineral water (Table 5.2.3.4.1.1). H_2SiO_3-type accounts for 336 (82.55% of the total number – 407), Sr-type accounts for 231 (56.75% of total number – 407).

Table 5.2.3.4.1.1 Statistics data for mineral springs (water wells) with different components, reaching norm standards

Order	*Components, reaching norm standard*	*Number of springs*	*% of total number*	*Remarks**
1	H_2SiO_3	134	32.92	
2	H_2SiO_3, Sr	133	32.68	
3	Sr	47	11.55	
4	H_2SiO_3, metals, halogen	39	9.58	Li, Zn, Sr; Br, I, Se
5	H_2SiO_3, CO_2, metals	30	7.37	Li, Zn, Sr; Fe, Se
6	Metals, halogen	13	3.20	Li, Zn, Sr; Br, I, Se
7	CO_2, metals	11	2.70	Li, Fe
	Total	407	100.00	

* One component or several components might be included.

5.2.3.4.2 *Thermal water*

According to statistics in 1992 year, 2,200 full-characterized thermal springs were registered, 3/4 of them are concentrated in six provinces (Yunnan, Tibet, Guangdong, Sichuan, Fujian, Hunan). Thermal springs with different temperature ranges are as follows (Table 5.2.3.4.2.1).

Table 5.2.3.4.2.1 Distribution of thermal springs with different temperature range

Temperature	*20–40 °C*	*41–60 °C*	*61–80 °C*	*> 80 °C*
Number of thermal springs	859	807	398	136
Percentage of total number	39.05	36.68	18.09	6.18

According to 'Karst hydrogeograghic map of China' (scale 1 : 4 000 000), the total of 226 thermal springs, with discharge rate more than 10 l/s, have been registered. Among them, 93.4% is concentrated in six provinces (Ywman, Sichnan. Guizhou, HWlan, Hubei, Jianxi) (Table 5.2.3.4.2.2).

Table 5.2.3.4.2.2 Thermal springs (Q >10 l/s) with different ranges of temperature in carbonate rocks in China

Temperature	*20–40°C*	*41–60°C*	*61–80°C*	*> 80°C*	*Total*
Yunnan	110	18	0	1	129
Sichuan	26	5	1	0	32
Gizhou	18	4	0	0	22
Hunan	13	1	0	0	14
Hubei	6	2	0	0	8
Jiangxi	5	1	0	0	6
Others	14	1	0	0	15
TOTAL	192	32	1	1	226

Since the 1970s, many prospecting works for buried thermal aquifers in cities have been made. Now in Beijing,Tainjin, Xian, Kunming, Fuzhou and other cities, thermal water has been widely used for bathing house heating, industrial processing, green housing, etc.

5.2.3.5 Concluding remarks

Hydrogeologic investigation and mapping (mainly in scale 1:200 000) have covered the whole inland territory of China during 1956–95 years. More than 1,200 water-well fields have been prospected. All these works, as well as other investigation and research projects, provide basic materials for regional evaluation of groundwater resources and for urban water supply planning.

Regional groundwater resources evaluation of the inland territory of China was completed in 1985. In the successive years, some new data were added. Official results were published in the yearbook *Report of Mineral Resources of China* (1996), edited by Mr. Song Ruixiang (Minister of Ministry of Geology and Mineral Resources, PRC, at that time). Other sources are published books, including our contributions.

Groundwater plays an important role in social and economic development. About one-third of urban water supply sources come from groundwater. In northern China, groundwater-irrigated farmland accounts for 40% of total irrigated farmland. Besides, groundwater development, with controlling optimal groundwater table, bring benefits for reducing soil salinization and water-logging farmland. Hydrogeologists made great contribution for searching for safe-drinking groundwater sources in severe water-shortage areas (karst area, loessal plateau, etc).

Water demand is increasing in accordance with population growth and economic expansion. Enhancement of groundwater monitoring and management is an important task in the twenty-first century. Some additional prospecting works are also needed, especially in the western part of China.

5.2.4 Groundwater resources and their use in Japan

Introduction

Due to the fact that groundwater is characterized by relatively high water quality and stable temperature, much groundwater has been exploited since ancient days. Drinking water, agricultural water, and industrial water usage are still dependent on groundwater. Beside, groundwater spring source is usually the oasis of local people to meeting point and sometimes is

thought to be a holy place. In Japan, however, groundwater has been excessively exploited in recent years because of lower investment cost in terms of development and exploitation. Subsequently, many adverse effects became apparent.

This article presents the current situation of groundwater quantity and quality in Japan. Besides, a new thinking-horizon among the researchers and engineers is briefly highlighted.

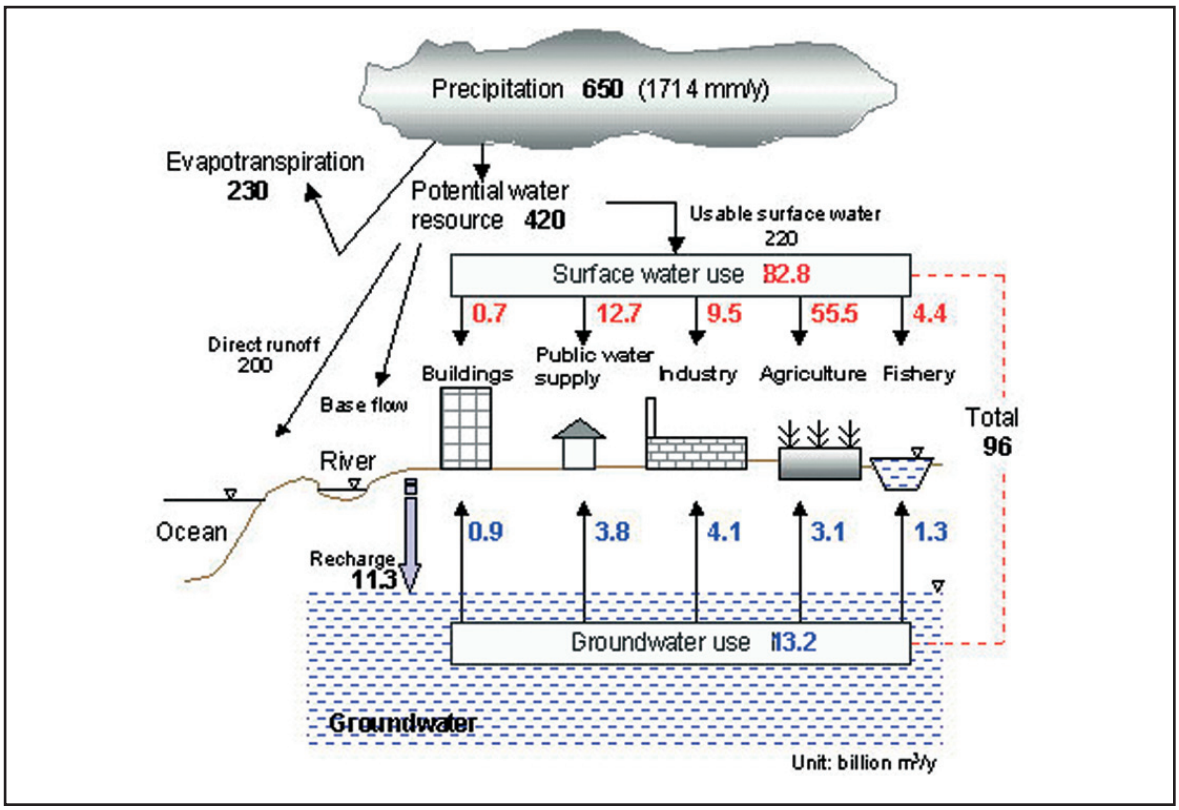
5.2.4.1 Groundwater exploitation and the present subjects

5.2.4.1.1 Water balance

Figure 5.2.4.1.1.1 shows water balance and water use in Japan (*Water resources in Japan*, 2001; Shibasaki, 1995). Japan is located within Asia monsoon region that is characterized by considerable amount of rainfall. The average annual precipitation covering a period of 30 years (1966–95) was 1,714 mm/yr. This is almost two times larger than the world average of 973 mm/yr. The total volume of water, calculated from the product of the precipitation and the land surface area of Japan (378×10^3 km^2), is approximately 650 billion m^3/yr. Water availability per person stands at a volume of 5,100 m^3/yr, which is about 1/4 of the world average of 21,800 m^3/yr per person. Thus, it can be said that though Japan has a large amount of annual precipitation, water availability per person is relatively small because of high population density.

In Japan, potential water resource is estimated to be about 420 billion m^3 because one third of the total volume of water from the precipitation is lost through evapotranspiration. Out of this quantity, 220 billion m^3 is considered as usable surface water that is distributed among water supply systems such reservoirs, weir and water delivery network. The remaining surface water of 200 billion m^3 is discharged to ocean as direct runoff. Total annual water use in Japan is about

Figure 5.2.4.1.1.1 Water use in Japan



96 billion m^3, 61% of which is used for agriculture, 17% for public water supply and 14% for industrial activities. Volume of water for agricultural use in Japan is extremely large relative to that of other usage because of paddy field irrigation. For the total volume of water use, surface water and groundwater provides 86% and 14%, respectively. This means that water use of 13.2 billion m^3/yr comes from groundwater, while, groundwater recharge is estimated to be approximately 11.3 billion m^3/yr2). Thus the total groundwater use exceeds groundwater recharge. This imbalance between recharge and exploitation may lead to the decline of groundwater level and cause various groundwater-related problems. However, the utilization of surface water (220 billion m^3) is not likely to increase because of conservation of the natural environment and of difficulty in respect of land acquisition. In areas where there is continuing increase in the utilization of good quality groundwater resources, there will is obviously an increasing need for a suitable groundwater management program and a real-time monitoring system of groundwater level to forestall overexploitation and possible associated deterioration in quality.

5.2.4.1.2 Use of groundwater in Japan

Groundwater in Japan is used for various purposes including agriculture, industry, public water supply and others such as fishery, air conditioning in buildings, snow melting etc. Public water supply comprises of the water usage in the households as well as in public facilities such as fire fighting, hospital and businesses.

Figure 5.2.4.1.2.1 shows the proportion of groundwater use by the various sectors relative to total groundwater usage. The largest user of groundwater in Japan is the industrial sector, while the groundwater use in agriculture and public water supply represent about one fourth of the total groundwater use each.

Table 5.2.4.1.2.1 shows contribution of groundwater to the total volume of water usage in Japan. In Table 5.2.4.1.2.1, 'Buildings' represents water usage for air conditioning and snow melting. Only 5.3% of the total agricultural water use comes from groundwater, while the main water source for agriculture is surface water. Therefore, groundwater has been considered as a supplementary water source in agriculture, especially during the period of April to September when it is used for paddy field irrigation. Furthermore, Table 5.2.4.1.2.1 shows that total water use

Figure 5.2.4.1.2.1 Proportion of groundwater use among the various sectors

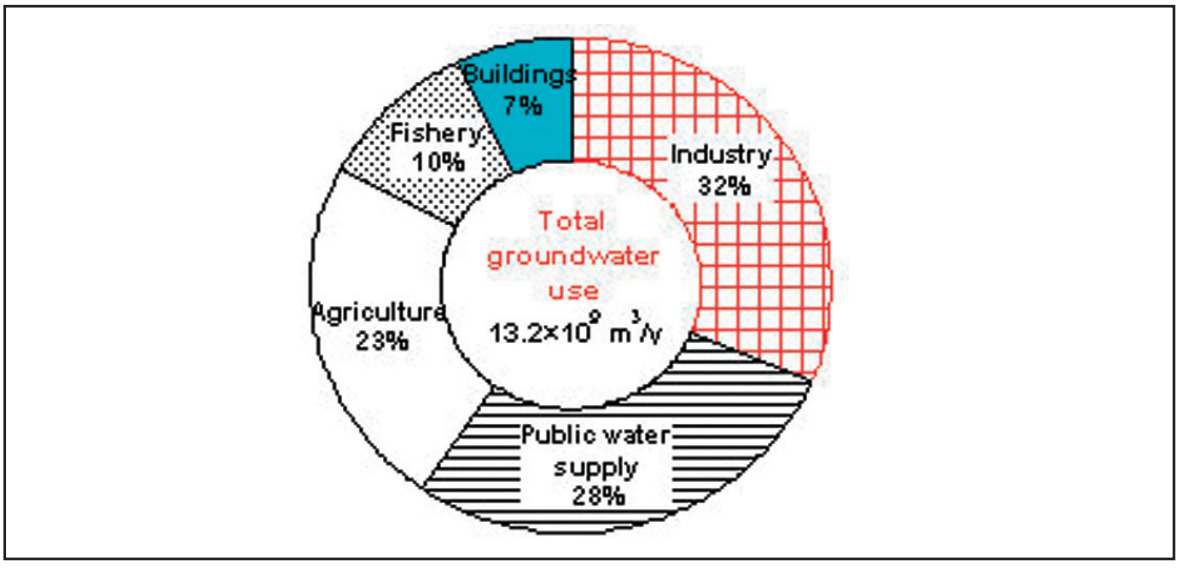


Table 5.2.4.1.2.1 Contribution of groundwater to total water use in Japan

	Groundwater use	*Total water use*	*Ratio of groundwater use to total water use (%)*
Industry	4.1	13.6	30
Public water use	3.8	16.5	23
Agriculture	3.1	58.6	5.3
Fishery	1.3		
Buildings	0.9		
TOTAL	132		

for industry is far less compared to that of agriculture. However, the dependency of industrial section on groundwater is high, constituting 30%, which is the highest proportion of groundwater among other uses. Also groundwater exploitation rate per well in case of the industrial use is much larger than that of the agricultural use. Especially during rapid economic growth and industrialization of Japan since 1955, more groundwater was pumped at lowland areas along coastal regions. Such over-exploitation of groundwater in coastal aquifers had resulted in groundwater-related problems such as land subsidence and seawater intrusion.

Figure 5.2.4.1.2.2 shows temporal variations in groundwater use from 1974 to 1998 in Japan. Groundwater use for industry has been decreased gradually, while that of public water supply has slightly increased. Groundwater use for agriculture has remained nearly level at about 3.8 billion m^3 until 1985. Recent investigation, however, showed that it has slightly decreased to 3.1 billion m^3 after 1996.

Figure 5.2.4.1.2.3 shows temporal variations of land subsidence of some areas in Japan. In 1960s, land subsidence of over 20 cm/yr was observed with the advent of the deep-well drilling. In Tokyo (Kanto Plain), Osaka (Osaka Plain), and Nagoya (Nobi Plain), where severe land subsidence had occurred in the past, land subsidence has slow down now or ceased because of the pumping restrictions by the Industrial Water Law (1956) and the Law Concerning Regulation of Groundwater Pumping for Water Use in Building (1962).

Figure 5.2.4.1.2.2 Temporal variations in groundwater use

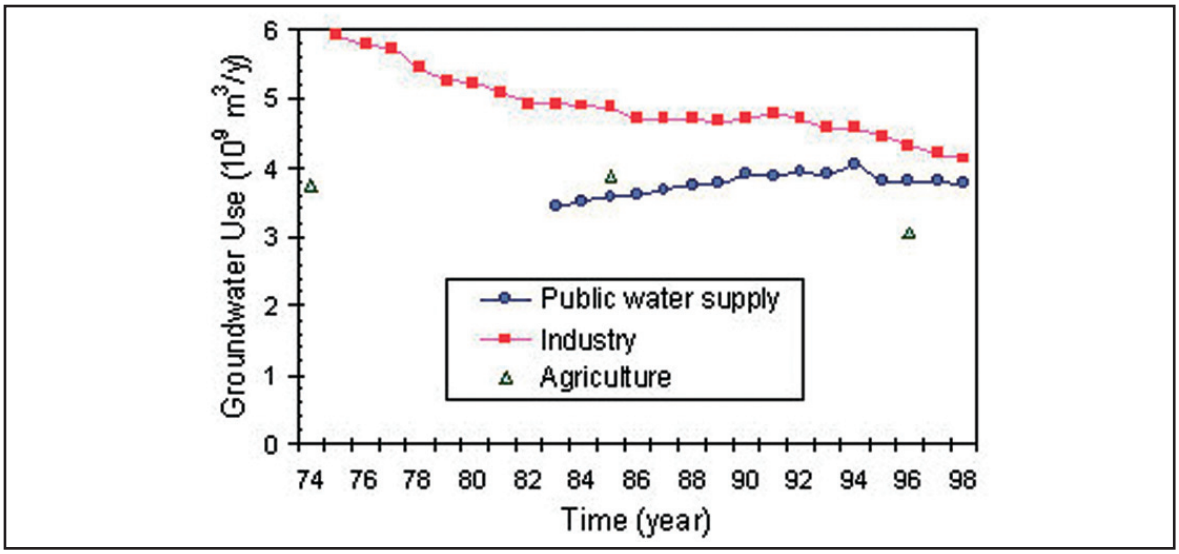
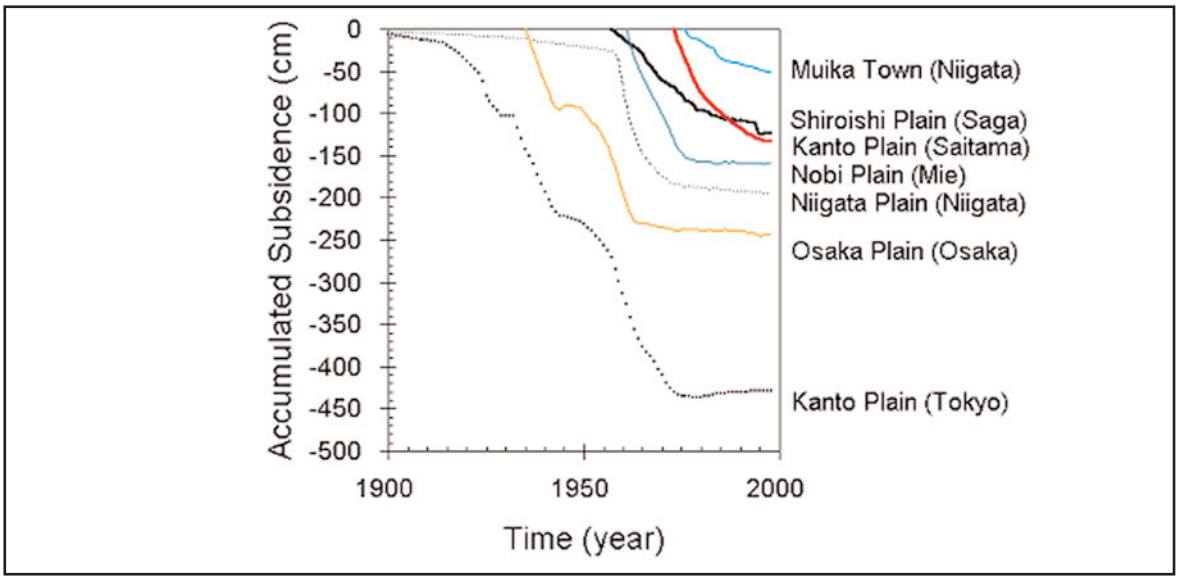


Figure 5.2.4.1.2.3 Temporal changes in land subsidence



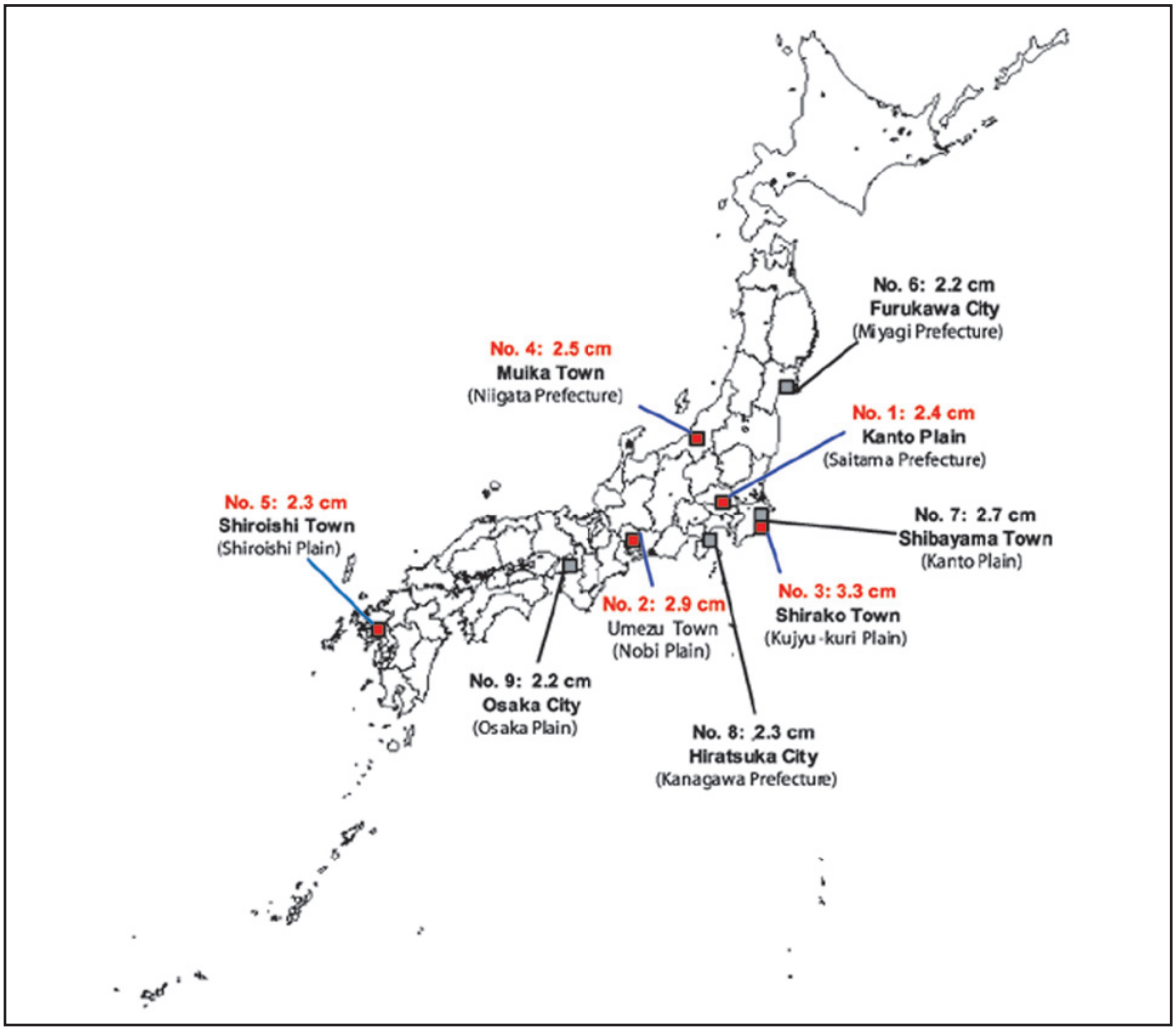
As a countermeasure against the decline of the groundwater level, there were some areas where the focus had shifted to surface water resources from groundwater. Nevertheless, land subsidence is still evident in many areas. In 1998, land subsidence was detected at 62 locations in 37 out of 47 prefectures of local government districts. Figure 5.2.4.1.2.4 shows nine areas where land subsidence of more than 2 cm/yr was detected in 1998. Among these areas, the land subsidence of Kanto Plain (No. 1) and Nobi Plain (No. 2) were caused by the increased water requirements due to expansion of urban areas. In Kujyu-Kuri Plain (No. 3) of Chiba Prefecture, the subsidence was caused by excessive groundwater pumping for natural gas extraction. In Niigata (No. 4), intensive groundwater withdrawal for melting snow on roads and roofs during winter season was responsible for the land subsidence. In the Shiroishi Plain (No. 5) of Saga Prefecture, because of a shortage of surface water, excessive pumping of groundwater for agricultural use during irrigation period resulted in the land subsidence. Notably, the subsidence of about 16 cm in the Shiroishi Plain was recorded in 1994, during the most serious draught year throughout Japan.

Figure 5.2.4.1.2.5 shows the case (*Land subsidence observed in the Saga Plain*, 1999) of the land subsidence in Saga Prefecture that is located close to the Ariake Sea. The groundwater is intensively exploited from the multiple aquifer layers that consist of alluvial deposits. The surface water alone cannot supply the irrigation water for rice production and drinking water due to the constraints of the flat topographic condition. Consequently, as the result of increasing demand for irrigation and drinking water, exploitation of groundwater started in the 1950s.

Groundwater and land level monitoring started when the land subsidence was first discovered in 1958. Figure 5.2.4.1.2.6 illustrates how groundwater extraction has affected the land subsidence. The land elevation is being affected by the seasonal drawdown of the groundwater level with some time lags. The variation in land elevation corresponds to the peak groundwater extraction during the period of paddy field irrigation. The land subsidence of 1994 was particularly serious due to the most severe drought in record. Due to shortage of irrigation water to be supplied from rivers and ponds, groundwater was excessively extracted almost three times more than in a normal year. As a result, the land subsidence reached approximately 16 cm/yr in 1994, which is almost four times the 3.7 cm/yr average subsidence of the previous four years.

Seawater intrusion is also a serious groundwater-related problem in coastal plains of Japan. It occurs when the groundwater levels become lower than sea level due to groundwater

Figure 5.2.4.1.2.4 Location map of land subsidence over 2 cm. Each value in cm indicates the land subsidence in 1998



withdrawals from coastal aquifers. To overcome the difficulties in the development, supply of fresh water resources and the seawater intrusion problems, subsurface dams are constructed for groundwater development in Japan. Such subsurface dam combined with the water supply system can effectively prevent seawater intrusion into inland areas and raise the groundwater level. This system is used not only for agriculture but also for public water supply.

Paddy fields in Japan also function as groundwater recharge zones, however systematic reduction in the area of paddy fields seems to have negative impacts of groundwater recharge. For example, area of paddy field of about 340×10^4 ha in 1970 is now presently put at 260×10^4 ha, which implies a reduction in the potential groundwater recharge area. Thus the expansion of impervious areas associated with urbanization such as transformation of paddy field to urban areas reduces natural groundwater recharge rate and has a possibility to cause the decline of groundwater levels. This is also one of the impacts of human activities on groundwater environment. Therefore it is indispensable to conserve groundwater as valuable natural resources for sustainable groundwater utilization as well as environmental protection.

Figure 5.2.4.1.2.5 Total land subsidence from February 1972 to February 1999. The contours represent areas of equi-land subsidence, dots are the monitoring stations of groundwater level (Courtesy of Saga Prefecture Office), 1999)

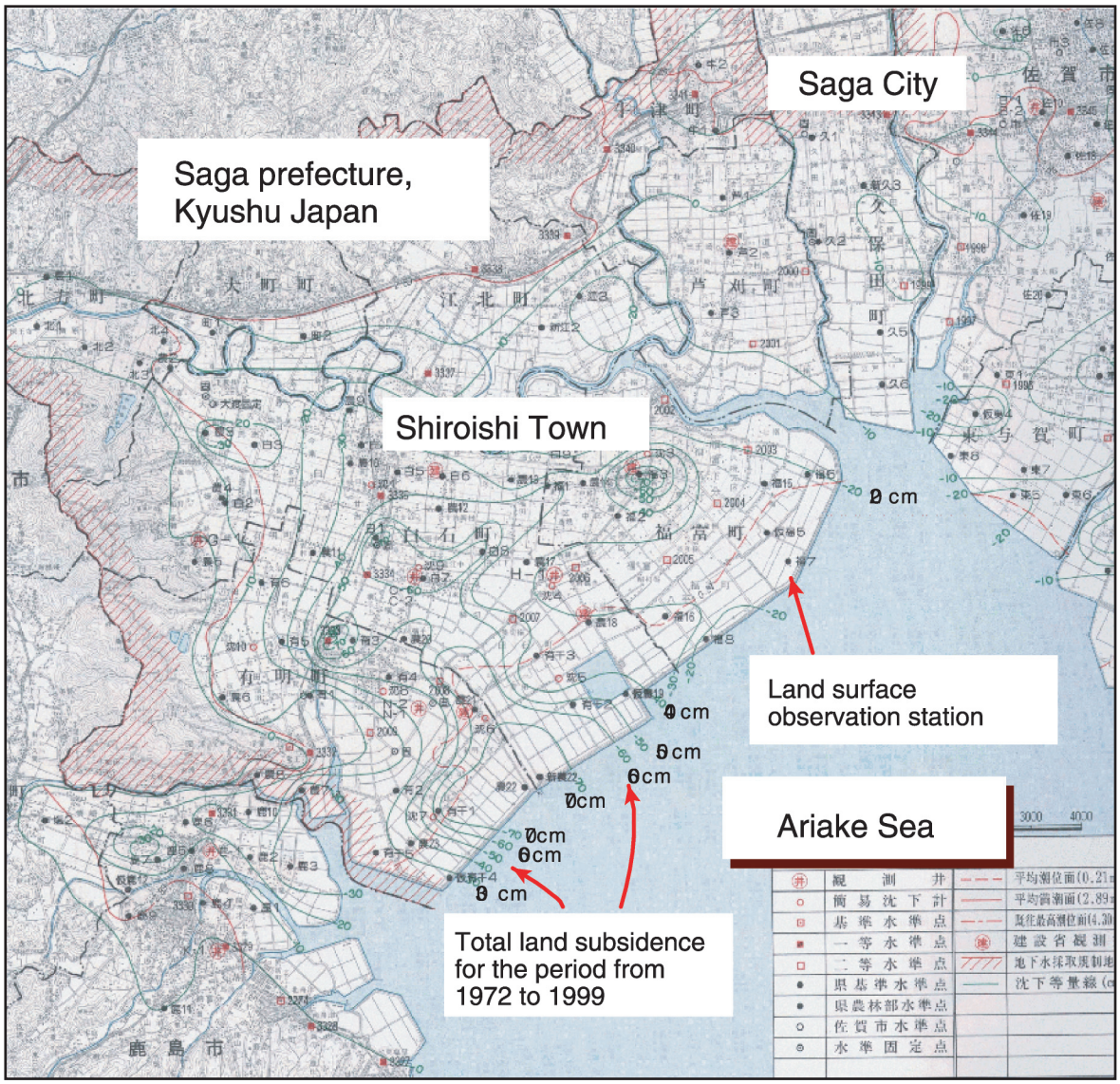
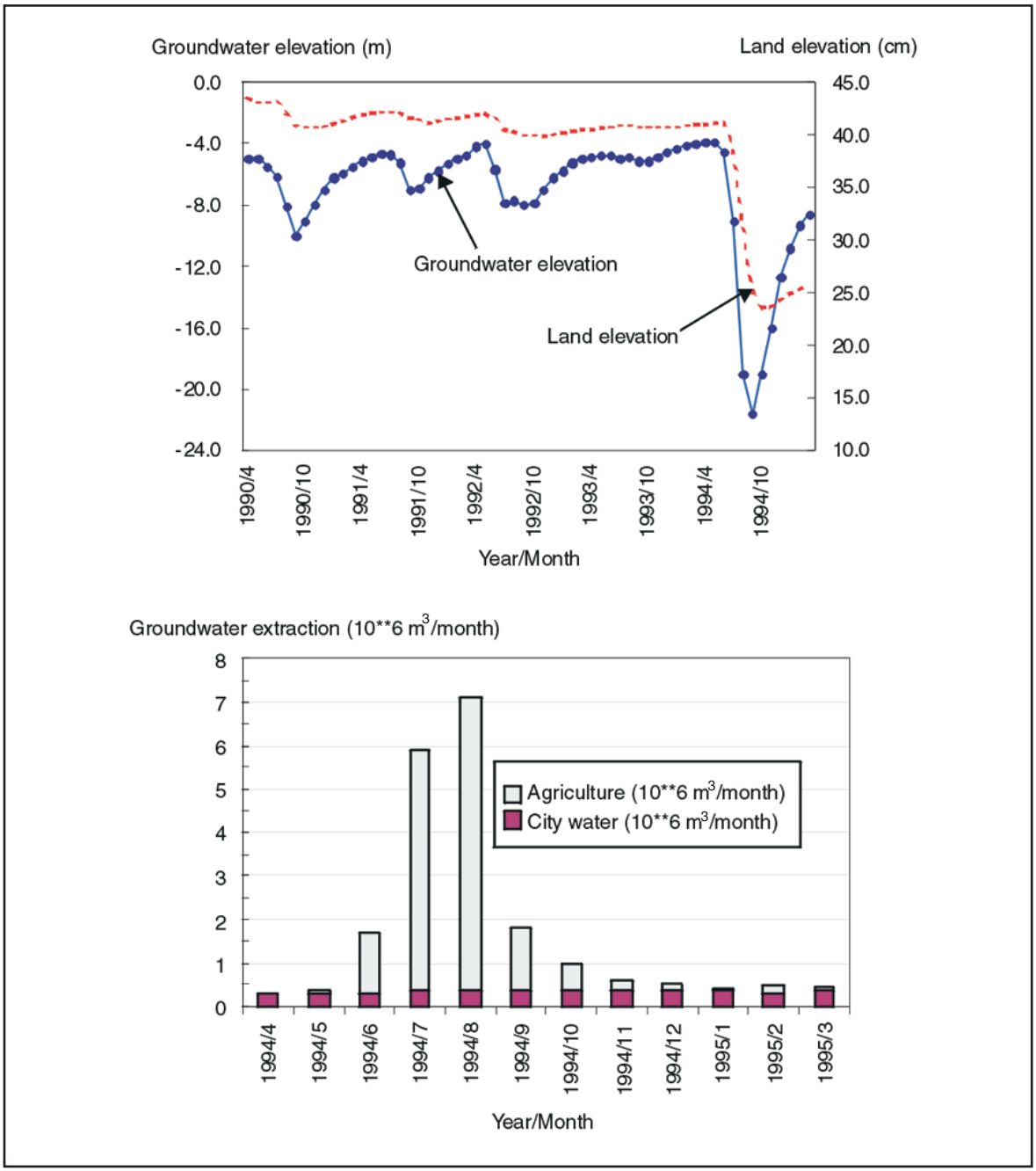


Figure 5.2.4.1.2.6 Land subsidence in Saga Prefecture, Kyushu. Japan and the variation of groundwater level, ground elevation and monthly groundwater exploitation



5.2.4.2 *Threat to groundwater quality in Japan*

5.2.4.2.1 *Introduction*

When discussing environmental issues in Japan, the history of industrialization in the nineteenth and twenty-first centuries should be referred. During that period, the most important nation-wide slogan of the Meiji Government, which was established in 1868 after Edo Feudal Period, was to modernize the country through industrialization to catch up with Europe and America. This policy was to educate the people and to import foreign technologies, judicial, administrative and

legislative systems. However, this rapid industrialization induced adverse influences on the environment.

Among the environmental pollutions in Japan, four major pollutions that emerged until now should be highlighted.

The first environmental pollution problem was from the suit of Asio Cupper Mine caused by the wastewater and emitted smoke from the refinery factory. It took almost one hundred years, until the suit was finally reconciled.

The second one is the seawater pollution named 'Minamata disease', which was occurred along the coast of the Shiranui Sea, Kyushu, in 1953. This pollution was caused by the discharge of the wastewater contaminated with methylmercury from chemical factory. It took almost 40 years until the government officially acknowledged that methylmercury was the causative agent.

The third one is the disease caused by the release of wastewater dissolved with cadmium from the metal mine to Jintsu River, which is the source of irrigation water for the rice farmland. A local medical doctor reported this disease in 1950s. The disease was called 'Itai-itai disease' that means that the patients could do nothing but repeat saying 'pain'.

The fourth one was the air pollution by the emitted sulphur dioxide from the petroleum plants in Yokkaichi City, Mie prefecture in 1960s. It also took almost 30 years until the case was finally reconciled.

Through these serious experiences of environment deterioration, the people acknowledged the importance of laws to control the environment. To regulate surface water pollution, the Water Pollution Control Law for the sea and surface water environment was enacted in 1970. Recently, however, another law for soil and groundwater environment became indispensable and then the additional law to regulate groundwater and soil quality was enacted in 1997.

The following articles are stated in the law of the groundwater and soil contamination. They consist of the four parts that emphasize the importance of monitoring plan, regulatory, counter actions and remediation as briefly summarized below (Japanese Environmental Protection Agency, 1998):

1. *Regular groundwater monitoring:*
   - 1.1 Duty of local government to implement a scheduled monitoring of groundwater quality;
   - 1.2 Duty of local government to monitor groundwater quality/Duty of the owner of wells to corporate with local government;
   - 1.3 Duty of local government to publicize the monitored data.
2. *Prohibition of toxic chemicals to infiltrate into underground:*
   - 2.1 Duty of the registered company that uses toxic chemicals;
   - 2.2 Prohibition of toxic chemicals release into underground;
   - 2.3 If the infiltration of toxic chemical is discovered, local government has to inspect the suspected plants. The suspected plant has to report on utilization and management of toxic chemicals;
   - 2.4 Order by local government to amend and improve the plants;
   - 2.5 If the suspected company does not obey the order of amendment, the company is to be penalized;
   - 2.6 Duty of the registered company that plans to use toxic chemicals;
   - 2.7 Examination of the plan of the company by local government;
   - 2.8 Order by local government to modify the plan of the company;
   - 2.9 If, the company disobeys to order to modify the plan, the company is to be penalized.
3. *Countermeasure for accidental leaks at the registered plant:*
   - 3.1 If leakage of toxic chemicals or oil is discovered at any registered plant, the company has to report to local government;

3.2 Duty of the registered plant to take emergency countermeasures and to report to local government;
3.3 Order by local government to take actions against the registered plant;
3.4 If the registered company disobeys the order to take countermeasures, the company is to be penalized.

4. *Cleaning up polluted groundwater:*
4.1 If leakage of toxic chemicals is discovered at the registered plants and the groundwater contamination has the potential to cause disease, an investigation of the source that causes the pollution should be carried out;
4.2 Inspection by local government and order to report on the accident to the plant;
4.3 Duty of the registered plant to co-operate with local government to clean up the pollutant;
4.5 If the company disobeys the order of local government to clean up the pollutant, the company is to be penalized.

Japanese industry and agriculture utilize similar chemicals as used in other industrialized countries. Besides, living style has been changed and the attitude of the people to water environment is no longer same as before when the people used to get water from their neighboring region. Unfortunately, the awareness of the people for the groundwater pollution is still relatively low. The scientists and engineers, however, nowadays feel that more strict regulations and countermeasures are necessary in Japan.

In this section, some examples of the groundwater contamination and remediation countermeasures are described.

5.2.4.3 Outlook of groundwater contamination in Japan

Table 5.2.4.3.1 shows result of the surveillance carried out by Japanese Environmental Protection Agency (JEPA) in 1998. The column listed at the right of the table indicates the standard applied in Japan. This standard is basically the same as WHO standard. In addition to the chemicals listed in the table, there are other regulated substances. As a whole, there are 29 standard chemicals in drinking water that are considered toxic to human health, 17 parameters that drinking water has to satisfy, 13 chemical parameters as favorable quality for drinking, and 26 chemicals that have to be carefully monitored from time to time.

From the table, it can be seen that approximately 2% of monitored 4,850 wells exceeded the standard limit. Specifically, chlorinated hydrocarbons are the major pollutants, while arsenic also exceeds the standard 0.01 mg/l. The reason for this fact is that the former standard for arsenic was 0.05 mg/l, while the present standard is reviewed in 1992 to the one fifth of the former standard. Therefore, 'arsenic pollution' occurred artificially as this standard is not yet thoroughly achieved. The groundwater contamination by nitrate, other fertilizers, pesticides, oil, other heavy metals, disease germ such as pathogenic colon bacillus is often reported. The details of other cases of the pollution in Japan are summarized in the literature (Shibasaki, 1995). However, it is anticipated that there should be more cases that are not yet reported and discovered.

5.2.4.3.1 An example of groundwater pollution by nitrate

Groundwater pollution by organic carbons like chlorinated hydrocarbons or oil used in the industries may indicate similar behaviors in aquifers as reported in other countries. On the contrary, the high contamination of nitrate in Japan as well as other Asian countries, where rice is a major food product, may show a unique behavior. This is due to the fact that rice farmland is also used for vegetables after rice season. While rice is cultivated, the ponded irrigation water

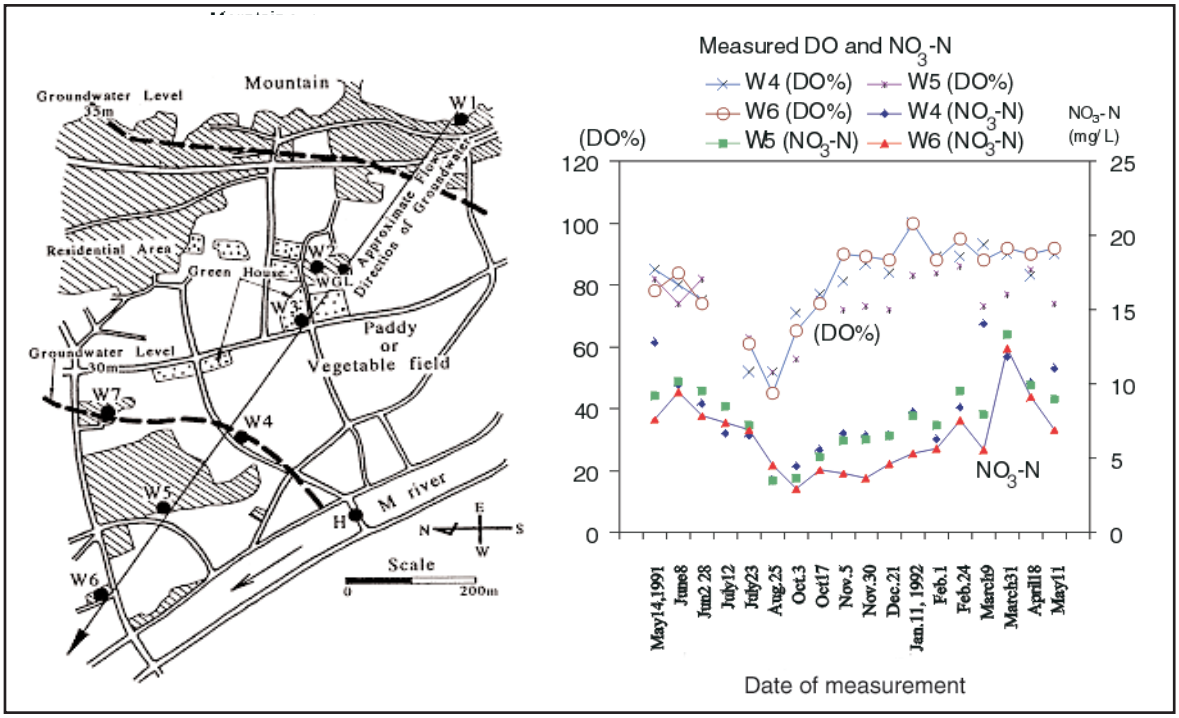
Table 5.2.4.3.1 Result of the groundwater quality surveillance in Japan (JEPA, 1998)

Chemicals	*Number of samples*	*Exceeded samples*	*Rate of excess*	*Regulatory standard (mg/l)*
Cadmium	3,102	0	0.0	0.01
Total Cyanide	2,659	0	0.0	–
Lead	3,312	8	0.2	0.01
Chromium (Ch)	3,232	0	0.0	0.05
Arsenic	3,424	45	1.3	0.01
Total Mercury	2,961	1	0.03	0.0005
Alkyl-Mercury	1,315	0	0.0	–
PCB	1,852	0	0.0	–
Dichloromethane	3,729	1	0.03	0.02
Carbon tetrachloride	3,631	2	0.1	0.002
1,2-Dichloroethane	3,580	0	0.0	0.004
1,1- Dichloroethylene	3,594	2	0.1	0.02
cis-1,2- Dichloroethylene	3,617	5	0.1	0.04
1,1,1-Trichloroethane	4,436	1	0.02	1
1,1,2-Trichloroethane	3,574	0	0.0	0.006
Trichloroethylene	4,492	17	0.4	0.03
Tetrachloroethylene	4,492	28	0.6	0.01
1,3-Dichloropropene	3,179	0	0.0	0.002
Thiram	2,764	0	0.0	0.006
Simazine	2,826	0	0.0	0.003
Thiobencarb	2,759	0	0.0	0.02
Benzene	3,536	0	0.0	0.01
Selenium	2,935	0	0.0	0.01
Total number of surveyed wells	4,850	101	2.1	

changes the soil water into reduced anaerobic condition and consequently induces denitrification of nitrate. In Japan this period starts at the beginning of May and ends at the end of August. After rice harvest, the farmland is then used for vegetables. Carrot, spinach and other vegetables that demand nitrogen as nutrient are cultivated under the aerobic condition in soil. Obviously, dissolved oxygen in soil water during this period is sufficient to change ammonium ion to nitrate and then excess nitrate contaminated in irrigated or rain water infiltrates into aquifers resulting in highly contaminated groundwater. Thus the seasonal variation can occur as shown in Figure 5.2.4.3.1.1. In the figure, nitrate concentration exceeds the drinking water quality standard (10 mg/l as NO_3^-–N). While rice is cultivated, dissolved oxygen decreases followed by nitrate with some delay.

The situation for green tea farmland is similar to the vegetable farmland, where more nitrogen than ordinary vegetable farmland is applied to sweeten and make green tea tasty. In many green tea producing areas, excess application of nitrogen induces acidification of water. This acidified water infiltrates into the unconfined aquifer below tea farmland and seeps out to neigh-

Figure 5.2.4.3.1.1 Farmland used for rice and vegetable cultivation



boring surface irrigation pond or streaks as highly contaminated water with dissolved aluminum ion from clay minerals.

In order to regulate excess application of nitrogen to farmland, the relation between the productivity and quality of vegetables and the amount of fertilizer is investigated in Kagamihara City, Gifu Prefecture. It wss revealed that carrot can grow sufficiently even when nitrogen is halved. It is therefore significant to investigate and determine appropriate amount of fertilizer or pesticide through the collaboration between farmers and scientists.

5.2.4.3.2 Remediation schemes

The term of 'in situ remediation' now gets popular among the geotechnical engineers working on the groundwater and soil pollution. It is estimated by the Ministry of Land, Infrastructure and Transport that US$ 1.1×10^{11} should be invested to clean up the entire polluted land. Obviously, an owner of polluted land is demanded to clean up and amend. Or, a buyer of the polluted land can claim the remediation cost against a seller. It is therefore important not only for geotechnical engineers but also the real estate companies to learn how to investigate the extent op spread of pollutant and the cost of remediation.

Figure 5.2.4.3.2.1 illustrates an example of groundwater remediation technique. The reactive permeable wall located downstream of the contaminated plume can function to clean up the contaminated groundwater through physical and bio-chemical processes. Obviously, the materials used for the wall need to be free from any additional adverse effects. Activated carbon for adsorption, inorganic ion for degradation of organic carbons etc are considered. Besides such subsurface wall, ordinary well-known remediation schemes are considered in Japan as presented in Table 5.2.4.3.2.1.

A new word 'natural attenuation' seems to have a special sound to author due to the fact that this word seems to allow the suspected companies and the responsible local governments and communities not take any counter actions.

Figure 5.2.4.3.2.1 Reactive underground wall to treat contaminated groundwater (Original figure M. Shimomura et.al., English explanations are made by the author under the permission)

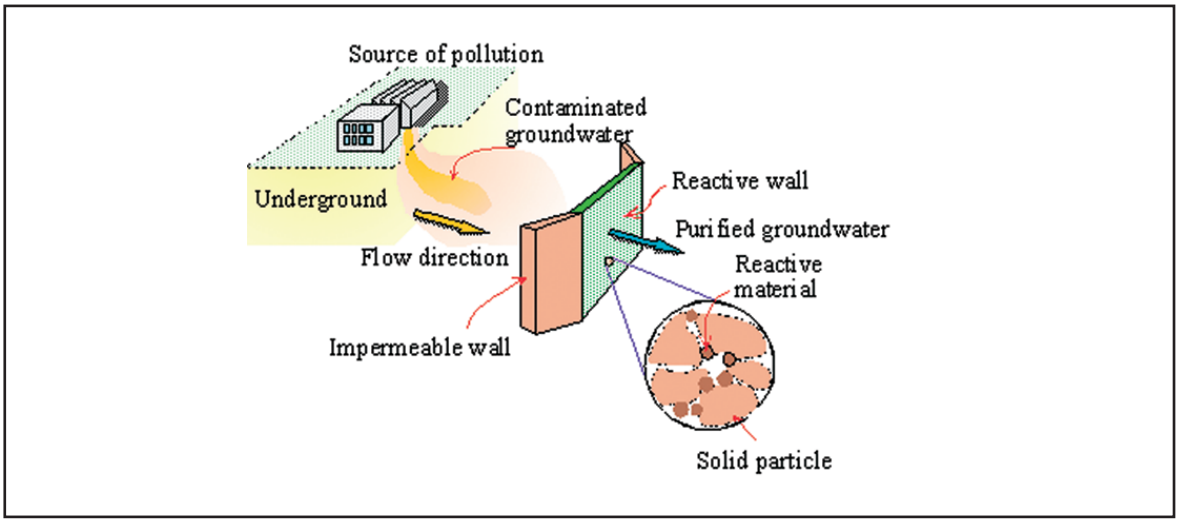


Table 5.2.4.3.2.1 Typical remediation technologies applied for contaminated soil and groundwater

Schemes	*Characteristics of the schemes*
Soil gas extraction	Construction of vacuum pump on site to collect volatile pollutant. Activated carbon is used for adsorption of chlorinated organic carbons. This scheme is a major technique in Japan at present.
Pumping up of contaminated groundwater	Treatment for pumped up contaminated groundwater by volatilization and adsorption. This scheme is also employed for remediation of organic carbons.
Excavation of polluted soil and treatment	Digging up and transportation of contaminated soil to the treatment plant. After exposing to air or by incinerating, the polluted soil is reclaimed.
Biological remediation and degradation on site	Utilization of bio-chemical degradation. Applicable to organic carbons. In order to enhance activities of bacteria, nutrient such as nitrate and phosphate is recharged into aquifers. In Japan, the application of this technique is yet limited.
Chemical degradation and treatment on site	Degradation of volatile organic carbons by oxidation, reduction and catalytic reaction. Two options either to treat on ground or in aquifer.

At present, 'natural attenuation' sounds like an indulgence for the undiscovered and untreated groundwater pollution, even though nature may attenuate the pollutant after long time.

5.2.4.3.3 What the Japanese geotechnical engineers are discussing at present

The problems of the soil and groundwater pollution and remediation are interdisciplinary subjects in nature, where different academic researchers and engineers need to be involved. The most effective way to solve such complicated subjects is the collaboration of the various experts. In Japan, however, such collaborations do not seem sufficient yet. To promote the collaborations, a

key person, who collates information from the experts and organizes fora for solving the problems, would be important. From the author's view for such collaboration, the following subjects should be indispensable:

1. Fundamental researches by collaboration of interdisciplinary research groups;
2. Feedback of the outcomes of fundamental researches to practitioners, and more quantitative schemes for evaluating actual pollutions based on the reliable monitoring.

Compared to the first two subjects, the last subject should be most crucial because the reliability of field data is directly dependent on the personnel skill and knowledge of chemistry and hydrogeology. Actually, the engineers at the polluted sites may encounter occasions in which they have to determine the depth of water sampling, sampling schemes, on site chemical analyses and preservation of samples for laboratory analyses and so on. In Figure 5.2.4.3.3.1, three significant phases are depicted. Hereafter, the 'phase' means the stage at which the judgment made by the engineers will affect the direction of follow-up counteractions. When the engineers encounter these phases, they need to refer to the standardized manuals and fundamental instructions that promise reliable sampling. In order to implement the above subjects, the geotechnical engineers have started to establish standard criterions that fit not only to the Japanese system but also the international standard.

In concluding this section on the problem of the groundwater quality in Japan, even though the discussions made herein do not cover the entire features in Japan, the pollution of groundwater and soil still remain an important subject. Remediation actions are taken by wealthy industries, however, the recovered areas are still limited. It will take years until the awareness of the people against the pollution grows.

5.2.4.4 Remediation of hydrologic cycle in urban areas

The word 'hydrologic cycle' has being used in the scientific world. Actually, Japanese hydrologists and meteorologists have researched into the hydrologic mechanism of water movement on global and regional scale. Nowadays, this word has a citizenship because the administrative boards, that are related to water policies like flood prevention, water environment, irrigation, urban planning, sewage and water resources development, sit on the same table of 'hydrologic cycle' to improve the situations in urban areas. They are now truly aware that rapid urbanization has brought the adverse effects on our living condition. For example, the impervious buildings and surface coverage reduced the rainwater infiltration and consequently the base-flow of rivers were decreased. Beside this alteration, there is not only a risk for flooding but also for deterioration in water quality.

The following example is the project made by a certain community that has just stepped out to improve their water environment (*Research Report of Water Resources Surveillance*, 2000). Figure 5.2.4.4.1 illustrates the concept to implement the recovery of hydrologic cycle in Onojyo City, Fukuoka Prefecture. In 1998 this community started three-year project to clarify water movement within its administrative area. Drinking, industrial and irrigation water uses were surveyed. Besides, the water balance within the community was also investigated by measuring the river discharge and groundwater level. The hydrogeological structure, change in the land use were also investigated. The change in the recharge rate of rainwater infiltration was calculated by applying the surface and subsurface flow model. As the area of rice farmland reduces since 1950s, recharge rate also decreases as can been shown in the figure. The results obtained by the surveillance are not only useful for the city but also valuable for inhabitants because they can know about their water situation, limitations of further water resources development and the risk of flood. Besides, the results can also be used for environmental education of children.

Based on similar idea, the Ministry of Land, Infrastructure and Transport selects four pilot

Figure 5.2.4.3.3.1 Geotechnical standardization of field surveillance

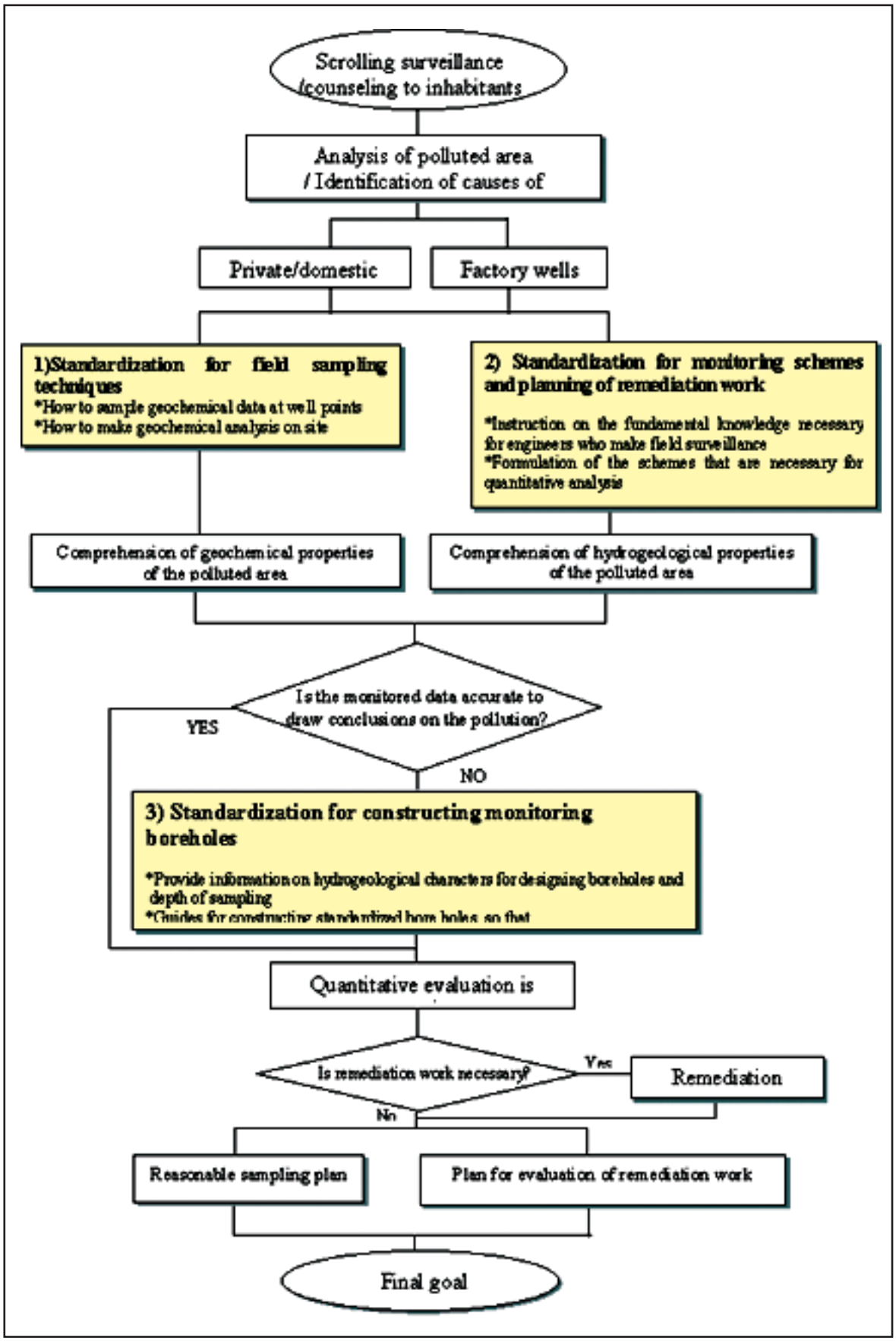
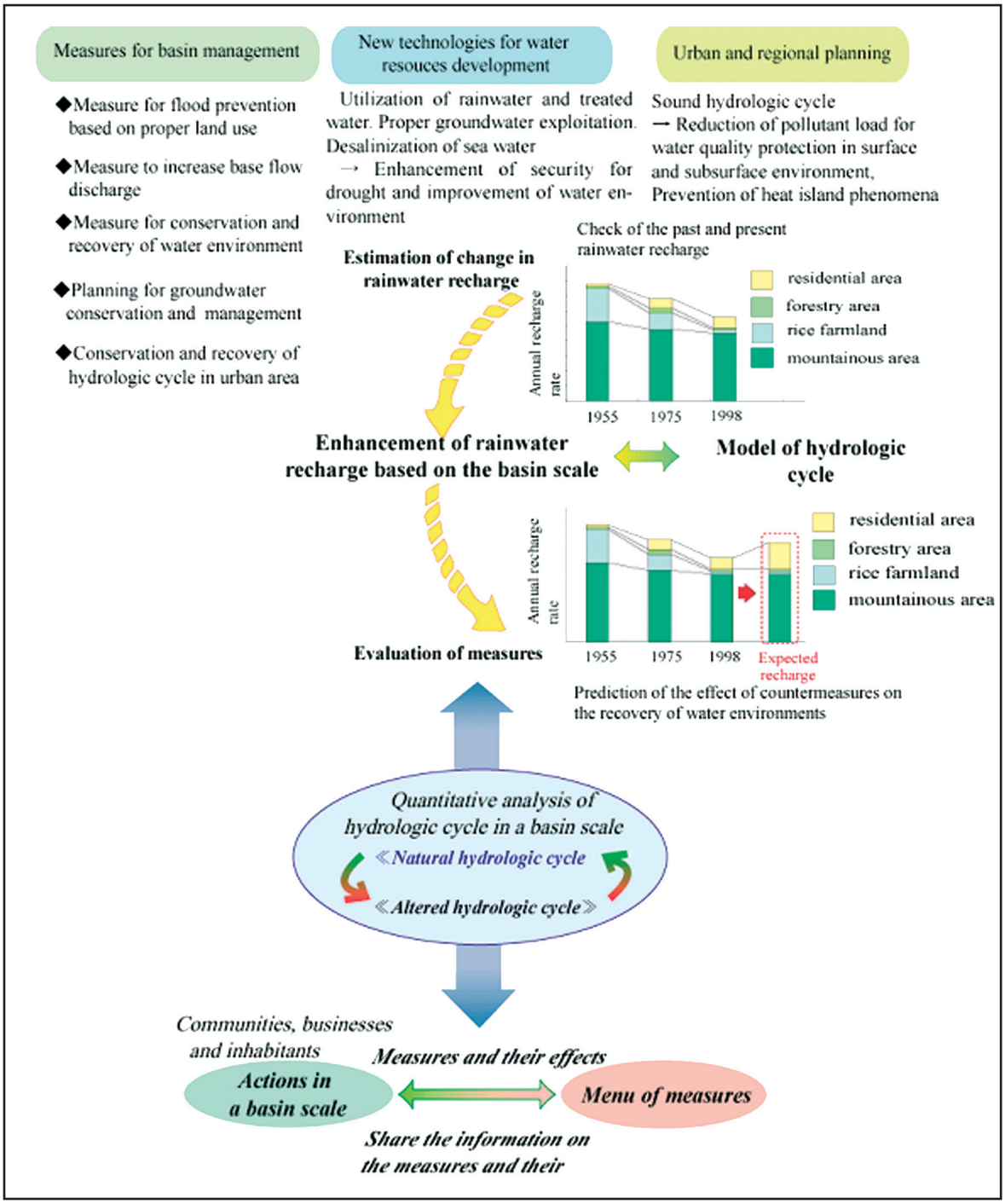


Fig. 5.2.4.4.1 Actions to recover hydrologic cycle in urban area



basins to discuss on 'What can be done and what would be the appropriate measure to improve hydrologic cycle?' In the forum of such pilot basins, several other ministries that are related to water also collaborate.

5.2.4.5 *Conclusion*

Unlike the pollutions such as in atmosphere, ocean, lake and river, soil and groundwater pollution has been acknowledged recently as an important subject in Japan. A lot of enterprises target on the

surveillance and remediation projects. Also the people are aware that the problems of quantity and quality of groundwater should not be discussed separately from the rest of the hydrologic cycle. An example of the effort of the community trying to recover the altered hydrologic cycle will be significant in terms of groundwater protection.

In conclusion, the improvement of the altered hydrologic cycle in urban areas of Japan at present is believed to be one of the important subjects for the recovery of water environment. Many classes of the society believe this concept is the basis to make a breakthrough for solving the problems of groundwater quantity and quality and that is indispensable for an integrated water resources management.

5.3 Groundwater resources and their use in North America

5.3.1 Introduction

Groundwater is an important and precious resource throughout much of North America. Many regional and local aquifers store and transmit groundwater. The geologic framework controls the hydraulic characteristics of these aquifers. A huge variety of rocks, some consolidated and some unconsolidated, occur in the large, geologically complex, North American continent. In this section, we address the regional geologic framework and how it is used to characterize aquifers throughout North America; the uses of groundwater for drinking water supply, irrigation, and other purposes; the effects of groundwater development; and the effects of human activities on groundwater quality. The discussion includes the countries of Central America as well as Canada, the United States, and Mexico. Many of the geographic features described in the text are located on Figure 5.3.1.1.

5.3.2 Geology

The generalized geology of North America is shown on Figure 5.3.2.1. Metamorphic rocks of Precambrian age form the vast Canadian Shield of northern and eastern Canada, an area of low relief that was repeatedly planed by continental glaciers during late Pliocene through Pleistocene time. Areas of flat-lying sedimentary rocks of early Paleozoic age locally overlap these metamorphic rocks. Consolidated sedimentary rocks of Cambrian through middle Tertiary (Eocene) age border the Canadian Shield on the south and west from the Great Lakes through the central United States of America and west-central Canada to the Beaufort Sea. These rocks are flat lying to gently dipping in many places but are downwarped and upwarped into large structural basins, arches, and domes in other places. Similar flat-lying consolidated sedimentary rocks underlie the Colorado Plateaus of the western United States of America.

Folded, consolidated sedimentary rocks of Paleozoic age underlie part of the Appalachian Mountains of the eastern United States of America and Canada. Similar rocks of Paleozoic to middle Tertiary age form the eastern Rocky Mountains of the United States of America and Canada and the Brooks Range of Alaska. The Sierra Madre Oriental of central Mexico consists of folded, consolidated Mesozoic sedimentary rocks.

The eastern part of the Appalachian Mountains and the gently rolling Piedmont area of the United States of America are underlain by Paleozoic metamorphic and igneous rocks, which are deeply weathered in most places. Fault-block bounded basins filled with early Mesozoic redbeds and mafic intrusive rocks occur in the Piedmont.

Figure 5.3.1.1. Geographical features of the North America (including Central America, Canada, United States of America and Mexico)

The central Rocky Mountains of Canada and the northwestern United States of America are underlain by extremely complex, highly folded and faulted igneous, metamorphic, and sedimentary rocks of Precambrian to Mesozoic age. The same types of rocks underlie the Alaska Range and Pacific Coast Mountains in westernmost Canada. Alaska's Aleutian Peninsula and Aleutian Island chain consist of Quaternary volcanic rocks.

The mountain ranges adjacent to the Pacific coast of the United States of America, California's Sierra Nevada, and Mexico's Baja California, Sierra Madre Occidental, and Sierra Madre del Sur consist of extremely complex volcanic, metamorphic, and sedimentary rocks of Tertiary and Quaternary age. Similar rocks of Precambrian to Mesozoic age extend eastward in a band from southern Mexico through northern Honduras. Extensive late Tertiary and Quaternary lava flows form high plateaus in western Canada, the northwestern United States of America, southern Mexico, and much of Central America.

Semiconsolidated clastic rocks form a wide band along the Coastal Plain of the eastern and southern United States of America and eastern Mexico. Extensive deposits of Mesozoic and

Figure 5.3.2.1 Map showing generalized geology of North America (Modified from Heath, 1988)

The rocks shown and the glacial deposits in the area of continental glaciation marked on the map are the sources of most groundwater supplies and are typically the dominant units of the groundwater system

Cenozoic limestone underlie the Coastal Plain of the southeastern United States of America and Mexico's Yucatan Peninsula, the Bahama Islands, and many of the islands in the Caribbean Sea.

Unconsolidated deposits of late Tertiary through Quaternary age cover large areas in low lying parts of Alaska, in California's Central Valley, and in the Great Plains of the west-central United States of America. The same type of deposits fill erosional and fault-block valleys in the eastern Rocky Mountains, the southwestern United States of America, and western and central Mexico. Deposits laid down by continental glaciers, mostly during the Pleistocene Epoch, cover bedrock in most of central and eastern Canada and large parts of the north-central and north-eastern United States of America.

5.3.3 Major aquifers

Although the geology described above is extremely complex, principal aquifers of North America

can be grouped into six simplified types, based on their typical water-bearing units: aquifers in unconsolidated sand and gravel, semiconsolidated sand aquifers, sandstone aquifers, carbonate-rock aquifers, aquifers in interbedded carbonate rocks and sandstone, and aquifers in basalt and other types of volcanic rocks. The location and extent of these types of aquifers at and near the land surface are shown on Figure 5.3.3.1. In general, the map shows the shallowest principal aquifer. In some places, other productive aquifers underlie those mapped. For example, the highly productive limestone that forms the Floridan aquifer system of the southeastern United States of America (No. 5 on Figure 5.3.3.1) underlies the entire Florida Peninsula and extends into Georgia, Alabama, and South Carolina. Only small areas of this aquifer system are shown on the map, because it is covered in many places by younger sand aquifers. In other places, local aquifers such as those along stream courses might overlie the aquifers mapped in Figure 5.3.3.1. Local aquifers are not shown because of the scale of the figure. Some aquifers in sedimentary rocks are overlain by confining units and extend into the subsurface beyond the areas shown on the map. Some deep aquifers that contain large volumes of water at depth, such as the Dakota Sandstone of the central United States of America, and the Madison Limestone of the north-central United States of America, are not shown on Figure 5.3.3.1.

The area in gray bounded by dashed lines on Figure 5.3.3.1 contains numerous glacial aquifers, many of which are the principal aquifers in this region. The sandstone and carbonate bedrock aquifers shown in this glaciated region are used primarily where the glacial aquifers are thin or poorly transmissive.

In addition to the sedimentary and volcanic-rock aquifers mapped on Figure 5.3.3.1, other igneous and metamorphic rocks are used for groundwater supply in some regions. An example is the fractured, crystalline rocks of the Appalachian Piedmont and Blue Ridge region; shown on Figure 5.3.3.1 as the large white area in the eastern United States of America.

Shallow parts of all the mapped aquifers will yield fresh water, or water that has a dissolved-solids content of less than 1,000 mg/l. In some places, deep parts of the aquifers might contain brackish or saline water. Aquifers adjacent to oceans, bays, and sounds commonly contain brackish or saline water near the shoreline.

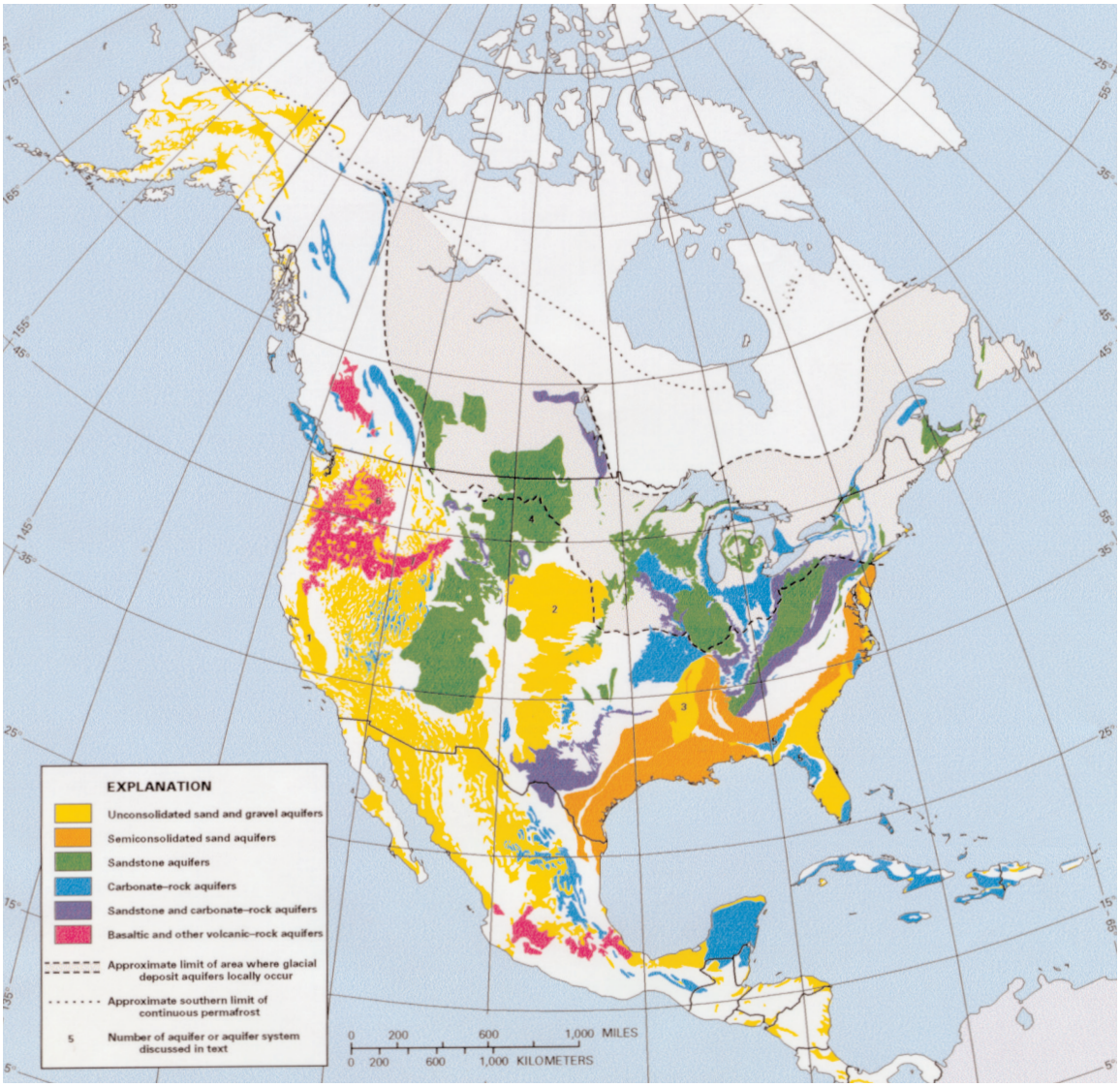
Permafrost, sometimes called 'perennially frozen ground,' consists of soil, rock, or unconsolidated deposits that have been continuously at a temperature of zero degrees Celsius for two or more years. Thick permafrost exists continuously in the area north of the dotted line on Figure 5.3.3.1. Although a huge supply of groundwater is stored in the permafrost, the water cannot be obtained. Thus, thick, continuous permafrost greatly limits the usefulness of shallow aquifers. Locally, small amounts of groundwater can be withdrawn from permafrost during the summer months.

The scale of groundwater flow systems varies among the aquifers mapped on Figure 5.3.3.1. Toth (1963) showed that groundwater flow can be described as being of local, intermediate, or regional scale, as demonstrated on Figure 5.3.3.2. From recharge areas, local flow moves relatively quickly along short flow paths and discharges as base flow to nearby tributary streams, which are usually small. Intermediate flow moves more slowly along longer flow paths and discharges to larger streams, and regional flow moves still more slowly to discharge areas such as major streams or the oceans. In terms of area, local flow systems cover tens of square kilometers, intermediate flow systems extend over hundreds of square kilometers, and regional systems encompass thousands of square kilometers. The scale of groundwater flow is described for each of the types of aquifers discussed below.

Unconsolidated sand and gravel aquifers

The aquifers mapped as unconsolidated sand and gravel are the most widespread aquifers in

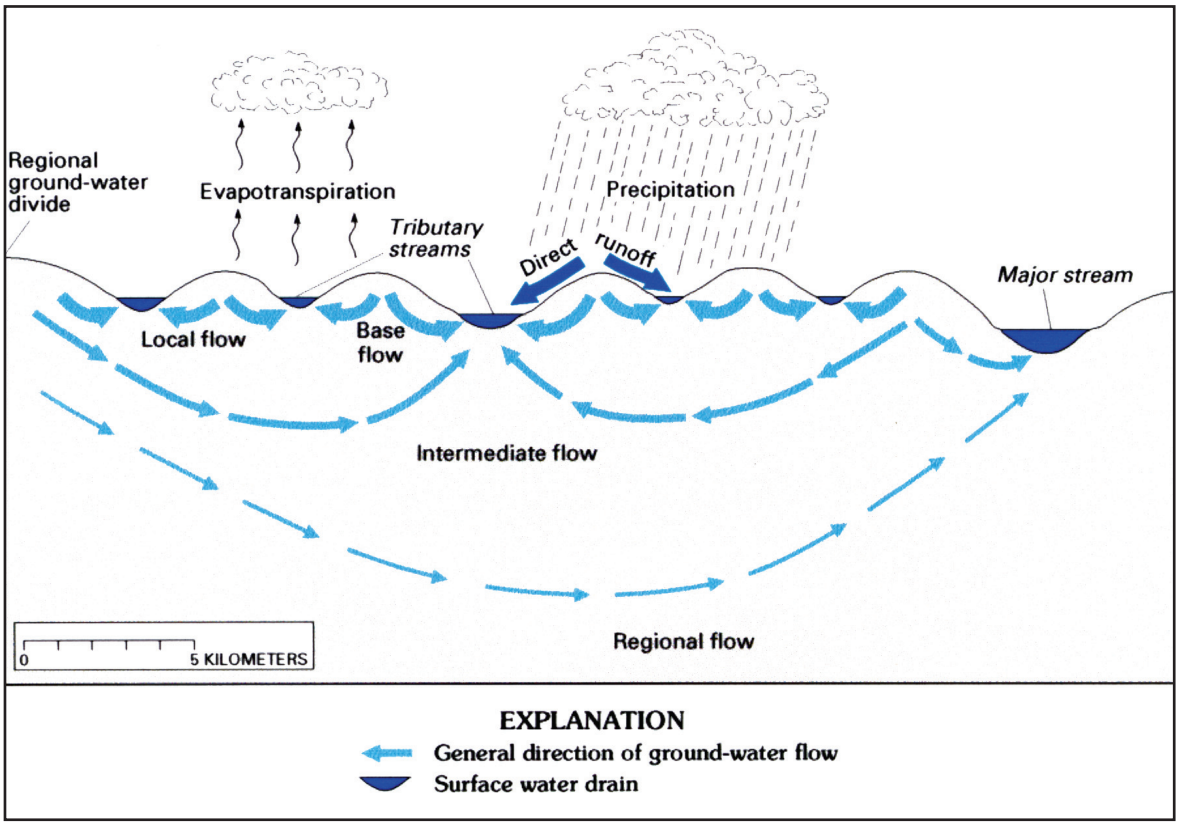
Figure 5.3.3.1 Map showing uppermost principal aquifers in North America (Modified from Miller, 1998; Heath, 1988; Back et al., 1988 and North American Geologic Map Committee, 1965)



The area in gray bounded by dashed lines contains numerous glacial aquifers, many of which serve as the principal aquifers in this region. The sandstone and carbonate bedrock aquifers shown in the glaciated region are used primarily where the glacial aquifers are thin or poorly transmissive. Rocks in uncolored areas tend to yield less water to wells than those in the colored areas, but may be important sources of water in some places.

North America and can be grouped into four categories: basin-fill aquifers (also called valley-fill aquifers), blanket sand and gravel aquifers, glacial-deposit aquifers, and stream-valley aquifers (generally of small extent and not shown on Figure 5.3.3.1. All four types have intergranular porosity and all contain water primarily under unconfined (water-table) conditions. The hydraulic conductivity of the aquifers is variable, depending on the sorting of aquifer materials and the amount of silt and clay present, but is generally high. Aquifer thickness ranges from a few meters or tens of meters in the blanket sands along the eastern Atlantic coast of the United States of America to several hundred meters in the basin-fill aquifers of the southwestern United States of America and central and western Mexico. The unconsolidated sand and gravel aquifers are susceptible to contamination because of their generally high hydraulic conductivity and good hydraulic connection to surface-water bodies, which might contain contaminants. Groundwater

Figure 5.3.3.2 Relation between surface drainage and scale of the groundwater-flow system (Modified from Toth, 1963)



flow in these aquifers is mostly local; however, all the basin-fill aquifers have intermediate flow systems, and the thick basin fill of California's Central Valley aquifer system (No. 1 on Figure 5.3.3.1) has a regional flow system. Likewise, the thick blanket sands of the High Plains aquifer (No. 2 on Figure 5.3.3.1) and the Mississippi River Valley alluvial aquifer (No. 3 on Figure 5.3.3.1) of the central United States of America have regional flow systems.

Basin-fill, or valley-fill, aquifers consist of late Tertiary and Quaternary alluvial and colluvial deposits that partly fill basins in Mexico, Central America, and the western parts of Canada and the United States of America. The basins were formed by faulting, erosion, or both. Fine-grained deposits of silt and clay form local confining units in these aquifers and thick sequences of the unconsolidated deposits become more compact and less permeable with depth. Most basins are bounded by low-permeability rocks, but some in central Mexico and the western United States of America are hydraulically connected to adjacent carbonate-rock aquifers. Recharge to the basin-fill aquifers is by infiltration of streamflow from adjacent mountains, and discharge is to streams that flow through 'open' valleys or to playas in the centers of 'closed' valleys, and by evapotranspiration from shallow water-table aquifers. Some basin-fill aquifers have supplied large amounts of water for irrigation and other uses, such as in parts of central and southern Mexico, the Central Valley aquifer system of California (No. 1 on Figure 5.3.3.1) and parts of Arizona. The small aquifers adjacent to the coasts of Mexico, Central America, the Caribbean Islands, and the Pacific coast of the United States of America are basin-fill aquifers.

Widespread, blanket-like late Tertiary and Quaternary deposits of sand and gravel also form important aquifers in the United States of America. These aquifers are in lowland areas of Alaska, atop lava plateaus in Washington, along the Atlantic and eastern Gulf coasts, along part of the lower reaches of the Mississippi River, and in the High Plains. These aquifers mostly consist of

alluvial deposits but locally include windblown and beach sands. They commonly contain water under unconfined conditions, and most groundwater flow is local to intermediate. The High Plains aquifer (No. 2 on Figure 5.3.3.1) is the most intensively pumped aquifer in North America. During 1990, about 56 million m^3 of water per day was withdrawn from the aquifer, primarily for irrigation.

Glacial-deposit aquifers form numerous local but highly productive aquifers in the area between the dashed lines on Figure 5.3.3.1. These aquifers consist of outwash, terrace, or ice-contact deposits and mostly occupy bedrock valleys. In places, the valley deposits are buried beneath low-permeability till. Groundwater flow in the glacial-deposit aquifers generally is local, from recharge areas near valley walls to discharge areas near streams in the valleys.

Semiconsolidated sand aquifers

These aquifers consist of semiconsolidated sand, interbedded with silt, clay, and minor carbonate rocks. Porosity is intergranular and the hydraulic conductivity of the aquifers is moderate to high. The aquifers underlie the Coastal Plains of the eastern and southern United States of America and eastern Mexico, are in rocks of Cretaceous and Tertiary age, and are of fluvial, deltaic, and shallow marine origin. The aquifers are in a thick wedge of sediments that dips and thickens coastward; in places, the sands of the aquifers are more than 650 m thick. The varied depositional environments of these sediments have caused complex interbedding of fine- and coarse-grained materials. Accordingly, some aquifers are local, whereas others extend over hundreds of square kilometers. The numerous local aquifers can be grouped into several regional aquifer systems that contain groundwater flow systems of local, intermediate, and regional scale. Water in topographically high recharge areas is unconfined but becomes confined as it moves coastward. Discharge is by upward leakage to shallower aquifers or to saltwater bodies in coastal areas. Because flow is sluggish near the ends of regional flow paths, the aquifers commonly contain saline water in their deeply buried, downdip parts. Where shallow aquifers have been heavily pumped near the coasts, saltwater intrusion has locally contaminated the groundwater. During 1985, more than 30 million m^3 per day was withdrawn from these aquifers.

Sandstone aquifers

Aquifers in sandstone are widespread in North America. Sandstone retains only a small part of the intergranular pore space that was present before the rock was consolidated: compaction and cementation have greatly reduced the primary pore space. Secondary openings, such as joints and fractures, along with bedding planes, contain and transmit most of the groundwater in sandstones. Accordingly, the hydraulic conductivity of sandstone aquifers is low to moderate, but because they extend over large areas, these aquifers provide large volumes of water.

The sandstone aquifers are flat lying or gently dipping. Because they are commonly interbedded with siltstone or shale, most of the water in these aquifers is confined. Groundwater flow systems in the mostly flat-lying, relatively thin (30–50 m thick) sandstone aquifers between and south of the Great Lakes in the east-central United States of America are local to intermediate. Regional, intermediate, and local flow is present in the other sandstone aquifers of the United States of America and Canada, except for those in Oklahoma, where the flow is local. Sandstone aquifers in eastern Canada and southward and eastward of Wisconsin in the United States of America are primarily in Paleozoic rocks (Cambrian through Pennsylvanian age). Locally, Precambrian sandstones border Lake Superior, and early Mesozoic sandstones fill fault-block basins that extend from Massachusetts to North Carolina. Elsewhere in the United States of America and Canada, the sandstone aquifers are in Paleozoic, Mesozoic, and Cenozoic rocks.

Because of their low permeability, many sandstone aquifers are incompletely flushed and contain highly mineralized water at depths of only a few hundred meters.

In Wisconsin and adjacent states, three Cambrian and Ordovician sandstone aquifers are combined into an aquifer system that is as much as 650 m thick. Paleozoic through Cenozoic sandstones that extend from Wyoming northeastward into Manitoba form the Northern Great Plains aquifer system (No. 4 on Figure 5.3.3.1) whose permeable parts are more than 2,000 m thick at some places in a deep structural basin. These thick aquifers, however, do not all contain fresh water.

Carbonate-rock aquifers

Aquifers in carbonate rocks are most extensive in the eastern United States of America and in the Bahamas and Caribbean Islands, but are also prominent in western Canada and in central, southern, and eastern (Yucatan Peninsula) Mexico. The rocks that form these aquifers range in age from Precambrian to late Tertiary (Miocene). Most of the carbonate-rock aquifers consist of limestone, but dolomite and marble locally yield water. The water-yielding properties of carbonate rocks vary widely. Some yield almost no water and are considered to be confining units, whereas others are among the most productive aquifers known. In scattered places in the United States of America and Canada, carbonate rocks are interbedded with almost equal amounts of water-yielding sandstone. These interbedded rocks are mapped as 'sandstone and carbonate-rock aquifers' on Figure 5.3.3.1 but are included in the discussion of carbonate-rock aquifers because, for the most part, the carbonate rocks of these areas yield much more water than the sandstones.

Most carbonate rocks form from calcareous deposits that accumulate in marine environments ranging from tidal flats to reefs to deep ocean basins. This range of depositional environments results in a range of primary porosity in the carbonate deposits from 1 to more than 50%. Compaction, cementation, and dolomitization processes might act on the deposits as they lithify and greatly change their porosity and permeability. The principal post-depositional change in carbonate rocks, however, is the process of dissolution of part of the rock by circulating, slightly acidic groundwater. Solution openings in carbonate rocks range from small tubes and widened joints to caverns which may be tens of meters wide and hundreds to thousands of meters in length. Where they are saturated, carbonate rocks with well-connected networks of solution openings yield large volumes of water to wells that penetrate the openings, even though the undissolved rock between the large openings may be almost impermeable.

Where carbonate rocks are exposed at the land surface, solution features create karst topography, which is characterized by little surface drainage and by sinkholes, blind valleys, sinking streams, and so forth. Because water enters the carbonate rocks rapidly through sinkholes and other large openings, any contaminants in the water can rapidly enter and spread through the aquifers.

Carbonate-rock aquifers in Paleozoic rocks are flat lying to gently folded in places, such as the area encircling Michigan, eastern Iowa and adjacent states, Missouri and adjacent states, and central Kentucky and Tennessee. Folded and faulted carbonate-rock aquifers are in the Appalachian and Rocky Mountain chains of Canada and the United States of America. Mesozoic rocks compose some of the folded carbonate-rock aquifers in western Canada and all of those in central Mexico and Central America. The carbonate-rock aquifers of the Caribbean Islands are in folded to gently dipping Mesozoic and Cenozoic rocks.

The carbonate-rock aquifers that underlie Florida and adjacent states and part of North Carolina (United States of America), the Yucatan Peninsula of Mexico, and the Bahamas are in Cenozoic strata that were deposited in warm marine waters on shallow shelves. These rocks, called platform carbonates, have intergranular porosity as well as large solution openings.

Submarine springs off the eastern and western coasts of Florida and the northeastern coast of the Yucatan Peninsula issue from solution openings in platform carbonate rocks. Large springs also issue from these rocks on land. Florida has 27 first-magnitude springs, or springs that discharge 2.8 m^3/s or more, all of which are fed by carbonate rocks.

Some of the platform carbonate rocks are highly productive aquifers. For example, about 13 million m^3/day was withdrawn from the Floridan aquifer system (No. 5 on Figure 5.3.3.1) of the southeastern United States of America during 1990. Despite the huge withdrawals, water levels in the aquifer have not declined regionally because withdrawals have been balanced by increased recharge and diversion of natural discharge to springs and streams (Johnston, 1997). The Floridan aquifer system has regional, intermediate, and local groundwater flow systems. The other carbonate-rock aquifers have only local and intermediate flow.

Basaltic and other volcanic-rock aquifers

Volcanic rocks have a wide range of chemical, mineralogic, structural, and hydraulic properties, due mostly to variations in rock type and the way the rock was ejected and deposited. Unaltered pyroclastic rocks, for example, might have porosity and permeability like poorly sorted sediments. Hot pyroclastic material, however, might become welded as it settles and, thus, be almost impermeable. Silicic lavas tend to be extruded as thick, dense flows and have low permeability except where fractured. Basaltic lavas tend to be fluid and form thin flows that have considerable pore space (vesicles) at the tops and bottoms of the flows. Numerous basalt flows commonly overlap, and the flows are separated by soil zones or alluvial material that form permeable zones. Columnar joints that develop in the central parts of basalt flows create passages that allow water to move vertically through the basalt. Basaltic rocks are the most productive aquifers in volcanic rocks.

Basaltic rocks form most of the volcanic-rock aquifers mapped on figure 5.3.3.1. These flows cover extensive areas in the northwestern United States of America and smaller areas in western Canada and southern Mexico. In places, the basaltic-rock aquifers are extremely thick. For example, those of the Columbia Plateau aquifer system in Washington (No. 6 on Figure 5.3.3.1) are more than 2,600 m thick in places, and those of the Snake River Plain aquifer system (No. 7 on Figure 5.3.3.1) are locally more than 800 m thick. In most places, however, the thickness of these aquifers is 100 m or less. Groundwater flow in the basaltic-rock aquifers is local to intermediate. In Idaho, the basaltic-rock aquifers are extremely permeable, and numerous large springs discharge several tens of cubic meters per second from them.

5.3.4 Groundwater use

Groundwater use varies widely among and within the countries of North America. Groundwater represents perhaps less than 5% of Canada's total water use (Van der Leeden et al., 1990); however, more than 6 million people, or about one fifth of the population, rely on groundwater for municipal and domestic use (Environment Canada, 1997). About two-thirds of these users live in rural areas, and the rest primarily in smaller municipalities. The province of Prince Edward Island is totally reliant on groundwater, and more than 60% of the population of New Brunswick and the Yukon Territory rely on groundwater.

It is estimated that about 1,290 million m^3/day of fresh water was used in the United States of America in 1995 for public supplies, rural domestic and livestock uses, irrigation, industrial and mining uses, and for thermoelectric power (Solley et al., 1998). About 22% of this water use (290 million m^3/day) was supplied by groundwater (groundwater was 36% of total water use excluding thermoelectric power). Five States, in descending order – California, Texas, Nebraska,

Arkansas and Florida – account for more than half the U.S. groundwater use. About 50% of the U.S. population depends on groundwater for domestic uses. Major cities and metropolitan areas that depend primarily on groundwater include Albuquerque, Long Island (New York), Memphis, Miami, and San Antonio. More than 95% of the households that supply their own drinking water rely on groundwater. The use of groundwater in the U.S. increased steadily from 1950 to 1980, and has declined slightly since 1980, in part, in response to more efficient use of water for agricultural and industrial purposes, greater recycling of water, and other conservation measures.

Groundwater is an important source of potable water throughout much of Mexico and Central America. In Mexico, where desert and semi-arid conditions prevail over two-thirds of the country, groundwater is widely used. Groundwater provides most of the domestic, drinking, and industrial water needs of Nicaragua (United Nations, 1976). Costa Rica, El Salvador, and Guatemala also use substantial groundwater, whereas Belize, Honduras, and Panama are less dependent on groundwater. In most rural areas of Central America, more than 80% of the population is supplied by either private or municipal well systems (Bethune et al., 1998). Urban areas in Mexico and Central America that use groundwater as their sole or principal source of water supply include Mexico City, Mexico; Guatemala City, Guatemala; Managua, Nicaragua; and San Jose, Costa Rica.

5.3.5 Effects of groundwater development

The development and use of groundwater resources can result in a variety of effects, including (1) regional declines in groundwater levels that may represent large decreases in aquifer storage, particularly in unconfined aquifers, (2) wells that become dry because water levels are drawn below their screened or open intervals, (3) increased pumping costs as the vertical distance that groundwater must be lifted to the land surface increases, (4) pumping-induced land subsidence, and (5) intrusion of saline groundwater. The flow of groundwater also has a major influence on fresh-water supplies in streams and rivers and on the health of river and wetland habitats for plants and animals. As surface water and groundwater become more developed, the need to evaluate both as a single resource has become increasingly recognized. Winter et al. (1998) have recently summarized many of these effects for a variety of physiographic settings.

Land subsidence has accompanied groundwater development in aquifers that have substantial reductions in potentiometric head and that contain many fine-grained compressible interbeds or confining layers, particularly in the southwestern United States of America and in Mexico. Areas that have significant land subsidence as a result of groundwater pumping include Mexico City, the Santa Clara Valley and Central Valley (No. 1 on Figure 5.3.3.1) of California, south-central Arizona, Las Vegas Valley (Nevada), and the Houston-Galveston area of Texas. In addition to compaction of clastic aquifers that contain fine-grained layers, pumping-induced subsidence also can occur from localized collapse in areas underlain by limestone, dolomite, or other soluble rocks. Some dramatic effects of sinkhole development have been seen in Alabama and Florida in the southeastern United States of America.

Many coastal areas of North America with significant population growth and use of the groundwater resource have had problems with seawater intrusion. These areas include much of the Atlantic and Gulf Coastal Plains, the carbonate aquifers of coastal Florida and the Yucatan, alluvial basins along the California and Mexico coasts, and the coasts of New Brunswick and Prince Edward Island in Canada. Konikow and Reilly summarize the occurrence and history of seawater intrusion in the United States of America.

The effects of extensive groundwater development are described below for several prominent cases. These examples illustrate some of the diversity of effects of groundwater development that exist throughout the continent.

High Plains

The High Plains is a 451,000 km^2 area of flat to gently rolling terrain in the central United States of America. Unconsolidated alluvial deposits that form a water-table aquifer known as the High Plains aquifer (No. 2 on Figure 5.3.3.1) underlie the region (Weeks et al., 1988). Irrigation has made the High Plains one of the most important agricultural areas in North America, and about 20% of the groundwater withdrawn in the United States of America is derived from the High Plains aquifer. The area generally has a low rate of recharge to the groundwater system. Particularly in the southern High Plains, the source of water for pumpage comes largely from irrigation-returned recharge and from water in storage. Large withdrawals have caused water-level declines of more than 30 m in the southern parts of the aquifer (McGuire and Sharpe, 1997).

Central Valley of California

The Central Valley of California (No. 1 on Figure 5.3.3.1), a semi-arid sedimentary basin that covers about 52,000 km^2, produces a large fraction of the fruits, nuts, and vegetables in the United States of America (Williamson et al., 1989). A large part of the water used for irrigation is derived from the alluvial deposits that fill the basin. Groundwater development during the 1930s to early 1960s caused water-level declines of tens to hundreds of meters. The water-level declines resulted in compaction of the alluvial deposits. Land subsidence of more than 0.3 m occurred over an area of about 13,000 km^2 (Ireland et al., 1984). Importation of surface water, beginning in the 1960s, led to a reduction in groundwater pumping and rising groundwater levels. Increased pumping during droughts of 1976–7 and 1987–92 caused temporary large declines in groundwater levels and some renewed subsidence.

Mexico City

Numerous productive springs provided an abundant supply of high-quality water for Mexico City for many years. Groundwater extraction from the regional aquifer beneath thick (50–80 m) lacustrine deposits began in the 1840s. Heavy pumping in the central part of Mexico City in the 1930s caused depressurization and consolidation of the fine-grained, low-permeability lacustrine sediments and greater than 8 m of land subsidence in the center of Mexico City. This rapid subsidence caused damage to buildings and municipal infrastructure. As a result, pumping rates in the urban core were reduced, surface water was imported from outside the valley in which Mexico City resides, and well fields were developed south of the city. Today, subsidence continues near the new well fields, and the Mexico City area may be the most rapidly subsiding urban area in the world (Ortega-Guerrero et al., 1993).

South-Central Arizona

Groundwater development for agriculture in the basin-fill aquifers of south-central Arizona began in the late 1800s, and by the 1940s many of the basins had undergone major groundwater development (Anderson, 1995). Groundwater depletion has been widespread over the basins, and locally, water-level declines have exceeded 100 m. These water-level declines have greatly increased pumping costs and resulted in regional subsidence. Numerous earth fissures have formed at and near the margins of subsiding basins. Development of groundwater resources in this arid area has also resulted in the elimination or alteration of many perennial stream reaches, wetlands, and associated riparian ecosystems.

Miami, Florida

The Biscayne aquifer in southernmost Florida is the sole source of water supply for the city of Miami and adjacent areas. Saltwater intrusion is a major water-management challenge to the area

(Cooper et al., 1964; Sonenshein, 1997). Under natural conditions, the saltwater interface was at or near the coast because of high water levels that occurred naturally in the Everglades (a large freshwater swamp). A network of drainage canals was constructed from 1909 through the 1930s. Throughout that period, the canals resulted in a continuous diversion of large quantities of fresh water to the sea, which lowered water levels in the Everglades area. This, combined with drawdowns from several coastal well fields that tap the Biscayne aquifer, caused saltwater in the aquifer to advance progressively inland, and several well fields were abandoned because of contamination. Additionally, seawater driven by tides flowed inland in the drainage canals and seeped into the underlying Biscayne aquifer. Today, control structures (or headgates) that are installed near the outlets of most canals can be raised or lowered to control the water levels in the canals. Keeping the canal water levels high competes with the use of the canals for drainage and flood control and presents a significant water-management challenge to the local water authority, the South Florida Water Management District. This agency also has regulatory authority to issue (or deny) permits to construct new wells and can impose water-use restrictions during periods of droughts.

Hermosillo, Mexico

The Costa de Hermosillo aquifer (Andrews, 1981; Steinich et al., in press) is used as the sole source of drinking and irrigation water for one of Mexico's principal agricultural districts. The district lies adjacent to the Gulf of California in the State of Sonora, Mexico. An unconfined aquifer of coarse-grained alluvial material and a confined aquifer are separated by thick marine clay. Water-table declines of as much as 40 m were generated in the interior regions of the district by 1973, and the natural hydraulic gradient towards the coast has been reversed. Major intrusion zones within the unconfined aquifer occur along buried alluvial channels, which function as conduits for the encroaching saltwater.

Chicago-Milwaukee Area

Chicago, Milwaukee, and other lakefront cities and towns along Lake Michigan have relied on groundwater to supplement water from Lake Michigan since 1864 (Avery, 1995). Deep wells (typically greater than 230 m in depth) provide high-quality water from a bedrock Cambrian-Ordovician aquifer system. During the late 1800s, the water supply from these wells was considered to be virtually inexhaustible, and the wells were allowed to flow freely under artesian conditions. Water-level declines that result from more than 100 years of groundwater withdrawals from the deep aquifers have created regional areas of water-level declines around the Chicago and Milwaukee areas. For example, by 1980, artesian pressure in the deep bedrock aquifers declined more than 280 m at Chicago. Increases in the water allocations from Lake Michigan to the Chicago area starting in 1980 have gradually reversed the water-level declines there. For example, recoveries of as much as 80 m were measured between 1991–5 (Visocky, 1997).

5.3.6 Groundwater quality

The protection and enhancement of the quality of groundwater resources is a high-priority environmental concern throughout North America. The sources of groundwater contamination are numerous and diverse, and contaminants can enter groundwater through many different routes, including downward percolation from land-surface and shallow-subsurface sources, direct entry through wells, cross contamination between aquifers in wells open to more than one aquifer, and interactions of groundwater with surface-water bodies. Four of the more widespread types of groundwater contaminants – nitrate, microbial contamination, pesticides, and volatile organic compounds – are discussed below.

Nitrate and microbial contamination

Nitrate and microbial contamination appear to be the most widespread water-quality concerns in North America. For example, the Government of Canada (1996) indicates that, in terms of the proportion of affected groundwater supplies, nitrate and bacteria represent by far the most common groundwater contaminants in Canada with 20 to 40% of all rural wells in Canada having nitrate concentrations or coliform bacteria occurrences in excess of drinking-water guidelines. Mexico and many of the countries of Central America have targeted microbial contamination of well water as a major health concern and implemented simple chlorination systems that have reduced the presence of fecal coliforms in public water-supply systems. Nitrate and other types of inorganic contamination are a second focus of concern for many of these countries. In the United States of America, groundwater is typically not treated prior to human consumption, but concerns about the effects of surface-water microbial contamination and other contaminants have led to recent attempts to identify 'groundwater under the direct influence of surface water' for treatment prior to use.

Nitrate contamination in the United States of America has been a concern for many years. Many practices have contributed to nitrate contamination, including disposal of human sewage, crop production, handling of animal manure, and industrial waste disposal. Domestic water-supply wells in agricultural areas are particularly susceptible to elevated concentrations of nitrate (Nolan et al., 1997). Major areas that exhibit problems with nitrate contamination of groundwater include (1) rain-fed grain production (particularly corn) that is marked by intensive row cropping and heavy fertilization, (2) intensive irrigated grain agriculture, (3) locally intensive animal feeding and handling operations and (4) irrigation and fertilization of vegetable and specialty crops. (Hallberg and Keeney, 1993).

Pesticides

Concerns with pesticide contamination of groundwater in North America began largely with the 1979 discoveries of aldicarb in groundwater on Long Island (New York), and dibromochloropropane (DBCP) in California, and the subsequent finding of these pesticides in groundwater elsewhere throughout the continent.

Generalizations about large-scale effects, such as climate and regional physiographic differences across North America, are difficult to make at this time because investigations of pesticides in groundwater in different localities have used different designs, pesticide analytes, reporting limits, and sample-collection methodologies. Several large-scale studies, such as the U.S. Geological Survey's National Water Quality Assessment Program (Alley and Cohen, 1991; Gilliom et al., 1995), which use more consistent designs and methods are currently underway. In addition, general conclusions from the numerous studies of pesticides in groundwater (primarily in the United States of America and Canada) have been summarized by Rao and Alley (1993), Crowe and Milburn (1995) and Barbash and Resek (1996), and include:

1. Pesticides from every major chemical class have been detected in groundwater. Pesticide concentrations measured in groundwater are generally low, however, compared with those commonly measured in soils and surface water.
2. Factors commonly associated with increased likelihood of pesticide occurrence in wells are high pesticide use, high recharge (by either precipitation or irrigation), high permeability soils and aquifers, and shallow, inadequately sealed or older wells.
3. Virtually all groundwater systems are vulnerable to some extent to contamination by pesticides, and pesticides have been found where they were not expected. For example, McNaughton and Crowe (1995) found pesticides in low permeability tills and lacustrine

sediments in areas that are characterized by low precipitation, high evaporation rates, and a deep water table in Saskatchewan, Canada. This finding presumably results from the combination of irrigation and recharge through vertical fractures in the low permeability sediments.

4. Findings about the spatial and temporal distribution of pesticides may turn out to be misleading in the absence of data on their metabolites (transformation products). For example, two of the broader geographic surveys of pesticides in North America (U.S. Environmental Protection Agency, 1990; Kolpin et al., 1995) found that the most frequently detected pesticide compounds were pesticide metabolites.
5. Most pesticide use occurs in agricultural areas, but frequencies of pesticide detection in groundwater can also be substantial beneath non-agricultural land, such as residential areas, golf courses, and rights-of-way, where application rates can exceed those for most crops.
6. Pesticide levels in groundwater show pronounced seasonal variability in agricultural areas with maximum values often following spring applications.
7. High concentrations of pesticide contaminants in rivers may lead to contamination of shallow groundwater during periods of extensive seepage of river water into underlying alluvial aquifers, particularly following spring applications, when pesticide loads and river flows are highest. Conversely, pesticides in shallow and alluvial aquifers may flow into adjoining rivers during periods of low runoff.

Volatile organic compounds

Contamination of groundwater by inadvertent release or improper disposal of organic chemicals has occurred throughout North America. The problem came to significant public attention in the mid- to late-1970s. Since that time, numerous instances of contamination from landfills, industrial waste sites, underground storage tanks, and other sources have been detected. The occurrence of volatile organic compounds (VOCs) is of particular concern because many are known or suspected carcinogens, many are widely used, and their chemical properties lead to high aqueous solubility, mobility, and persistence in groundwater. Mackay and Smith (1993) summarize surveys of VOC contamination in the United States of America. Methyl tertiary-butyl ether (MTBE), a volatile gasoline additive, has recently been detected widely in groundwater in the United States of America, and is of particular concern because it appears to degrade much less rapidly than other associated gasoline compounds. Marin et al. (1998) note that organic contaminants are a growing concern in Mexico. Sampling for organic compounds is less prevalent in Central America, but VOCs have been reported in wells in major urban areas such as Managua, Nicaragua (Bethune et al., 1996).

5.3.7 Concluding remarks

The climate, geology, groundwater resources, extent of groundwater use, and the manner in which humans have affected groundwater resources in North America are highly varied throughout the continent. Groundwater is a precious resource, and its protection and management are important to assure its future sustainability and environmental integrity.

5.4 Groundwater resources and their use in South America, Central America and the Caribbean

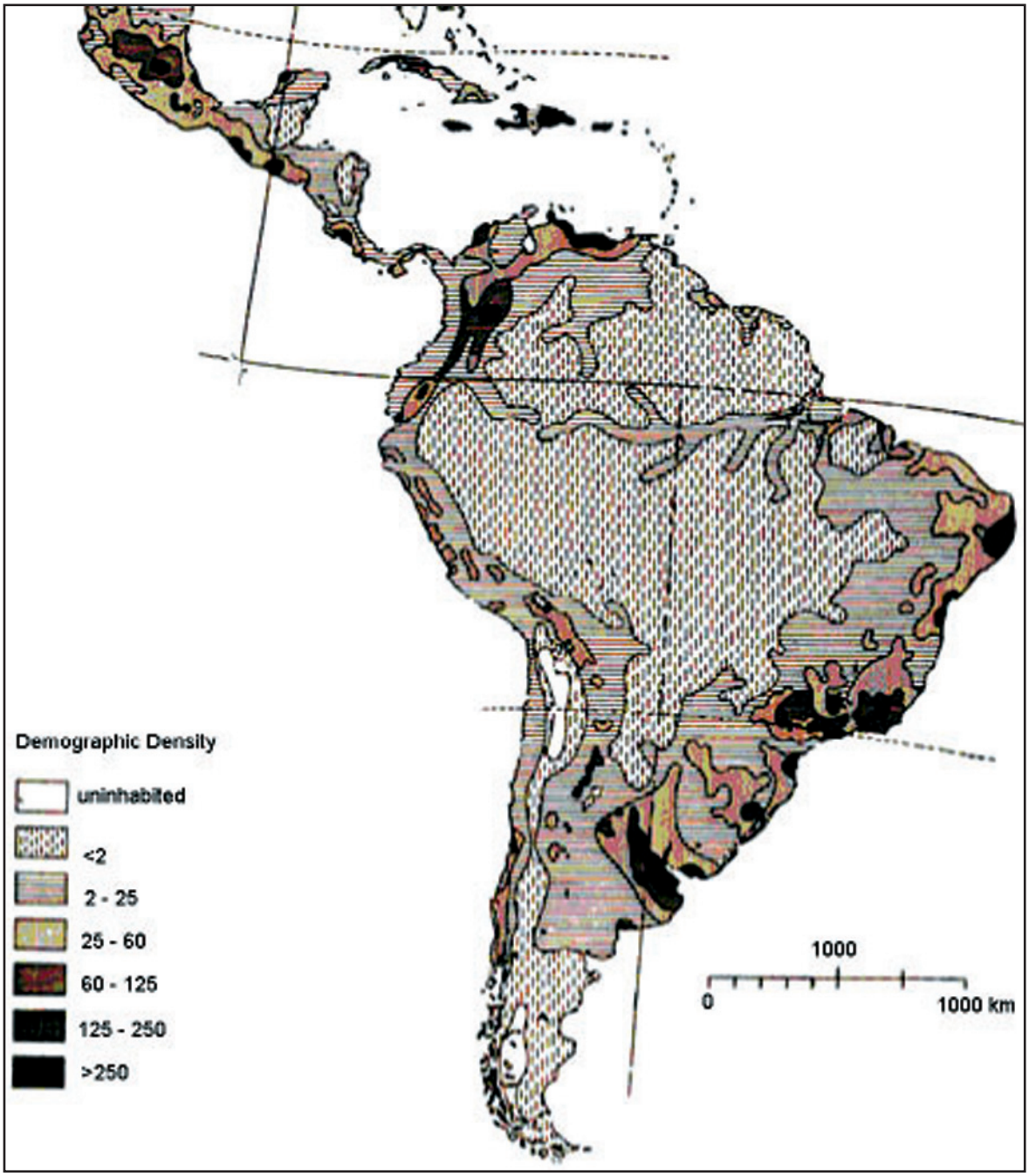
5.4.1 Introduction

This huge area includes the Isthmus of Central America (523,115 km^2), the Caribbean Countries or Dependent Territories (224,000 km^2) and the continent of South America (17,534,730 km^2). The region extends from Belize/Guatemala northern border – near Lat. 18°N – down to Chile's southernmost outpost – near Lat. 56°S, as shown in Figure 5.4.1.1.

According to the United Nations projected growth rates, the population will reach 498.4 million inhabitants in South America, 51.6 million in Central America and 52.2 million in Caribbean countries, by the year 2025. As presented in Figure 5.4.1.2, demographic density is less than 2 inhab/km^2 over the most extensive areas and may reach more than 250 inhab/km^2 in the

Figure 5.4.1.1 Geographical region

Figure 5.4.1.2 Population distribution (PNUMA, 1996)



27 crowed urban areas where population ranges between more than one million up to more than 10 million inhabitants.

The countries range from the relatively industrialized Brazil, responsible for 42% of the Latin America GNP, to tiny Central America nations largely dependent on forestry, fishing, agriculture, and Andean nations such as Peru and Colombia that host ancient cultures.

This geographical extension enjoys the most abundant river flow. In fact, if the ratio of total river runoff to total land area is used as an index, South America has twice the runoff of all the other continents taken together. The Amazon river discharges of around 202,000 m^3/s are the world's largest. In this region, the river discharges constitute the bulk of the freshwater taken for use in most countries, and concerning groundwater withdrawn from aquifers (taken for use), is difficult to estimate because most comes from uncontrolled private and public wells.

The human settlements and industry are growing fast, however, often faster than waste-water treatment facilities can be provided. Thus, much untreated domestic wastewater is discharged into rivers, making the water unsuitable for drinking, even after conventional treatment technology, or for water contact uses, at least locally. As a result, groundwater is increasing in importance in South America, Central America and the Caribbean water supplies, in part as a response to the growing costs and other constraints in storing and treating surface water and partly because the advantage of groundwater are now better understood.

5.4.2 Environment and climate features

Environment overview

The general topography runs high in the west side of South and Central America and low in the east. The entire Caribbean islands arc is, in fact, a partially submerged cordillera whose highest peak is found in the Dominican Republic (2,175 m).

The west side of South America is dominated by Andean Cordillera, a mountain chain that shapes continental (and global) climate features and economic development. On its slopes and plateaus are ancient cities and modern capitals, dense populations, intensive cultivation, and massive erosion, both natural and that caused by human activities.

The region extends over a vast ecological range. It is the most forested of all developing regions, with around one billion hectares of forest covering 48% of its land area. It has the huge watershed of the Amazon River basin and its namesake tropical forest, the largest in the world, and the Atacama, the world driest desert. There are substantial areas of tropical forest in Central America as well, and large unforested areas potentially suitable for farming or rangeland on the Brazilian, Uruguay and Argentina 'pampas'. But, increasingly environmental degradation are blighting the natural resources of the region, decreasing its productive potential for current and future generations, and threatening human health and the very existence of countless plant and animal species.

Major climate features

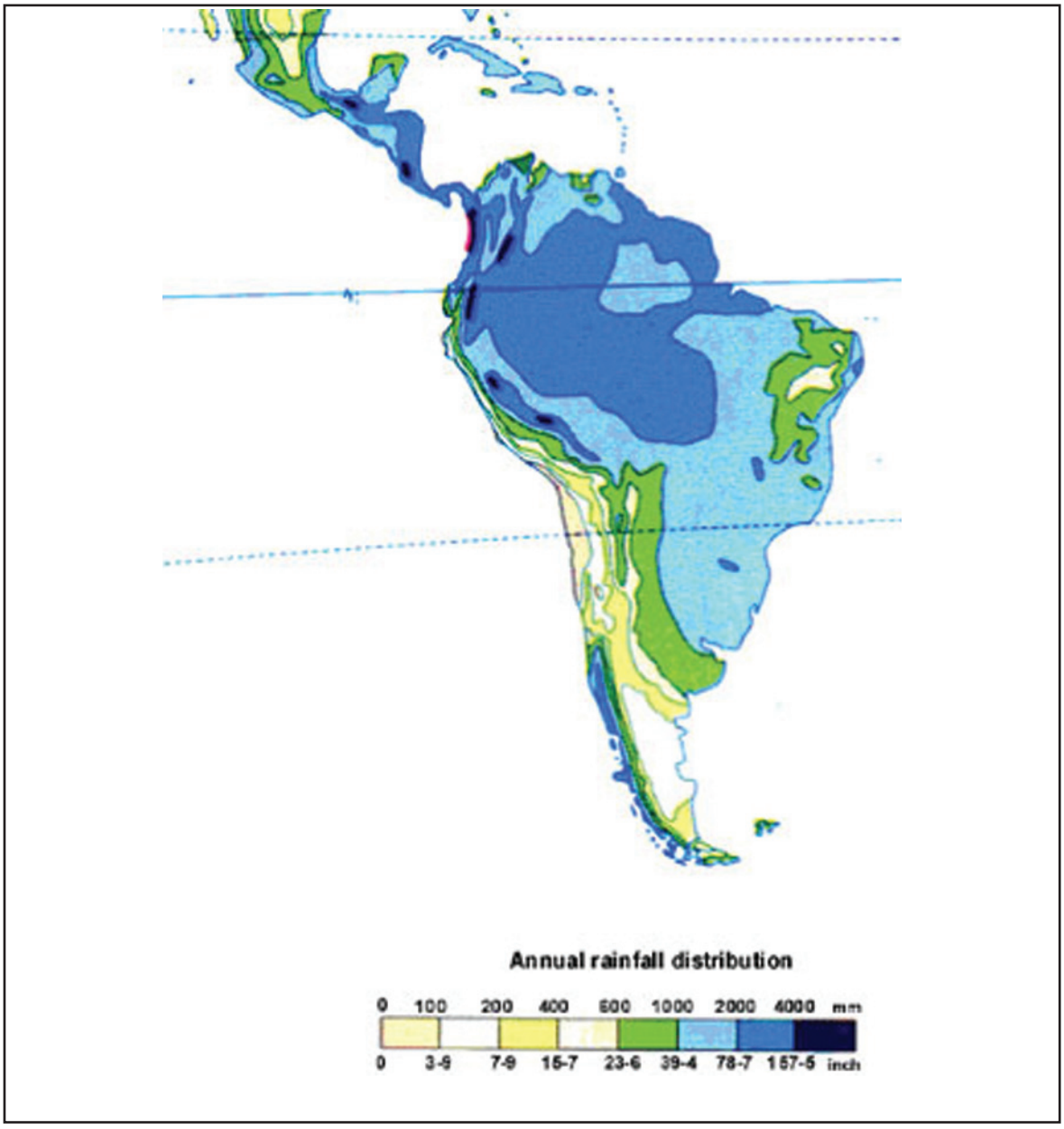
In this huge geographic region, the Andean Cordillera performs decisive orographic effects on rainfall patterns distribution. Precipitation that falls on the land is the main source of freshwater. Moreover, precipitation may be temporarily stored as snow on Andean peak mountains before it is released mostly to streams in the spring and summer.

As presented in Figure 5.4.2.1, in the southern part of Chile and in some Andean peaks in Colombia, Ecuador, Peru and Bolivia annual rainfall amounts more than 4,000 mm. In the arid Pacific shoreline of South America, however, the annual rainfall is less than 100 mm. The Atacama Desert is a cool, arid region (1,000 to 1,100 kilometers) long in northern Chile, where annual rainfalls do not exceed 10 mm, even during some years do not occur. Moist air masses coming from the tropical Amazon Basin tend to be blocked by Andes, making the Atacama Desert one of the driest regions in the world.

The aridity of the Pacific shoreline of South America is the consequence of the Peru (Humboldt) Current that brings cold water from the Antarctic, causing a thermal inversion – cold air at the surface of the ocean and warmer air higher up. This condition produces fog and stratus clouds, but no rain.

But, most of South America continent and Caribbean Island receive an annual average rainfall between 1,000 and 2,000 mm. Moreover, Amazon rain forest and most of Central America receive an annual average precipitation between 2,000 to 4,000 mm. In both cases there is a

Figure 5.4.2.1 Average annual rainfall distribution (UNESCO, 1998)



significant water surplus – precipitation greater than evapotranspiration – that may run off directly to streams or recharge groundwater storage, which discharge to the rivers. As a result, most of the hydrographic network is perennial.

River runoff hydrograph separation with allowance for bank storage is widely used for computation of the contribution of aquifers, hydraulically connected with rivers. The influence of some factors – climate, geomorphological, geological, structural, and hydrogeological conditions of individual regions – are being more clearly established by studying conditions of groundwater generation in individual river basins.

As presented in Figure 5.4.2.2, distribution of groundwater discharge to rivers is similar to overall rainfall distribution. Values are highest in the humid equatorial zone, especially in the basin of the Amazon, the largest river discharge in the world, and in the Isthmus of Central America.

Only a small part of northeastern region of Brazil, the central part of the Andean Cordillera,

Figure 5.4.2.2 Groundwater flow to rivers (WRI, 1991)

and the Atlantic Andean southeastern slope are relatively deficient in rainfall (200 to 600 mm/yr). In these areas groundwater flow to rivers is less than 10 mm/yr.

The most critical problems of the region include river water pollution in crowed urban areas where little if any of the urban sewage is treated. Moreover, imported and local out-mode industrial process frequently produce waste, broadly categorized as heavy metals or synthetic organic compounds, some of it toxic even in micro quantities.

Hydrogeological provinces in South America

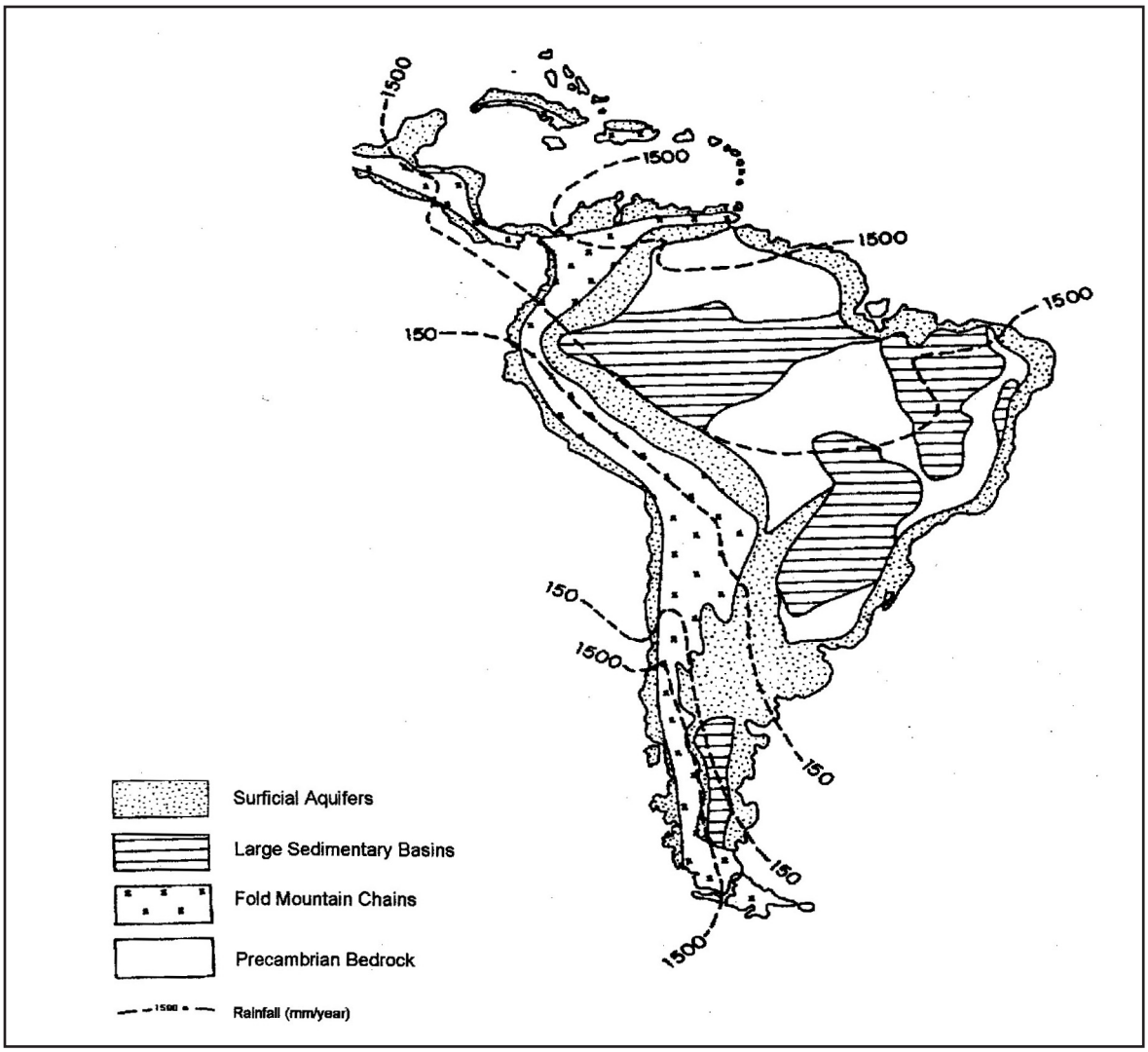
On the basis of the regional geological and tectonic features, four major water-bearing domains have been distinguished: (1) surficial deposits, (2) deeper aquifers in sedimentary basins, (3) folded mountain chains, and (4) pre-Cambrian basement bedrock, as shown in Figure 5.4.2.3 (Rebouças, 1991).

This grouping is unavoidably somewhat imperfect and is subject to revision as hydrogeological information accumulates, such as in South America.

In the surficial deposits and basement rock aquifer zones the unconfined conditions are dominants, instead in the sedimentary basins and in the folded mountain belts the confined aquifers are of greatest significance for supply purposes. On the whole, however, the surficial younger formations are more extensively used for water supply. As a rule, they lie nearer to the surface and are less cemented and less compacted by pressure. Hence, as a rule, they are more porous and more easily recharged.

Vast areas of South America, mostly in Brazil, are floored by Precambrian crystalline basement rocks. As a rule they are greatly deformed and metamorphosed and include large bodies of intrusive or plutonic igneous rocks. Although associated aquifers – fractured hard rocks and/or

Figure 5.4.2.3 Major hydrogeological domains (Rebouças, 1991)



weathered zones – are not highly productive, they are of considerable importance, particularly for water supply, industrial use, livestock in rural areas, and small irrigation schemes.

Hydrogeological conditions vary widely, but crystalline rocks with a deeply weathered mantle or detrital cover deposits (10^{50} m average thickness) can be distinguished from crystalline rocks with less than 10 m of regolith or detrital covers.

In deeply weathered Precambrian basement rocks, where average rainfall is more than 1,000 mm/yr, the most productive zones are usually situated between 50 and 100 m in depth, corresponding to the transition zone of the weathered profile and the associated fractured zone below (Rebouças, 1991).

For example, in the Great São Paulo metropolitan area around 5 thousand wells have been drilled in the aquifer zones of the deeply weathered and/or fractured crystalline rocks, mostly used by industries. The depth of wells reaches an average of 110 m (range 50–300 m) and an average yield of 7.7 m^3/h (5–50 m^3/h). Although the yield looks modest, are usually reliable and of good quality for domestic and industrial uses – TDS less than 200 mg/l (Rebouças et al., 1994).

Excellent aquifers are found in alluvial fan deposits on both sides of the Andean Cordillera and in the sedimentary basins where groundwater is used for domestic, industrial supply and irrigation. Even in the humid tropical zones of Central America and in the Caribbean Islands groundwater has been rapidly developed for municipal water-supply since mid 1960s, mainly San José de Costa Rica, Guatemala, Cuba and many other Caribbean countries or Dependent Territories. Tunnels are used, mostly in some Central America countries, such as Guatemala, Nicaragua, Cuba and in the Andean countries (i.e.) Peru, Chile and Colombia (Rebouças, 1991).

The *Hydrogeological Map of South America* (1996), Scale 1 : 5 000 000, shows sixteen hydrogeological provinces, as presented in Figure 5.4.2.4 (UNESCO/IHP, 1996)

Province 1 – Pacific Andean Slope

This province covers a long narrow area along the Pacific coast line. A great variety of rocks, from pre-Cambrian to Quaternary are present, and consequently there is a wide range of water-bearing formations. The most productive aquifers, and consequently the most developed ones, are formed by alluvial fans, by volcanoclastic materials and by lacustrine deposits. Unconfined aquifers and sometimes confined ones are formed with thickness ranging between a few ten meters to more than 200 meters (Da Franca and Mente, 1996).

Recharge occurs mainly from river floods that come from the mountains, and in some cases from snow melting, irrigation systems and water supply network leakage in urban areas.

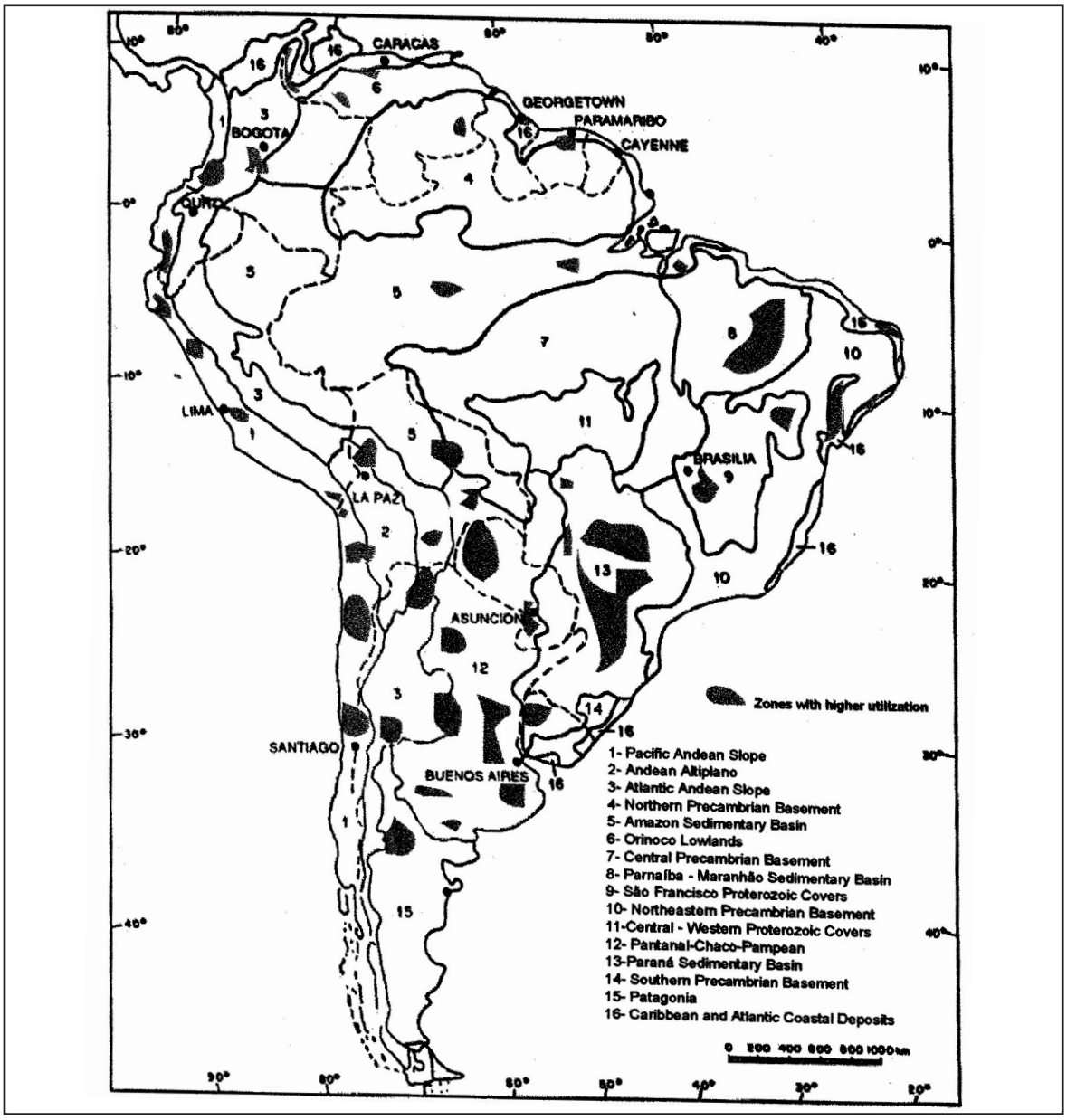
Groundwater is generally obtained from dug and drilled wells. Most of these drilled wells are generally 150 mm or 200 mm in diameter and around 100 m deep; only a small proportion are over 200 m in depth. Well yields generally vary between less than 10 to more than 300 m^3/h, with specific capacities ranging between less than 1 m^3/h.m and 10 m^3/h.m (Rebouças, 1991).

Province 2 – Andean Altiplano

This context includes extensive closed drainage basins where water-bearing formations are formed by Tertiary-Quaternary volcanic deposits. Occasionally and locally the aquifers are unconfined, semi-confined or confined, with thickness that may attain 150 m. Specific capacity of wells vary between 3 m^3/h.m and 18 m^3/h.m, and is mostly used to domestic and industrial water supply.

Groundwater quality is generally good for domestic usage, but in certain areas may be affected by thermal and salt springs. The spring waters may contain dissolved minerals of many different types or certain dissolved gases, are under artesian pressure and are supplied by confined aquifer systems. The 'Salaris' that occur in this context are, in some

Figure 5.4.2.4 South America: hydrogeological provinces and zones with higher utilization of groundwater (UNESCO, 1996)



order, discharging playas supplied by spring systems, with fairly constant discharge, elevated temperatures, and high concentrations of dissolved salts (Rebouças, 1991, Da Franca and Mente, 1996).

Province 3 – Atlantic Andean Slope

This hydrogeological context extends all over the east Andean foothill, and includes important water-bearing formations, mainly represented by alluvial fans and volcanic pyroclastic materials, fractured volcanic rocks and associated lacustrine deposits. Recharge occurs mainly from precipitation, river floods on alluvial fans, and snow melting in the south region of the Continent. The alluvial fans and foothill associated sediments with thickness of more than 500 m constitute the best aquifers used mainly for urban supply (Cochabamba - Bolivia) and for irrigation (Córdoba, Mendoza and Tucumán - Argentina). The aquifers conditions may vary from unconfined to confined or semi-confined and well specific capacities may reach 80 m^3/h.m (Rebouças, 1991).

Province 4 – Northern Precambrian basement

The rock types include gneiss, granite, diorite, quartzite forming the hills and schist or similar types in the topographic low lands. The main water-bearing formations are represented by the deeply weathered basement mantle or regolith and cover deposits. The vegetation is relatively dense, and annual rainfall exceeds 2,000 mm. Topographic low spots provide the simplest mechanism for the formation of depression springs, as well as, contact springs that may result where permeable rock units overlie rocks of much lower permeability. In view of the very scarce hydrogeological information the groundwater use is supposed very low. One of the most common well types is the dug or Amazon-type well mostly in the low topographic areas and near the rivers. Wells of this type have yielded as much as 5–10 m^3/h and water quality is characterized by its very low STD content and pH usually around 4–5 (Rebouças, 1991, Da Franca and Mente, 1996).

Province 5 – Amazon Sedimentary Basin

Groundwater is increasing in importance in Amazon water supplies, despite the abundance of surface water resources, in part as a response to the growing costs and other constraints in treating surface water and partly because the advantages of groundwater are now better understood. Data on the geology of the huge Amazon Sedimentary Basin comes from exploration bore holes drilled for petroleum research. The basin covers around 1.3 million km^2 and has been filled to 7,000 m, largely with Paleozoic and Cenozoic deposits. The former, mostly fine-grained sand stones, outcrop in long narrow areas along both the north and the south sides of the lower Amazon Basin; some may yield significant supplies of groundwater.

Most groundwater comes, however, from the Cenozoic water-bearing formations, which covers about 1,5 million km^2 at an average thickness of 600 m. Groundwater is generally obtained from drilled wells, which mostly have 15 cm in diameter and around 100 m deep; only a small proportion are over 200 m in depth. In metropolitan areas in Brazil, such Manaus, Santarém and Belém, well yields are ranging between 60 m^3/h and more than 400 m^3/h, or specific capacities ranging between 2 m^3/h.m and 20 m^3/h.m (Rebouças, 1988, Tancredi, 1997).

The volume of freshwater stored in the water-bearing formations of the Amazon Sedimentary Basin is estimated at 32,500 km^3. TDS are less than 100 mg/l, but chemical corrosion can cause severe damage in wells. In fact, groundwater is rich in carbon dioxide (CO_2), oxygen (O_2), hydrogen sulfide (H_2S), mainly (Rebouças, 1988, 1991).

Province 6 – Orinoco lowlands

This province corresponds to the lowland plans of Colombia and Venezuela. The main water-bearing formations are represented by alluvial and eolian deposits of Quaternary age, and in minor part from Cretaceous and Tertiary geological periods. Groundwater is generally extract from drilled and dug wells. Most of the drilled wells are generally 150 mm in diameter and around 100 m deep, but some may reach 300 m in depth and have yielded up to 500 m^3/h, with specific capacity of 10 m^3/h.m. Groundwater quality, generally is good for domestic usage (Rebouças, 1991; Da Franca and Mente, 1996).

Province 7 – Central Precambrian basement

In this case one have Precambrian rock units covered locally and occasionally by discontinued mantle of Cenozoic deposits or older rock formations. The very scarce hydrogeological studies is a result of the low population density (2 to 5 inhab/km^2) combined with the abundance of surface water in rivers and springs – depression springs, contact springs, joint springs or fracture springs. In the most important cities, well are yielding between 5 up to 50 m^3/h and groundwater is use to domestic supply and industries (Rebouças, 1991).

Province 8 – Parnaíba-Maranhão Sedimentary Basin

Paranaíba-Maranhão Sedimentary Basin, with an area of 700,000 km^2 and a maximum thickness of 3,000 m is another important source of groundwater in Brazil. Strata dip gently towards the center of the basin and are cut by local faults, which are the loci for diabase dikes.

Among the most important water-bearing formations are the Serra Grande sandstone of Silurian age (50–700 m), the Devonian Cabeças sandstone (200–300 m), and the Carboniferous Piauí and Poti sandstone (200–300 m). These are separated by prominent shale beds, which also have many sandy beds that yield water, most of which is too salty to be used.

Some thousand wells penetrate the principal aquifers and furnish supplies for domestic, industrial usage and irrigation. Many are less than 100 m deep, and only a small proportion are deeper than 300 m. Water quality in these Paleozoic rocks depends on its position in respect to the drainage level, which is controlled by the local intermediate or regional groundwater flow systems, rather than on the formation that contains it. As a result of the general groundwater flow systems, the water up to 1,000 m below the surface is generally of good quality, though rather hard, for domestic usage and with high sulfate contents for irrigation.

The Mesozoic deposits that outcrop in Maranhão state comparatively yield water in moderate quantities, but enough for domestic and for industrial uses and for small irrigation schemes. The environmental conditions and groundwater potentials for fruits production are specially favorable in this area.

The volume of freshwater stored in the water-bearing formations of the Paranaiba-Maranhão Sedimentary Basin is estimated at 17,500 km^3 and existing wells yield as much as 50 to 500 m^3/h. Based on the river baseflow data natural recharge have been estimated at around 3.0 km^3/yr (Rebouças, 1976, 1988, 1991).

Province 9 – São Francisco Proterozoic covers

This context is formed by Paleo-Proterozoic covers such as quartzite and meta-conglomerates with fractured aquifer zones and Upper-Proterozoic formations showing karst dissolution in limestone and dolomite. Well yields vary widely from less than 10 to more than 100 m^3/h, and are used for domestic supply and irrigation, mainly. The volume of freshwater groundwater is estimated at 400 km^3, and based on the river base flow data, the natural recharge have been evaluated at 4,0 km^3/yr (Rebouças, 1967, 1988, 1991; Da Franca and Mente, 1996).

Province 10 – Northeastern Precambrian basement

This province represent the semiarid region of Precambrian rocks of Northeast Brazil, extending over 600,000 km^2 and around 20 million inhabitants, where drought is an usual occurrence. This area is floored by hard rocks terrains comprising a great variety of igneous and metamorphic rocks, nearly impervious bottom on which fractured rocks zones and rest of younger deposits with various water-bearing beds and alluvium covers are the main aquifer.

About 50,000 water wells have been drilled during the last Century in this province, but only from less than a third of this amount it is possible to obtain some kind of useful information in different scattered files (Costa, 1986; Manoel Filho, 1996). During the last three decades an improvement may be observed on most of the aspects of the well location, construction and groundwater recovery equipment – wind mills and electrical pumps –, when the first systematic scientific researches start to be done.

In both quantitative and qualitative aspects of the groundwater so obtained, the climate – in terms of water surplus or deficiency – is presently recognized as the most important

independent variable. The quantity and quality tends to be poor where the average annual rainfall is less than 600 mm. Under these conditions, recharge is very limited and evaporation exceeds precipitation, concentrating and accumulating salts in the residual groundwater. In the semi-arid zone, in Northeastern region of Brazil groundwater from fractured rock aquifers commonly has TDS content higher than 2,000 mg/l, for a range of 500 and 35,000 mg/l. In areas with rainfall values higher than 800 mm/yr, existing wells have mean yield of 10 m^3/h and groundwater TDS content is generally less than 100 mg/l.

Many papers (e. g. Cruz and Melo, 1968; Rebouças, 1973, 1988; Costa, 1986; Oliveira, 1997) have already focused attention on the importance of these climatic aspects.

Subordinate aspects are regional tectonic framework (Paleotectonic and Neotectonic) and technical assistance during all phase of well location, design, construction and usage, are the other important factors to be taken in due consideration. Based on the regional tectonic aspects, five rock systems have been recognized: (1) Cratons and massifs, where specific yields of wells are greater than 1.5 m^3/h.m of very good quality water; (2) Cratonic areas Proterozoic Covers, where values of Q/s are generally greater than 0.5 m^3/h.m, being very common values in the range 1–10 m^3/h.m, and many times above it. Some special cases over 50 m^3/h.m have been recorded in the Chapada Diamantina, Bahia, State; (3) Marginal Fold Belts, where in the majority of the cases the values obtained for specific yield are over 0.5 m^3/h.m and some local cases of exceptionally high values up to 20 m^3/h.m and no quality constraint; (4) Interior Fold Belts, where the general hydrogeological conditions (lithology and structures) of these belts tend to be unfavorable, besides the groundwater quality problem, due to the high index of aridity in these areas; (5) Shear Belts or 'Lineaments', where only fault zones reactivated by Neotectonic events of extensional character are of hydrogeological interest. There are some quite few cases with excellent results, Q/s over 5 m^3/h.m, which is an incentive for further research programs (Brito Neves and Albuquerque, 1997).

Statistics on drilled wells in crystalline fractured rock aquifer zones generally present values of specific yields pretty low, as follows: around 34% below 0.1 m^3/h.m; 34% between 0.1 and 0.5 m^3/h.m; 13% between 0.5 and 1 m^3/h/m and around 13% above 1 m^3/h.m (Rebouças, 1973; Manoel Filho, 1996).

The frequency of occurrence of productive fractures in these crystalline rocks decreases with depth, with the optimal zone considered to be around 30 m. The suggested limit for economic drilling is 60 m.

Province 11 – Central-Western Proterozoic covers

This province is totally located in Brazil and is formed mostly by paleo-Proterozoic covers. The best aquifers are formed by residual deposits – Mesozoic sediments such as sandstone, siltstone, and Cenozoic fluvial deposits. Groundwater is generally obtained from dug and drilled wells which yields vary between 2 and 20 m^3/h, and are mostly used for domestic supplies (Da Franca and Mente, 1996).

Province 12 – Pantanal-Chaco-Pampean

It is formed by a huge tectonic-structural depression filled by sediments, mostly of Quaternary age. The Pantanal Sub-province represents a very extensive wet land. Some excellent aquifer are formed by sand layers insert between clay and silt beds. Existing wells have mean depth of 50 m and provide practically all the domestic supplies (Rebouças and Lastroia, 1989).

The Chaco Sub-province is located in the western region of Paraguay, and extending into southeastern Bolivia and northeastern Argentina. Some excellent aquifer are found in the thousands of sediments which thickness may reach 8,000 m in depth. However, most surficial aquifers occurs in alluvial deposits associated with Tertiary-Quaternary uncon-

solidated sediments. High yields characterize many of the sand and gravel aquifer, but the latter vary greatly in vertical and lateral directions. Existing wells have depths ranging between 60 and 300 m and have average specific capacity of 1.6 m^3/h.m (Da Franca and Mente, 1996).

The Pampean Sub-province represents the southern extension of the Chaco, and it is entirely located in Argentina territory. Aquifer conditions may vary greatly from unconfined, to confined or semi-confined. Existing wells have specific capacities ranging from less than 1 m^3/h.m up to more than 10 m^3/h.m. TDS values are between 300 mg/l up to 2,000 mg/l (Da Franca and Mente, 1996).

Province 13 – Paraná Sedimentary Basin

The Paraná Sedimentary Basin underlies the most developed region of Brazil – around 1,000,000 km^2 (partially interesting the states of Minas Gerais, São Paulo, Mato Grosso, Mato Grosso do Sul, Paraná, Santa Catarina and Rio Grande do Sul), and extends into eastern Paraguay (100,000 km^2), northwestern Uruguay (100,000 km^2) and northeastern Argentina (400,000 km^2). The sedimentary sequence (Silurian to Cretaceous) in this inter-shields basin is almost undisturbed, with gentle dips towards the center of the basin. Local faults may have served as channels for the extruding basalt flows (Rebouças, 1976).

Among the most important aquifers of the Paleozoic sediments are the Furnas sandstone of the Devonian Paraná Group, the Aquidauana and Itararé sandy beds of the Lower Permian (Tubarão Group, in part), the Rio Bonito Formation of the Middle Permian part of the Tubarão Group, and the Rio do Rasto Formation of the Upper Permian Passa Dois Group. As a rule, in the central areas of the basin , the water in these sandstone is rather highly mineralized, but along the outcrop areas the quality is generally better except that it is rather hard or rich in fluoride and sulphurous gas (Rebouças, 1976, 1994a).

Paleozoic aquifers are significant only along the eastern, southern and northwestern narrow margins of the Paraná sedimentary basin, where well yields range up to 10 to 50m^3/h and TDS contents vary widely, from less than 100 mg/l to more than 2,000 mg/l.

More important as a source of water are Triassic-Jurassic and Cretaceous formations of the Paraná Basin. They are separated by an extensively developed and widespread basaltic package. The Triassic-Jurassic deposits form an aquifer of continental dimensions, the Botucatu aquifer, also called Guarany aquifer (Rebouças, 1976, 1994; Araújo et al., 1995).

This aquifer is confined by the Cretaceous basalt of the Serra Geral Formation and by underlying Permo-Triassic sedimentary rocks of low permeability. This extends over 839,000 km^2 in Brazil and 355,000 km^2 in the eastern part of the Chaco-Paraná Basin: Paraguay (71,700 km^2), Argentina (225,500 km^2) and Uruguay (58,500 km^2). Jurassic eolian sandstone everywhere form the best part of the aquifer whereas more argillaceous fluvial-lacustrine Triassic sandstone is notable inferior (Araújo et al., 1995).

A thick basaltic package (up to 1,500 m) overlies this aquifer, reducing its exposed areas to only 10% of the total area it underlies. Not surprisingly in view of the great depths it reaches (almost 2,000 m) and the thick confining basaltic cover, the water stored in the Guarany aquifer system is relatively hot (50–90°C).

The volume of water stored in these aquifer systems was estimated at 50,000 km^3, and the natural recharges based on the river baseflow data was estimated at 234 km^3/yr (Rebouças, 1976).

About 70% of its confined area has artesian conditions. Some thousand wells deeper than 500 m that reach the Botucatu or Guarany aquifer have obtained yields of hundreds or even thousands of m^3/h, to supply cities, industries and hydro-thermal installations or SPA. The specific capacities of wells vary from 4 m^3/h.m to more than 30 m^3/h.m. TDS contents are generally less than 200 mg/l. The production costs per cubic meter of water from well of

depths between 500 and 1,000 m and yielding between 300 and 500 m^3/h vary from US$ 0.01 to US$ 0.08, representing only 10–20 percent of the cost of storing and treating surface sources (Rebouças, 1976, 1994*b*).

Basalt flows cover about 1,000,000 km^2 of the Paraná Sedimentary Basin. Groundwater occurs within the inter-flow zones and along cooling joints of the basalt flows. The 'intertrap' sediments greatly increase the average porosity of large volumes of the basalt rocks. Some 5,000 wells provide yields between 5 m^3/h and 20 m^3/h for domestic usage and small industrial plants. Depths of wells are generally in the order of 100 m, and TDS of water is generally less than 300 mg/l, but sometimes may present excessive iron and silica contents (Rebouças, 1978).

Bauru-Cauiá water-bearing formations of the Cretaceous, which cover some 315,000 km^2, with an average thickness of 100 m, are fairly cemented, and the water is usually of good quality. About 5,000 wells (mostly 150 mm in diameter to depths around 100 m) have been drilled over wide areas of the region, mostly in São Paulo State. They provide practically all the domestic supplies and many of the small industrial and public supplies (Rebouças, 1976).

Province 14 – Southern Precambrian basement

This province is located in the southeastern shared Brazil and Uruguay Atlantic shoreline. The storage groundwater capacities is restricted to the interconnected systems of fractures, joints and fissures, such opening being primarily the result of regional tectonic phenomena. The well yields range between 1 and 36 m^3/h and TDS value of water is generally low, with mean value of 230 mg/l. Groundwater obtained from these aquifer zones are commonly used for domestic supplies, livestock in rural areas, and small irrigation schemes (Rebouças, 1976, 1988).

Province 15 – Patagonia

At the end of the Paleozoic era great changes took place in the physical geography of South America and hence in the regions in which sediments accumulated. The Paleozoic formations are not very satisfactory with respect to quantity and quality of their contained water. Among the most important aquifers are the Upper Cretaceous and Oligocene water-bearing sediments, forming the hydrothermal system with thickness up to 1,500 in Bahia Blanca, where well yields range up to 400 m^3/h and are used for domestic supply and industrial purposes. Most groundwater comes from the Tertiary-Quaternary deposits with average thickness up to 100 m and TDS content around 320 mg/l. Existing wells yield as much as 20 to 100 m^3/h (Da Franca and Mente, 1996).

Province 16 – Caribbean and Atlantic Coastal deposits

In the relatively narrow and discontinuous coastal sedimentary basins, large quantities of groundwater have been developed from sand aquifers, which dip gently and become thicker seawards. The most important aquifers are Cretaceous and Tertiary sandstone.

As a rule, Cretaceous aquifers are confined, such as Açu-Beberibe, São Sebastião sandstone where productive wells may reach 1,000 m depth, where wells have obtained yields of hundreds m^3/h (Rebouças, 1973, 1988).

The Tertiary formations of the coastal region from Belize to Uruguay consist mainly of sand and clay, which overlie Cretaceous formations or basement rocks. Like the Cretaceous sedimentary deposits, they dip gently seawards, and they include a number of good aquifers, chiefly the beds of sand, which form unconfined or semi-confined aquifers. Their water is generally of good quality, but the iron content is sometimes up to 15 mg/l.

Some excellent aquifers are found in sand dunes, in Terciary sandstones and even in Cretaceous sedimentary deposits of the Atlantic shoreline basins. However, sanitary leakage infiltration and sea water intrusion are the major constraints in groundwater use and

development in the surficial coastal aquifers. In areas of dense population one must add the high to extreme pollution vulnerability. Important cities of Brazil, like Fortaleza-Ce, Natal-RN, Recife-Pe, Maceió-Al are supplied almost totally or complementary from coastal aquifers (Costa et al., 1998, Melo, 1995, Cavalcante, 1998).

An executive overview of Latin America-Caribbean situation in relation to potable water-supply, shows that the most widespread and serious groundwater pollution risks appear to be associated with sewer leakage in urban areas, uncontrolled cesspit use both in urban and rural areas, unregulated domestic solid waste disposal and various aspects of industrial activity, especially the disposal of liquid and solid wastes (Foster et al., 1987).

5.4.3 Groundwater resources withdrawal and use

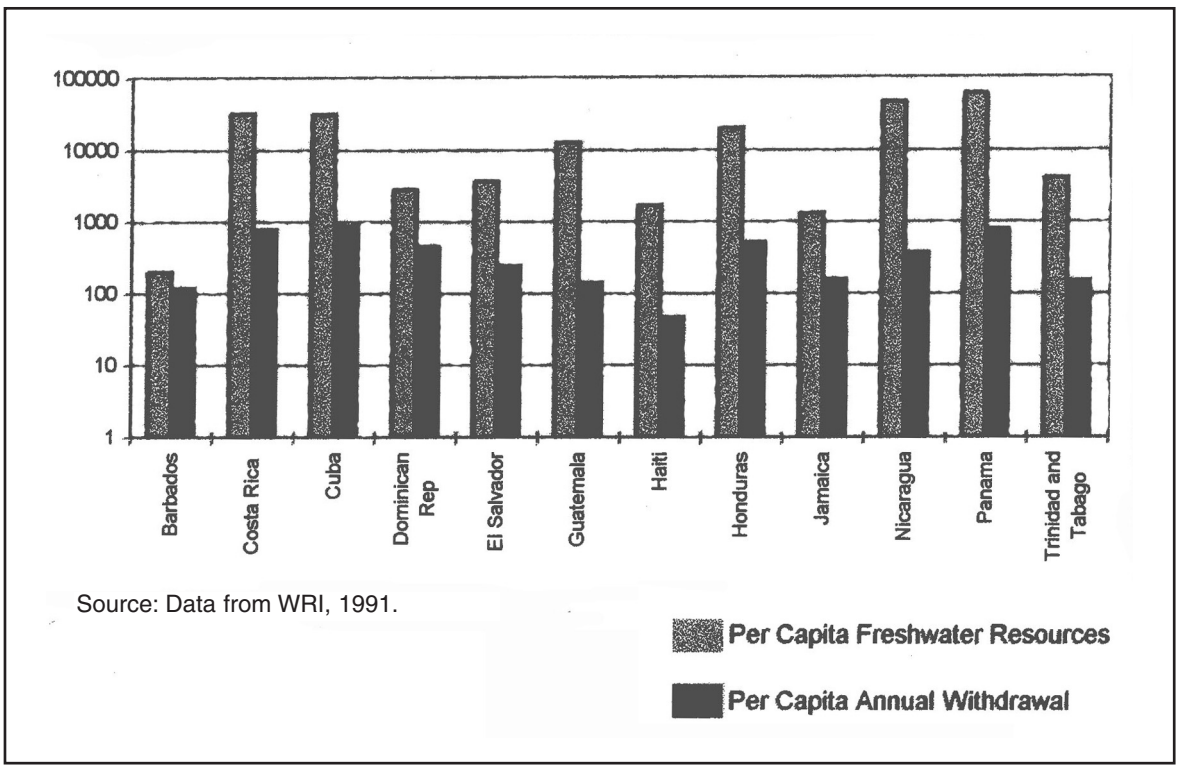
River flows constitute the bulk of usable surface water in most countries, and have been the main source of water supply. Figure 5.4.3.1 shows that, according UN evaluations severe freshwater problems may arise in Barbados, Haiti and Jamaica because they have less than 2,000 m^3 per capita/yr in the rivers. In South America, only Peru shows relative water scarcity.

Although overall rivers discharge in a region may be high, seasonal fluctuations may result in water scarcity during parts of the year. Moreover, the corresponding increase of waste products from domestic, industrial, and agricultural activities, affects seriously the water quality of the receiving bodies, restricting their actual or future utilization as supply sources.

Thus, from an economic point of view, groundwater storage is particularly important because it remains comparatively stable over time and comparatively best protected. It should be emphasized that the amounts of groundwater discharge, characterizing the natural productivity of aquifer systems, are the main indicator of groundwater resource availability in an area.

Groundwater reserves are evaluated at 238,000 km^3 and the discharge to rivers in Central

Figure 5.4.3.1 Available annual per capita freshwater resources resources in rivers and withdrawal in Central American and Caribbean (Rebouças, 1994)



America, Caribbean Islands and South America at 3,898 km^3/yr. This means that the annual amount of renewable groundwater resources should represent 6,000 m^3 per capita/yr in 2025. Thus, groundwater availability is three times greater than the 2,000 m^3 per capita/yr estimated by UN as enough to have a good standard of life and a sustainable economic development.

Furthermore, the long-term experience in groundwater development shows that is advisable to overdraft, up to certain limits, the natural recharge of the local and intermediate groundwater flows and even of the regional flows systems, because that increases the possibility of groundwater withdrawal for different purposes (Johnston, 1997).

Surprisingly, although the groundwater resources are very important to the health and economy of the Central America, Caribbean and South American nations, its occurrence is poorly understood and is the subject of many misconceptions. As a result, groundwater resource is still frequently approached as something mystic or metaphysical by the population in general, and even by professionals.

Consequently, present total withdrawal from the aquifers is difficult to estimate because most comes from uncontrolled private and public wells, without a single central data-base. Usually, data got from many different archives and files are heterogeneous, difficult for statistical treatment and sometimes contradictory.

Based on the latest UN estimates, between 50–60% of total population in Latin America take groundwater for use, mainly to self supply domestic and industrial demands. Thus, considering the present population of South America, Isthmus of Central America and Caribbean Islands – 328 million inhabitants –, and a per capita rate of 200 l/day, the amount of groundwater that is withdrawn (taken for use) from aquifers should be between 12 and 14 km^3/yr. Under these conditions present use of groundwater is very low, comparatively to the available renewable resources of around 4,000 km^3/yr.

The first use of groundwater as a source of supply in this region is lost in pre Colombian times. Shallow, hand-dug wells and crude water-lifting devices marked the early exploitation of groundwater, since the early colonial times. In fact, in almost all the fortress, monastery and other colonial constructions dug wells are still there.

The introduction of well drilling machinery and motor-driven pumps, in the mid of the last century, made possible the recovery of groundwater in large amounts and at increased depths.

As drilling and pump technologies have improved and the electrical network supplies spread out in almost all the countries of the region, the benefits of groundwater development have become increasingly important. Presently, groundwater use for domestic purposes in urban and rural areas, usually, has the highest priority, followed by industrial requirements, and then agricultural usage, mostly irrigation.

Following the privatization trends of water supply services, development of the groundwater resources of the Central America, Caribbean region, and South America has been increasing in recent years, in part as a response to the growing costs and other constraints in storing and treating surface water and partly because the advantages of groundwater are now better understood.

But, vast majority of the hydrogeological studies have been relatively desk studies, that is, comprehensive analysis of existing information on geology, existing wells, hydrology, chemical analysis, administrative and legal constraints to solve local problems of water supply.

Reconnaissance, including field investigation and analysis of existing geological maps, inventory of existing wells, pumping tests, estimate of groundwater resources, is available in most of the countries. However, the development of groundwater resources is concentrated in certain areas of economic or politic interest, or where surface water are under stress, and there are vast areas with scarcity of data or no data.

Latin nature or culture being what it is, interest in groundwater and associated problems is

usually stimulated only in times of crisis such as those produced by the extreme droughts. These so called 'natural' disasters are normally short term phenomena that frequently generate a public response of similar duration intercepted with periods of massive indifference. In these circumstances it must be recognized that only a serious effort can bridge the gap. Although, if this hidden resources is to assist in the future alleviation of water-supply problems, then a more fundamental understanding of how it occurs and functions is necessary, but it is up to governments and their advisers to ensure that the technical and financial resources continue to be made available to make this possible.

The sums involved to resolve world scale water supply and sanitation problems are small in relation to the potential benefits to mankind – around US$ 40 billion per year or 0.25% of the World GP – according to the latest evaluation of the United Nations.

Total water withdrawal from the aquifers is difficult to estimate because most comes from uncontrolled private and public wells. Nevertheless, one estimate that more than half the population depends on groundwater for survival.

In the region, as a whole, groundwater is generally obtained from three types of wells: drilled, dug and driven. The later two predominate for self domestic supplies.

About half million deeper wells have been drilled in the last 20 years and are currently in use, mostly supplying public water systems, industries and for agricultural concerns.

Most of these wells are generally 150 mm in diameter and around 100 m deep; only a small proportion are over 200 m depth. In the large sedimentary basins in Brazil are many wells deeper than 500 m. some between 500 and 1,000 m and very few with more than 1,000 m to 2,000 m in depth. These characteristics are based on data presented by several authors during ABAS, ALHSUD and IAH-Argentina Congresses, 1978–98.

Obviously, the amount of groundwater which can be produced will vary under varied patterns, which include a statement of the legal and economic constraints, as well as the limiting values of environmental damage. In any event, the pumping cone will continue to grow until it has sufficiently reduce natural discharge or increased recharge to balance the volume of water withdrawn.

Managing water quality will be increasingly important. So far, current problems of diffuse and point-source pollution from domestic, industrial and agricultural origin highlight one of the most important duties of the present-day hydrogeologist: the maintenance of groundwater quality.

Initially pollution from sanitary wastes and the salty process of irrigation systems were the major problems. To them must now be added concern about heavy metals, nitrates and organic contaminants. In urban and industrial areas groundwater may become contaminated as a result of leakage from septic tanks and cesspools, gasoline leakage from underground storage tanks, sewage effluent leakage or spreading ground, landfills, garbage dumps, or similar features for the disposal of industrial, domestic and animal waste. Other sources of contamination, which are becoming of increasing concern in many areas are improperly constructed or abandon unsealed wells, other subsurface structures and excavations.

To address these problems, some detailed studies have been made, mostly by research groups in the most important Universities. Therefore, one know that groundwater is still relatively the best protected source for water supply, even in urban and industrial areas.

As a rule, most of the inhabitants of the rural areas use groundwater, and in many metropolitan areas it is used as a complementary resource, because it is the cheapest and safest source.

Currently, only around 9% of the land area is under cultivation. Although there are no inherent physical or chemical constraints on agriculture on fully 15% of the area. Water pollution from agricultural activities is therefore expected to be relatively less severe in this region. Nevertheless, fertilizer consumption in many countries of South America and in the Caribbean

Region increased 97% from 1973 to 1990 and, in some countries, has reached developed country levels. Brazil, for example, ranks among the top five countries in the world in terms of pesticide use (Rebouças, 1991).

Pollution of surface water frequently results in a situation where the contamination can be seen or smelt. However, contamination of groundwater most often results in a situation that cannot be detected by human senses. Moreover, to respond to economic problems, especially those arising from external debt, the Governments in these Regions are more likely to ignore industrial and agricultural water pollution than decrease productions. Likewise, austerity measures in many countries are reported to have left environment control agencies without enough skilled professionals to carry out their basic tasks.

Currently, specialists and even decision-makers from most of the countries agree that for the sustainable economic and social development, as well as for the rational utilization and protection of water resources, it would be very useful to have more integrated policies.

There are, therefore, a number of management issues central to the analysis of water resource problems and their inter-relationships are complex in nature. Regarding groundwater the following substantive aspects can interact with each other and with government policies: (1) water supply (domestic, industrial, agricultural), (2) pollution control, involving the establishment, monitoring and enforcement of standards, regulations and incentives.

These substantive groundwater issues may be interrelated with other policy areas ranging from agriculture, industry, urban and regional development.

Unfortunately, comprehensive data are not available on the proportion of water withdrawn from groundwater resources. Thus, to illustrate the vital role played by groundwater the main zones with greater utilization are shown in 5.4.3.2, and some specific cases are described in South America. In Central America and Caribbean nations, groundwater is mostly used for domestic supply in urban areas.

Argentina

Groundwater is mainly used for cattle-breeding all over the country, for domestic and industrial supply in metropolitan area of Buenos Aires, La Plata, Bahía Blanca, and for irrigation mostly in Córdoba, Mendoza and Tucumán.

Bolivia

Groundwater is mostly used for human consumption and industry and, secondary for irrigation. The areas of most intensive use are: La Paz, Oruro, Potosí, Cochabamba, Chuquisaca, Tarija, and Santa Cruz de la Sierra.

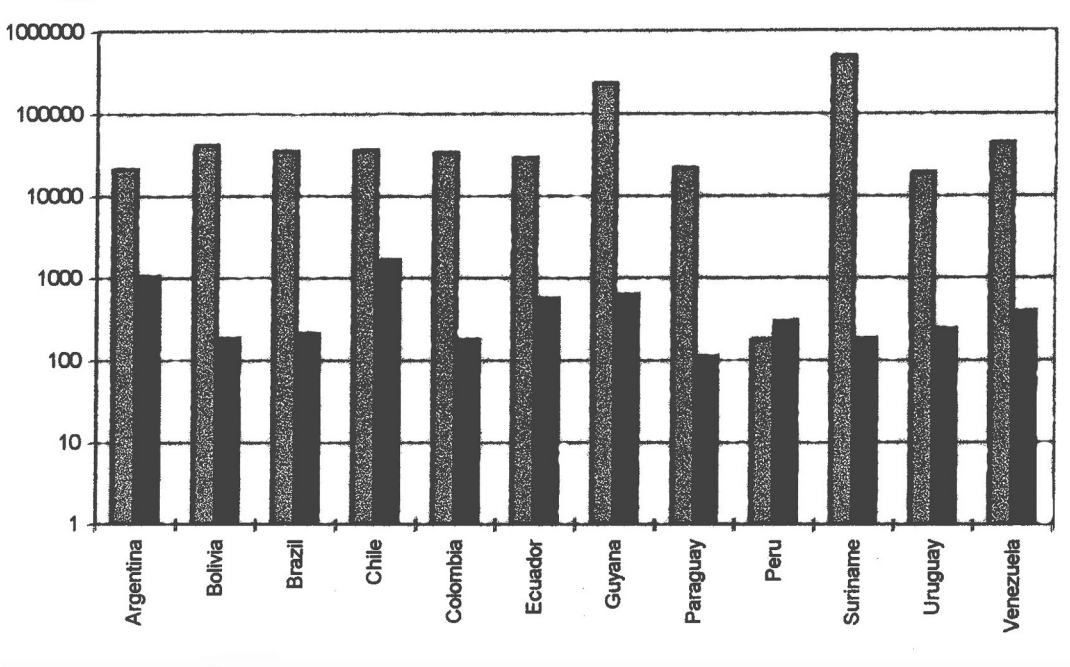
Brazil

Groundwater was considered to be a 'local' resource in the early phase of its development, serving domestic and rural needs. Expanded use for municipal and industrial purposes has been experienced over the past 25 years or so. Thus, significant attention has been devoted to defining the regional characteristics and appraising the development of major aquifer systems in the 11 hydrogeological provinces, mainly in the Northeastern region to supply the population during the drought periods, and in the Southeastern regions to supply the population of medium and small cities and industries. Currently, between 70–90% of the municipal water supply services and 95% of industries take groundwater for use.

These efforts have yielded a great deal of valuable information to guide management of the nation's groundwater resources. About 250,000 deep wells have been drilled in the last 30 years by municipalities and industrial concerns.

In almost all the largest metropolitan areas (population between more than 1 million and 16 million inhabitants), such as Manaus, Belém, São Luis, Fortaleza, Recife, Salvador, São Paulo and Curitiba, despite the benefits of surface water supply service, thousands of uncontrolled private wells provide significant groundwater for hotels, hospitals, residential

Figure 5.4.3.2 Available annual per capita freshwater resources resources in rivers and withdrawal in South America (UNESCO, 1996)



Source: Data from WRI, 1991.

buildings and industries. This contributes substantially to reduce month public water bill and the problems generated by the frequent water shortages.

As a rule, most of the inhabitants of the rural areas, 90% of industries and almost 60% of the urban dwellers of Brazil use groundwater.

Chile

The main zones with great groundwater withdrawal are in the river basins of Aconcagua, Alqui, Copiapó, Maipo and the metropolitan area of Santiago. In these areas groundwater is mainly used for domestic and industrial purposes, and secondary for irrigation.

Colombia

Groundwater is being more intensively used, such as in the Cauca valley for sugar-cane irrigation, in the Savannah of Bogota for flower crops, industrial purposes, breweries and gaseous water factories, in the northern Colombia which is affected by droughts, groundwater is basically used for domestic supply, livestock in rural areas, and small irrigation schemes.

Ecuador

Groundwater is used primarily for domestic supply, and secondary for industrial purposes and irrigation. In sixteen cities groundwater is of considerable importance, particularly for domestic use.

Paraguay

Groundwater is mainly used for domestic supply and industrial purposes in the metropolitan area of Asuncion. The areas with comparatively the best groundwater resources are

the Chaco Alto, Patiño, Misiones and Caacupé. In the Chaco western extension, brackish groundwater has been found, forming three different situation: (1) area with surface salt water bodies overlying fresh groundwater aquifer beds; (2) areas with significant amount of shallow fresh ground-water overlying deeper salt groundwater; and (3) areas without significant amount of fresh groundwater.

Peru

Groundwater is usually used mainly in the coastal arid zone for domestic supply and irrigation. In the metropolitan area of Lima – 5.5 million inhabitants – some 320 production wells provide around one million cubic meters of freshwater per day or 80% of the total volume taken for use. Some others twelve urban areas, such as Ciudad Trujillo, Piura, Arequipa, are supplied by drilled wells to depths from 30 to 65 m, yielding 70 to 198 m^3/h. They provide, practically, all the domestic supplies and many of the industrial and irrigation demands. Groundwater quality is generally good for domestic usage, industrial and irrigation activities.

Uruguay

Groundwater is increasing in importance in Uruguay water supplies, as a response to the growing costs and other constraints in storing and treating surface water. Currently, in the Montevideo metropolitan area (1.6 million inhabitants) hundreds of wells provide groundwater for around 20% of this population. However, most of the inhabitants of the rural areas and around 80% of the urban dwellers of Uruguay use groundwater.

The continued expansion in the use of groundwater, mostly in the areas of Tacuarembó aquifer, Ragon aquifer and Mercedes aquifer, resulted in an ever-increasing need for skilled professionals in the field of resource evaluation, well technology, and water use and protection.

Venezuela

Groundwater development in Venezuela is significant, mostly in the Maracaibo plain, Quibor region, basin of Valencia and Quanipa terraces. Groundwater is considered to be of great importance for municipal, industrial and irrigation purposes. Groundwater is generally obtained from drilled wells. Most of these are generally between 150 and 200 mm in diameter and depths between 50 and 100 m deep, yielding between 50 m^3/h and around 150 m^3/h. Groundwater quality tends to be good – TDS values ranging from 100 mg/l and 700 mg/l.

An infiltration gallery may be considered a horizontal well or subsurface drain that intercepts underflow in permeable materials or infiltration of surface water. They are used, mostly in some Central America countries, such as Guatemala, Nicaragua, Cuba and in the Andean countries (i.e. Peru, Chile and Colombia).

Caribbean Islands groundwater evaluations face fundamental hydrogeological problems, including the great variations in the geographic sizes, island sea water interfaces, salt water intrusions, either in porous media, fractured and karst aquifers, and great variations in groundwater knowledge.

An executive overview of Caribbean situation in relation to potable water-supply, shows that the most widespread and serious groundwater pollution risks appear to be associated with septic tanks leakage, garbage dumps and various aspects of industrial activity, especially the disposal of liquid effluents.

5.4.4 Groundwater resources management and its sustainability

Groundwater tends to become the most important source of water supply in these regions due to

certain characteristics such as economic feasibility, large storage, natural protection from pollution and climate variability, such as induced by El Niño recurrence.

Globalization and privatization new paradigm is inducing the development of groundwater resources, mostly because are relatively more flexible phased and costs are generally lower than alternative surface water schemes.

Thus, groundwater use should be managed both from the economic efficiency point of view and from the environmental point of view by safeguarding quality through controlling depletion.

Specific strategies are needed to deal with the high level of uncertainty in groundwater management: in particular, additional information needs to be acquired to reduce uncertainty, but at the same time cost-effective action is needed to avoid the possibility of future degradation of groundwater resources. Research should be an integral part of groundwater policy to reduce lack of information and to develop cost-effective technical solutions to co-ordinated management of surface and groundwater. Local level agencies should ensure that land use planning and water planning are more closely integrated.

These assessments encourage the adoption of integrated approaches by systematically requiring decision makers to address the various environmental externalities involved in the development of water resources and their management.

The current problems of point-source pollution from domestic and industrial origins in urban areas highlight one of the most important tasks.

The aquifers occurring in alluvial fans (i.e. Pacific Andean Slope Province) are under an increasing over exploitation. Here regulation and distribution are referred to in a wide sense to indicate the overall management of water resources to the various users through systematic planning, the optimization use of surface and groundwater, considering aquifer as storage and distribution functions.

The management objective for groundwater resources should be long-term efficiency. This means that its quantity and quality should be maintained at an economically, socially and environmentally optimal level, taking into account the long-term uncertainties and the real long-term costs of controls on its use, protection and remediation.

To achieve the above objective groundwater management should be comprehensive, which means, integrated management between national, regional, local authorities and stakeholders.

Within the overall framework of water resource management and given the importance of water demand, there is a need now for governments to develop specific strategies for efficient use of groundwater resources. There should be a strategy for conjunctive use of surface and groundwater and within this strategy full account should be taken of alternative water supply sources, their quality and their relationship within the hydrological cycle. Taking regional characteristics into account, high quality groundwater would be reserved for drinking water and other high quality uses. The resource pricing principle where all consumers, discharges and polluters pay for the services received should be applied. To achieve this objective, permit systems for abstraction, whatever the extent of public control and the form of private use right, should be carefully designed.

5.4.5 Conclusions

Groundwater in this huge area – Central America, Caribbean Islands and South America – is unevenly distributed in quantity, but the quality is usually good for domestic and industrial supply. Groundwater is an important resource in many areas and has been highly committed in several locations, mainly in most populated areas for domestic and industrial purposes. Further development of groundwater resources to satisfy urban, industrial, agricultural and mining demands, which are numerous and on which region's economy is highly dependent, can be

achieved even in developed areas, provide up to date technological and management techniques are applied.

Thus, the exploitation of groundwater resources in Central America, Caribbean Region and South America, poses three sets of challenges: problems of knowledge, problems related to the legislation and its implementation to provide compatible development and conservation strategies, and problems related to the selection of ways and means of action.

It is necessary to find appropriate ways and means of disseminating basic information and of popularizing understanding of the nature of groundwater.

5.5 Groundwater resources and their use in Africa

Some 5 million Years ago humankind is believed to have evolved in eastern Africa, and the first great civilization arose 6,000 years ago along the banks of the Nile in Egypt. Records of the Nile levels can be traced back to about 3000 to 3500 BC. 'Nilometers' were used to measure the levels of the Nile. King Menes, the Pharaoh who ruled around 3000 BC dammed the Nile south of Memphis and diverted its course (Biswas, 1972).

Centered on the equator, the mass of Africa consists of crystalline and metamorphic Pre-Cambrian rocks. The African basement crops out over vast expanses of the continent and generally slopes from southeast to northwest where depressed areas are filled with a thick succession of continental and marine deposits. Much of these large sedimentary basins are covered by sand dunes in a vast belt of deserts which includes the Sahara in the north and the Libyan, Egyptian and Nubian deserts in the northeast. This arid and hyperarid zone extends from the Atlantic in the 'Western Sahara' to the Red Sea coast in Egypt and Sudan. Towards the south the desert belt gives way to grass land and rainforest. Savanas clothes much of the more than 23 million km^2 of Sub-Saharan Africa. Only 65,000 are irrigated (GSA, 1995). Unreliable rainfall, poor soils and scarcity of water make farming marginal in much of the continent. Desertification afflicts the semi-arid regions bordering the Sahara. The United Conference on Desertification estimated that 75 million people in Sub-Saharan Africa live in regions prone to desertification, and in central Africa forests and woodland are disappearing.

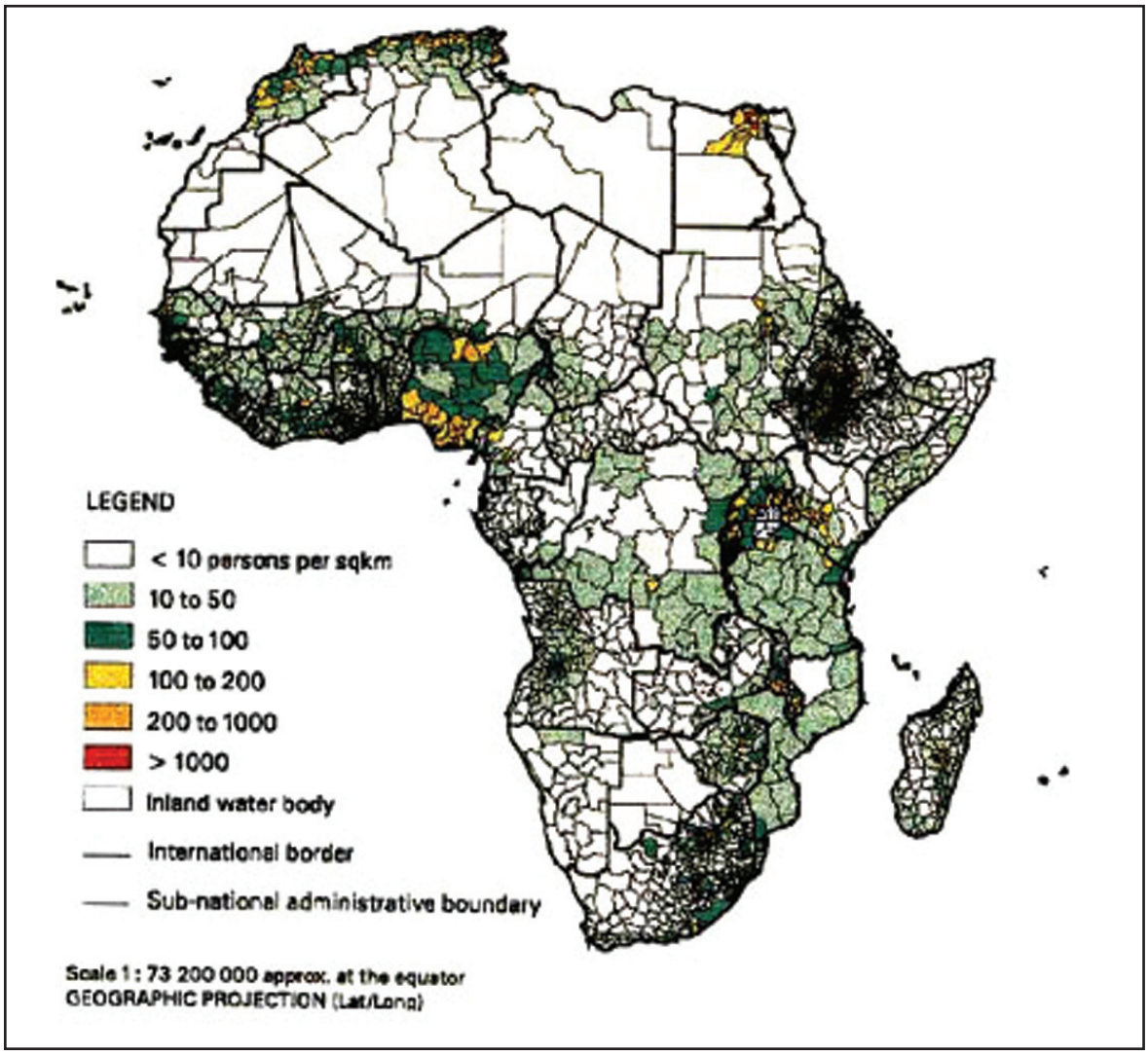
Africa population, about 720 million (GSA, 1995) live in 53 countries. Africa, however is unevenly populated (Fig. 5.5.1), 135 million live along the Mediterranean coast and about 100 million live in Nigeria alone. About 75% of African population still live in farming villages.

Groundwater has a growing role in the economic and social development of Africa. The development of irrigated agriculture through the use of groundwater is possible in areas underlain by extensive regional aquifer systems or local aquifers with adequate replenishment. Favorable conditions exist in alluvial, lacustrine, basaltic and wadi aquifers. Conditions are unfavorable in the outcrops of the crystalline and metamorphic basement. In these very extensive areas, which occur mainly in tropical Africa, groundwater resources are limited and are used, primarily, for domestic water supply and livestock watering. The sustainable use of non-renewable water resources, occurring mainly, in large sedimentary basin, underlying the Sahara, needs a special approach. Mathematic modeling is an important tool in this regard. It is also a useful tool for the management of renewable groundwater resources.

5.5.1 Regional geology

The Precambrian basement outcrops over vast areas in the African continent. Major outcrops occur in the Sahara, west, east and south Africa. The crystalline basement consists, mainly, of meta-

Figure 5.5.1. Density of population in Africa by administrative units (estimated for 1994)



morphic, granitic and volcanic rocks. It is overlain by sedimentary deposits, mainly limestones and dolomites, belonging to the Infra-cambrian.

Immense fractures developed in the basement follow two principal direction at right angles to each other, SW-NE and SE-NW, Tectonic basins and uplifted basement blocks were developed through several cycles of uplifts and subsidence. Depressed areas in the shield were filled with continental and marine sediments. From the Mesozoic until Recent, the African continent was generally in a state of extension. This resulted in the formation of a series of intra-continental rift basins. Several episodes of rifting have been recognized (Tanssen et al., 1993). The first (Late Carboniferous to Middle Jurassic) includes the Karoo rifting in southeast Africa. During the second phase (Late Jurassic to early Aptian), the west and central African rift system developed. During the third phase (Aptian-Albian) E-W to ENE-WSW basins developed. High spreading rates in the Indian ocean occurred in the fourth phase (Maestrichtian to Paleocene) and in the late Eocene (Phase 5) rifting resulted in separation of Arabia and Africa, and opening of the Red Sea, Gulf of Aden and East African Rift System occurred in the Neogene (Tanssen et al., 1993, Brinks and Fairhead, 1992).

There are several important volcanic phases connected with the great fracture zones of the continent during the Miocene, Pliocene and Quaternary. The principal volcanic terrain's are

situated along two main fracture zone: the Cameroon-Tibesti trough and the great raft valleys (Ethiopian plateau, Mount Uhurn, Mount Kenya and Mount Ruwenzori) (UN, 1973).

5.5.1.1 Major aquifers

Several factors have contributed to the development of aquifer systems in Africa. Among these the tectonic and climatic environment are the most basic. These factors have controlled the depositional environment in two completely different geological domains: the mobile belt of the Atlas range and the African platform, separated by the South Atlas Rift. The mobile belt, although does not occupy more than 3% of Africa, is an important part of the continent because it sustains over 10% of its population.

Folding has created numerous intermontane or sub-montane basins of limited areal extent and reserves, in the Atlas zone, in contrast to the African Platform, which, under the influence of rifting is sub-divided into large superelevated blocks and depressed or subsided areas underlain by extensive aquifers of huge reserves.

Major aquifers of the folded zone

In the folded zones of northwest and south Africa, the depositional environmental favored the accumulation of fine grained rocks and carbonate rocks. Compression metamorphism and diagenesis has reduced permeability and produced in many groundwater basins impermeable schists, flysch, quartzites or crystalline rocks.

In South Africa the areas between the cape and Durban the 'folded' zone comprises two main types of aquifers;

1. Paleozoic limestones
2. Paleozoic sandstones, quartzites and shales.

In the Atlas fold zones several aquifers and aquicludes are recognized. These include:

1. Fissured carbonate aquifers; mainly limestone and dolomite of Jurassic and Cretaceous age. They occur, mainly in High Atlas, High Plateau and in the coastal and intermontane basins, interbedded with clastic porous aquifers.
2. Detrital (clastic) aquifers; consisting mainly of sandstones and sand of Barremian-Albian age. They occur in the High Plateau, in Algeria and the Saharian Atlas.
3. Alluvial aquifers; of Neogene and Quaternary age, occurring in wadis (ephemeral streams), intermontane and coastal basins. They are more extensive in Tunisia and the Atlantic coasts of Morocco. They often form multi-layered aquifer systems. In the Sous basin, east of Agadir 5 inter-connected auqifers consisting of conglomerates, gravels, sandstone and sands alternate with carbonate aquifers (Pliocene) and overlie older formation belonging to the Cambrian and Cretaceous.

Notwithstanding the high rainfall of the Atlas domain, extensive and prolific aquifers are lacking or rare. In most areas runoff is high and in the Rif Chain (1,000 mm) and the Tellian Atlas erosion is high. Soil conservation and watershed management is the main concern of the Maghreb countries.

Impermeable rocks comprise in addition to the Rif-Tellian coastal chain, which consists of 'schists, flysch, clays and marls'. The extensive Pre-Cambrian massif of the Anti-Atlas consisting mainly, of sehist, granite and quartzite.

Major aquifers of the African platform

The sandstones and carbonates are, generally, recognized as the platform facies (Pettijohn, 1957).

Commonly this facies rests unconformable on the relatively stable crystalline basement with few or several tenths of meters conglomeratic material. This basal conglomerate is found in the Nubian Basin in northern Sudan (Khartoum or Bitana area), but the association itself exists only in northern Egypt and Libya. Negative areas, which were covered by the Sea, do not extend into the margins of the large sedimentary basins and most marine transgressions, have not extended to the basins of Central Africa. The Lower Paleozoic transgression has covered northern Africa. South of the Equater Paleozoic rocks occurs chiefly in South Africa. The marine Mesozoic and Tertiary covered the northern part of Central Africa, west and east coast of Africa and the eastern 'horn' of Africa (UN, 1973).

Continental deposits are predominent in Africa. They are interbedded with marine sediments in the coastal and northern basins and may pass into carbonate facies in the coastal zones. Major aquifers in the stable part of the continent may thus be classified, on the basis of their pre-dominent lithology, as follows (Fig. 5.5.1.1.1);

1. Continental sandstone aquifer systems;
2. Carbonate aquifer systems;
3. Sandstone-carbonate (complex) aquifer systems;
4. Alluvial aquifer systems;
5. Basaltic aquifer systems;
6. Crystalline basement aquifer 'systems'.

The term 'aquifer system' includes all aquifers, aquitards and aquicludes that are interconnected in a groundwater basin. Thus the 'Nubian Aquifer System' includes the lower Paleozoic sandstone

Figure 5.5.5.1.1.1. Major hydrogeological formations in Africa

aquifer, the Paleozoic shale, the Upper Paleozoic-Mesozoic sandstone aquifer, the Mesozoic clay-silt aquitard, the Nubian sandstone aquifer, the Tertiary carbonate aquifers and aquitards, as well as the Miocene sandstone aquifers.

Continental sandstone aquifer systems include, addition of the Nubian aquifer system of northeast Africa, the Continental Intercalaire of the Sahara, the Karroo (Carboniferous-Triassic) aquifer system and the Kalahari (Neogene-Pleistocene) aquifer system of South Africa (Africa south of the equator).

The carbonate aquifer systems are particularly important in the coastal basins such the Jabal Akhdar-Sirte basin in northern Libya. The calcorio-dolomoitic sedimentary complex of the Upper Pre-Cambrian and Lower Cambrian, constitutes one of the most important carbonate aquifer in Africa. They are particularly extensive in Congo (Lubumbashi dolomites), Gabon, Zaire, Angola, Namibia, Tanzania and Zambia.

The sandstone-carbonate association (complex) is of common occurrence in the major groundwater basins of Africa. This is the 'Complex Terminal' of North Sahara basin (Margat, 1991) (Algeria, Tunisia). It is of wide occurrence in the major basins of North Africa. Since carbonate deposition was very extensive in the Cretaceous and continued in the Paleogene and to a limited extent during the Neogene, they form often a confining layer or aquitard above the more widespread continental sandstone formations, or they may be interbedded with sandstone facies. The sandstone-limestone hydrogeological complex occurs mainly in coastal basins in Mauritania, Senegal, Côte d'Ivoire,, Cameron, Gabon, Angola, Somalia, Mozambique and the West Coast of Madagascar.

Alluvial aquifers constitute a promising source of freshwater when the alluvium is of a suitable nature. The alluvial fill of the Congo basin and the Sabi river of Zimbabwe, and the extensive alluvial fill of Burundi graben form important sources for the population of these basins. The Niger and Nile alluvial aquifer is often clayey. In the latter basin, the Egyptian capital Cairo separates the Nile valley aquifer from the Nile Delta Aquifer. Both aquifers are composed of sands and gravel with intercalated clay lenses; and are underlain by a thick sequence of Pliocene clays.

The thickness of the alluvial aquifer increases northward from few meters at Cairo to about 1,000 m at the Mediterranean Coast. The southern part of the aquifer is highly productive and generally contains freshwater. The northern part of the Delta Aquifer is less productive and contains brackish or saline water (RIGW/IWACO, 1988, Hefny et al., 1991).

Fissured aquifers usually include carbonate, volcanic (basalt) and crystalline (metamorphic and igneous rocks). Carbonate rocks have the advantage of gaining additional 'Secondary permeability' through solution of the carbonate. Weathering of volcanic rocks on the other hand, may reduce their permeability. Because fractures may become clogged with clayey material, the main product of weathering. The productivity of volcanic and crystalline rocks depends primarily on the density of fractures and joints and such interconnected fractures are produced by cooling or tectonic forces. Crystalline and volcanic rocks, are impermeable except in faulted, fractured or weathered zones. Impermeable clays form the highest 'horizon' in granites and orthogneisses (soil more or less lateritic), whereas basalt effusions, occurring in different geological times are often covered by impermeable clay layers, creating multi-layered aquifer systems. The lower horizons in areas underlain by crystalline rocks may include sands, sandy clays or fractured zones.

The Precambrian crystalline basement rocks crop out over vast expanse of the continent. Their outcrops or 'suboutcrops' form more or less, a continuous band in western Africa, Equatorial Guinea, Gabon, Congo, Zair, Angola, Namibia and Eastern Africa: Rwanda, Burundi, Tanzania, Kenya and Zimbabwe. They also outcrop in the Sahara and form a broad band of outcrops in the equatorial and tropical zone of the continent. The basaltic rocks form an important outcrop in Ethiopia and in the Rift Valley: in Kenya, Tanzania and Rwanda. Minor outcrops of basalts and basic rocks occur in Madagascar, South Africa, Botswana Zimbabwe, Swaziland and Mauritania.

In general important volcanic phases were connected with two fracture lines, during the Miocene and the Pliocene: the Cameroon-Tibesti trough and the east African rift system (UN, 1973). Outside these rift zones, the Hoggar, the Air and the Fizzan occur in the Sahara.

5.5.2 Water resources

Renewable water resources in Africa, was estimated at 4,040 km^3 by Shiklomanov (1989) and at 3,998 km^3 by FAO (1997) . It seems that 4,000 km^3 is reasonable estimate of available resources. Of this total, about 2,400 km^3 is readily accessible for human use (UNESCO, 1978).

Table 5.5.2.1 Surface and groundwater resources in Africa (in billion m^3)

Country/ Region	*Surface water*	*Ground water*	*Overlap*	*Total bcm*	*Inflow*	*Global water resources*
Northern	*28.61*	*12.21*	*1*	*49.82*	*67.55*	*117.37*
Algeria	13.2	1.7	1	13.9	0.43	14.33
Egypt	0.5	1.3	0	1.8	66.7	68.5
Libya	0.1	0.5	0	0.6	0	0.6
Morocco	22.5	7.5	0	30.0	0	30.0
Tunisia	2.31	1.21	0	3.52	0.42	3.94
Sudano-Sahelian	138.28	62.62	33.5	170.2	258.5	428.7
Burkina Faso	13	9.5	5	17.5	0	17.5
Cape Verde	0.18	0.12	0	0.3	0	0.3
Chad	13.5	11.5	10	15	28	43
Djibuti	0	0.3	0	0.3	0	0.3
Eritrea				2.8	6	8.8
Gambia	3	0.5	0.5	3	5	8
Mali	50	20	10	60	40	100
Mauritania	0.1	0.3	0	0.4	11	11.4
Niger	1	2.5	0	3.5	29	32.5
Senegal	23.8	7.6	5	26.4	13	39.4
Somalia	5.7	3.3	3	6	7.5	13.5
Sudan	28	7	0	35	119	154
Gulf of Guinea	925.8	320.5	294.5	951.8	142.4	1,119.5
Benin	10	1.8	1.5	10.3	16	25.8
Côte d'Ivoire	74	37.7	35	76.7	1	77.7
Ghana	29	26.3	25	30.3	22.9	53.2
Guinea	226	38	38	226	0	226
Guinea-Bissau	12	14	10	16	11	27
Liberia	200	60	60	200	32	232
Nigeria	214	87	80	221	59	280
Sierra Leone	150	50	40	160	0	160
Togo	10.8	5.7	5	11.5	0.5	12
Central				*1,946*	*694*	*2,640*
Angola	182	72	70	184	0	184
Cameroon	268	100	100	268	0	268
Central African Republic	141	56	56	141	0	141
Congo	222	198	198	222	610	832
Equatorial Guinea	25	10	5	30	0	30
Gabon	162	62	60	164	0	164
Sao Tome and Principe				2.18	0	2.18
Zaire	934	421	420	935	84	1,019

Eastern	*374*	*67.7*	*59.5*	*259.1*	*46*	*305.1*
Burundi	3.5	2.1	2	3.6	0	3.6
Ethiopia				110	0	110
Kenya	17.2	3	0	20.2	10	30.2
Rwanda	5.2	3.6	2.5	6.3	0	6.3
Tanzania	80	30	30	80	9	89
Uganda	35	29	25	39	27	66
Southern	*209.9*	*79.6*	*21.5*	*270.61*	*211.01*	*482.62*
Botswana	1.7	1.7	0.5	2.9	11.8	14.7
Lesotho	4.73	0.5	0	5.23	0	5.23
Malawi	16.14	1.4	0	17.54	1.14	18.68
Mozambique	97	17	17	97	111	208
Namibia	4.1	2.1	0	6.2	39.3	45.5
South Africa	40	4.8	0	44.8	5.2	50
Swaziland				2.64	1.87	4.51
Zambia	33.1	47.1	0	80.2	35.8	116
Zimbabwe	13.1	5	4	14.1	5.9	20
Indean Ocean Islands	334.03	55.68	50.5	340.23	0	340.23
Comoros				1.02	0	1.02
Madagascar	332	55	50	337	0	337
Mauritius	2.03	0.68	0.5	2.21	0	2.21
Seychelles	–	–	–	–	–	–
TOTAL	372.1	1,517	1,370	3,988		

Source: FAO, 1997.

Per capita availability in Africa is 5,555 m^3, which is fairly high compared to the world's average (7,300 m^3 per person per year according WMO, 1997). The main problem however is not total water availability, but the uneven distribution of water resources in space and high rainfall variability, exacerbated by recurrent drought. The Congo-Zaire river basin alone carries about one third of the river flow in all Africa. The lowest water availability is found in North Africa, where it is as low as 160 and 250 m^3/yr, in Libya and Djibuti, as can be seen from the Table 5.5.2.2 (Khouri, 2001).

Table 5.5.2.2 Per capita availability in water scarce countries in Africa

Country	*Population*	*Per capita water availability (m^3/year)*	*Water scarcity*
Libya	6,562	160	Very high
Djibuti	991	252	
Algeria	32,360	464	High
Tunisia	9,480	489	
Egypt	68,520	870	Moderate
Morocco	28,780	1,042	

Groundwater resources were estimated at 1,517 km^3. Of this amount some 1,370 km^3 flows into river courses to sustain the base flow. Thus groundwater which flows into the sea or into sabkhas (desert depressions) is of the order of 147 km^3. Since groundwater occurrence is arealy extensive, and it is less vulnerable than surface water, it constitutes the main source for rural water supplies

and for the domestic water supply of small urban countries, and for these reasons it is developed irrespective of the impacts of development on the base flow of river systems. A conjunctive and integrated use is, however, a fundamental need in many areas.

5.5.3 Hydrogeology of Africa, major basins

As mentioned above, much of the equatorial rainforest zone of Africa is occupied by the crystalline basement, which has very small groundwater storage capacity. Recharge in this zone is, however, high. On the other hand the extensive arid belt of the northern part of Africa, and the deserts of the southern part of Africa (Kalahari and Namib deserts) are underlain by large sedimentary basins, characterized by large reserves and very low recharge. These dry regions have very low population density, whereas the tropical regions are, generally, densely populated. An initial impression could be that deserts and sahara (hyperarid deserts) are the least predictable of all environment. People living in the Sahara, however, know what to expect and are able to cope with it. It is true that unforeseen cloud threaten desert inhabitants: the torrential rains and subsequent flooding in upper Egypt in November, 1994, and the unexpected rainstorm at the Jalo Oasis in Libya (Abdusalaam, 1978) are examples of this phenomenon (Biswas et al., 1997).

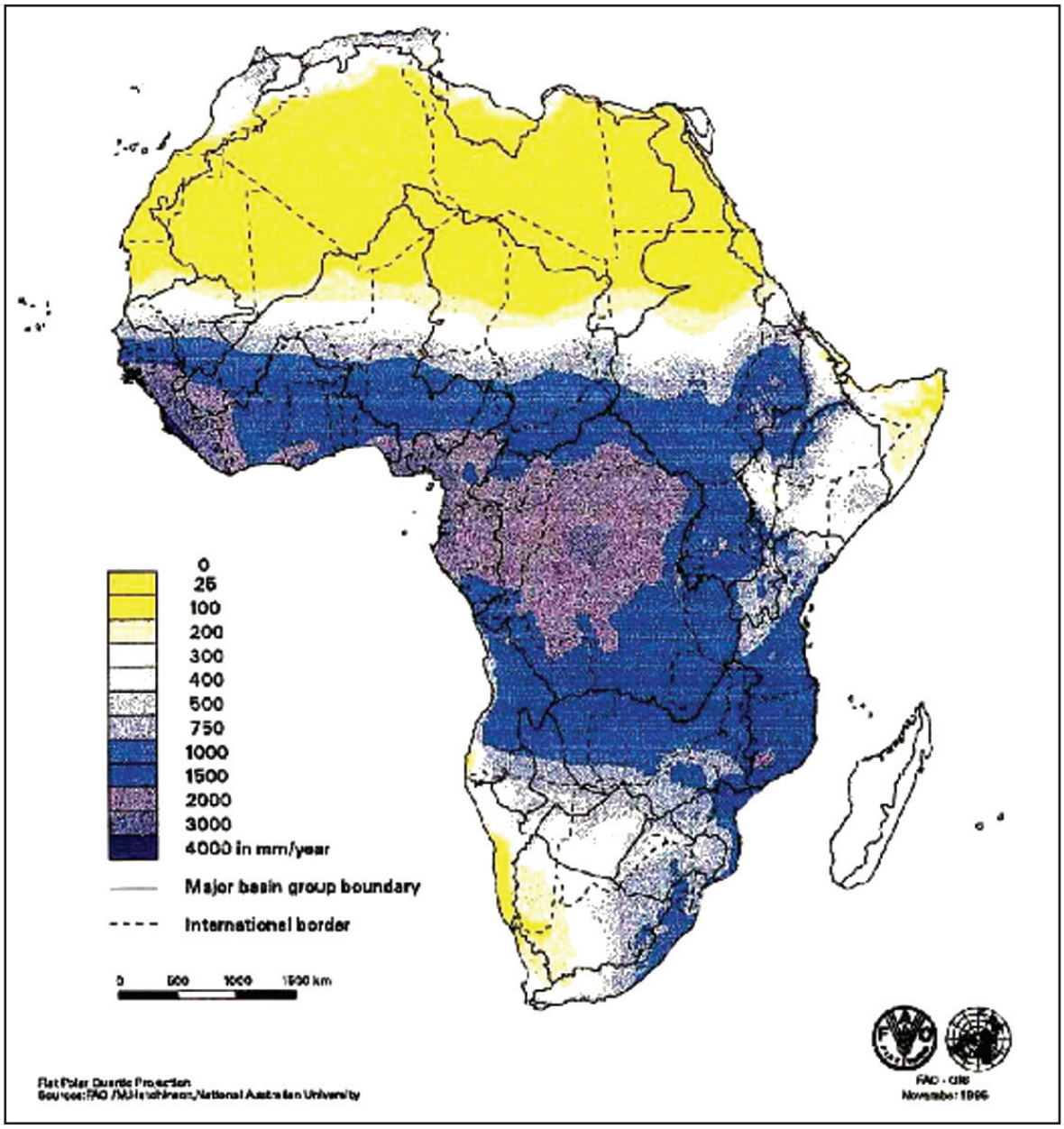
Variation of precipitation through time and limited availability of groundwater, which characterize and semi-arid belts of Africa, presents the greatest challenges to the management of water resources of these parts of Africa. Variance in precipitation increases as desert conditions are approached. That is the dryer the climate the more unpredictable precipitation becomes, and as the predictability of rainfall decreases, the predictability of drought becomes more certain (Biswas et al., 1997). The Sahelian zone, is characterized by erratic rainfall, frequent droughts and flash floods.

In the semi-arid areas of Kenya, mean annual rainfall ranges between 700 and 200 mm. The high evaporation rate, about 2,300 mm/yr, accompanied by unreliable rainfall makes these areas prone to droughts the frequency of which ranges between 4 and 7 years interval. The Sahelian and Sudanian zone as well as many other semi-arid areas in Africa, present some of greatest challenges to modern water management. Human beings, however, can survive and adapt to extreme wet or dry climates (Fig. 5.5.3.1).

Vulnerability has been defined as 'an intrinsic property of a groundwater system to human and/or natural impacts (Vrba and Zaporozec, 1994). The definition includes quantity as well as quality of groundwater. The sensitivity of aquifers to drought depends on the amount and mode of recharge whether direct from precipitation or indirect from 'Wadi' flow. The latter is the most important source in semi-arid zones (Edmunds et al., 1987). The development of the concept of groundwater vulnerability to include quantitative aspect simulates mapping activities in this context. Such maps would be of considerable value for the estimate of potential vulnerability to drought and would be an important tool for drought preparedness planning (Khouri and Miller, 1994). Methods of assessment of susceptibility of aquifer systems to exploitation side-effects have been proposed as important tool for planning and management of groundwater resources (Adams and McDonald, 1995).

Groundwater susceptibility was presented as a potential adjunct to aquifer vulnerability in order to provide resource managers with an additional method of evaluating potential aquifer degradation resulting from intensive development in semi-arid zones. Vulnerability in terms of quantity is of special importance to groundwater management of the semi-arid zones of Mediterranean and Sahelian zones. It would be equally pertinent to consider groundwater vulnerability to desertification in these regions, since desertification tends to increase runoff and decrease infiltration. Areas of aquifers that are sensitive to drought are usually the most vulnerable to desertification (Khouri and Miller, 1994).

Figure 5.5.3.1 Average annual ranfall in Africa



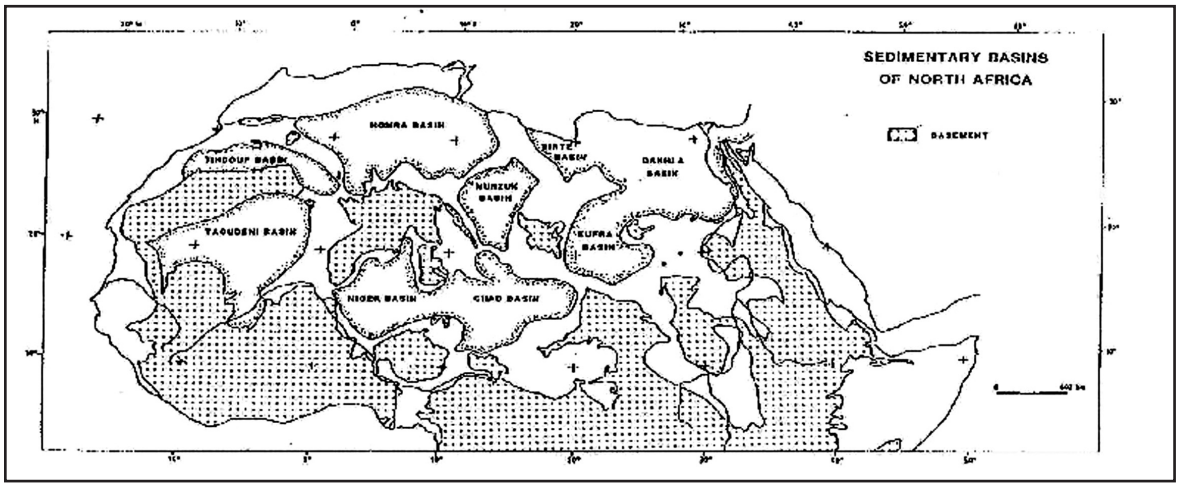
Most of the coastal plains are underlain by alluvial, proluvial or limestone aquifers. These phreatic aquifers, receive abundant rainfall and/or are recharged from perennial or ephemeral (wadis) rivers or even from large continental rivers. Most of the large cities of Africa are situated in these coastal plains.

On the basis of this brief review of the hydrogeological conditions in the continent of Africa, the following major groundwater basins are recognized.

In the arid and semi-arid zones north of the equators the following basins have been delineated (Fig. 5.5.3.2) (Margat and Saad, 1984):

- The Nubian basin;
- The Sahara basin;
- The Chad basin;
- The Niger basin;
- The Taoudeni basin.

Figure 5.5.3.2 Major groundwater basins in North Africa (Source: Thorweihe and Heinl, 1996)

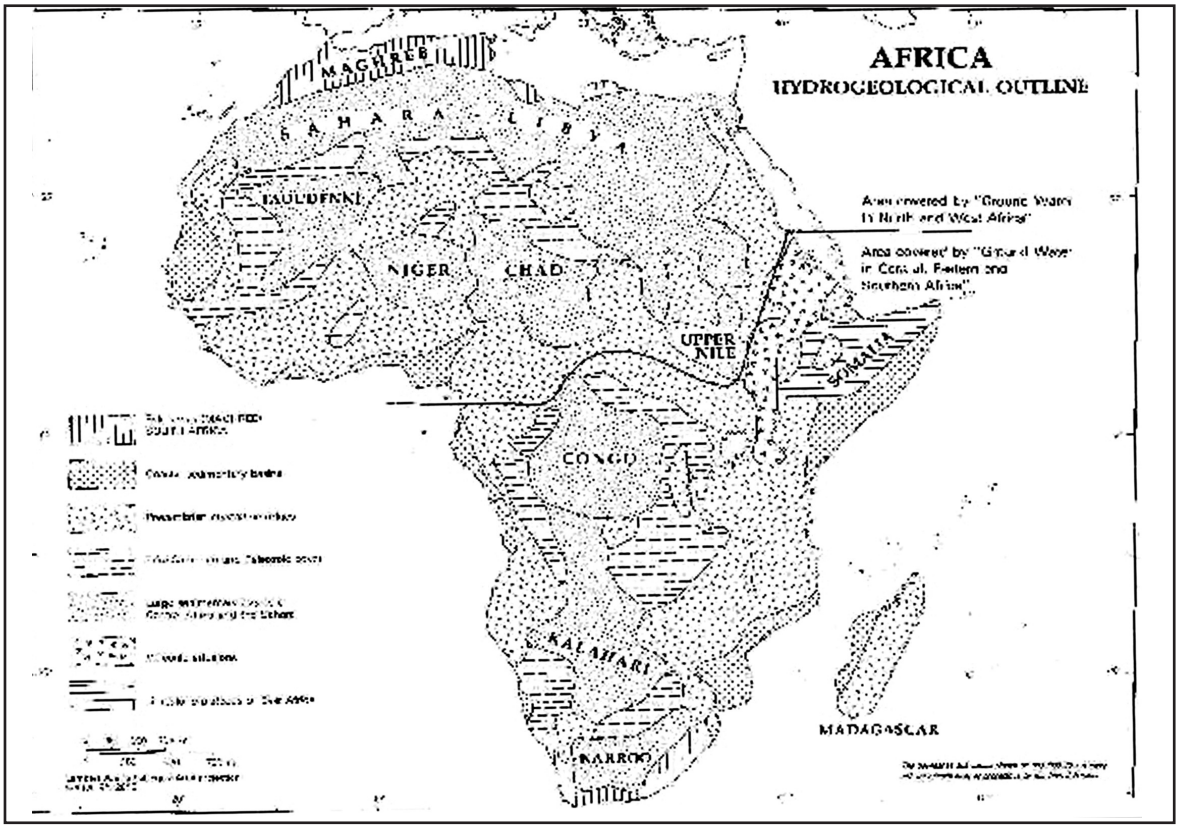


In the equatorial zone and south of the equater three large basins are recognized (Fig. 5.5.3.3) (UN, 1989):

- The Congo basin;
- The Kalahari basin;
- The Karro basin.

In the coastal zones, several basins have been recognized in Africa, north and south of the equator. Although they are normally, narrow and of limited areal extent, they are of almost importance, for these populated areas, and many of them have been intensively developed for urban and rural water supplies.

Figure 5.5.3.3 Major groundwater basins Africa (Source: United Nations, 1989)



5.5.3.1 The Nubian Basin

Regional basins are of widespread occurrence worldwide. In earlier decades groundwater investigations started often at the local level, within national boundaries and were rarely concerned with regional aquifer systems. In the last decades the study of regional aquifer systems, received increasing attention. In evaluating the impacts of development on groundwater resources, on the basis of local studies, questions have often risen regarding the extent of the development effects beyond the areas that were studied locally. Regional aquifer systems underlying large basins usually comprise an extensive set of aquifers and confining units that act on the regional scale as a single system. The objectives of regional studies is to provide complete description of the hydrogeology, hydraulic properties, regional flow system and water quality. The effects of development are assessed using maps of estimated pre-developmented potentiometric surface and a series of post-development potentiometric maps.

The extent of regional basins varies widely. In the United States of America, a Regional Aquifer System Analysis program conducted during the period 1978–92 by the U.S. Geological Survey delineated 25 regional aquifer systems underlying large basins ranging typically, between 100,000 and 600,000 km^2 (Sun and Johnston, 1994).

The great basins of the northern part of Africa rank among the largest regional basins in the world. The largest of these basins, underlain by the Nubian regional aquifer system encompasses about 2.5 million km^2 in parts of Sudan, Chad, Egypt and Libya (Fig. 5.5.3.1.1).

The Nubian groundwater reservoir contains huge reserves estimated at about 150,000 km^3 (Thorweihe and Heinl, 1996). It offers to countries sharing the basin an important source of freshwater which could contribute substantially to their socio-economic development. The rate of recharge, however is so low that the water of the aquifer system is considered to represent, to a large extent, a nonrenewable resource at the human time-scale. The need therefore arose for a special conception of the groundwater resources and special approaches for their assessment and management.

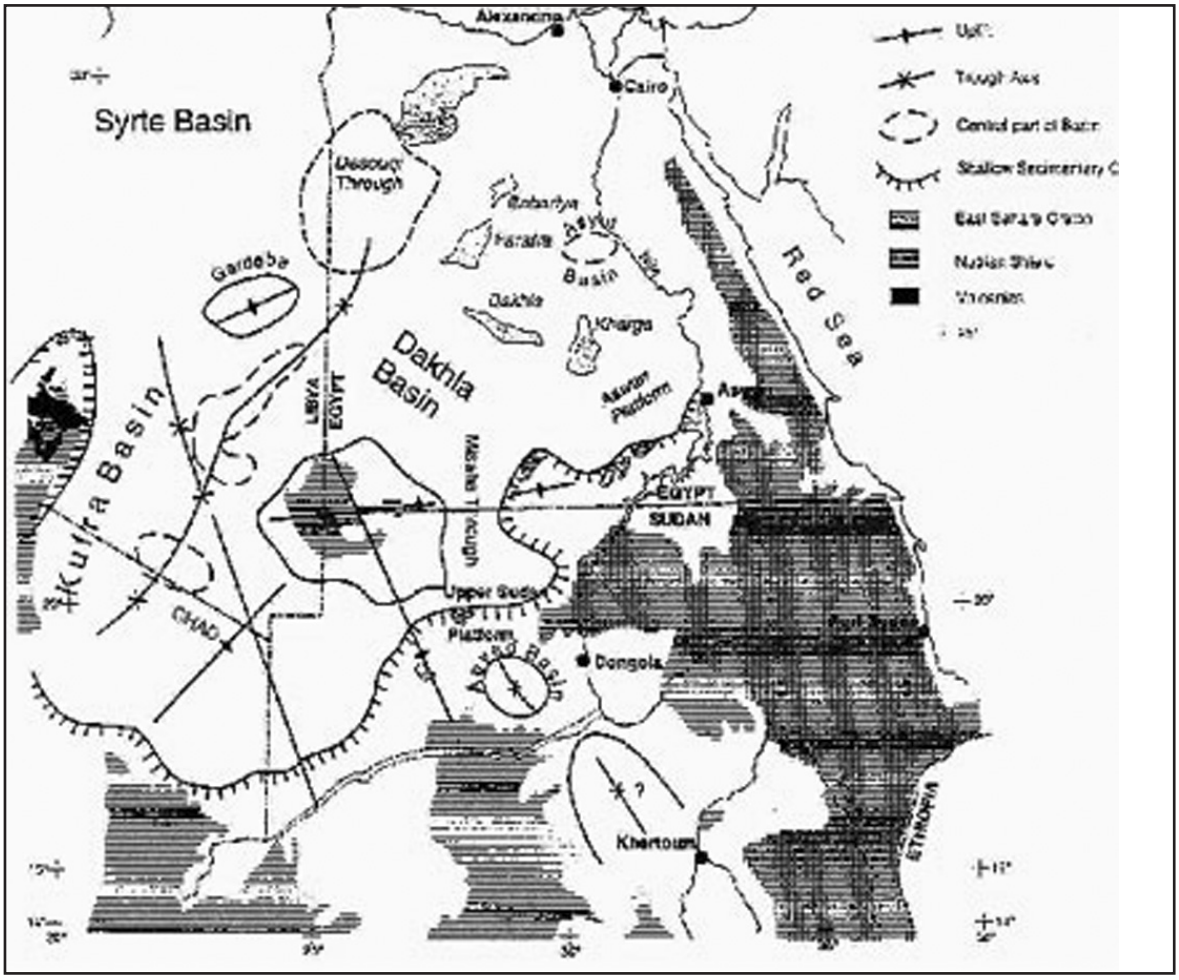
The regional hydraulic continuity in the Nubian Aquifer System permits the development of regional and sub-regional models which could be utilized to understand and analyze the groundwater flow patterns, provide quantitative information on the regional assessment of the aquifer system and furnish boundary conditions for sub-regional and local simulation studies. The countries sharing the aquifer system have recognized the importance of co-operation to improve the management of its groundwater resources. The investigation of the regional aquifer system can establish common principles that could guide future developments in the countries concerned. The regional study is needed to establish a framework of background information, that can be used for the regional assessment of the groundwater resources and in support of more detailed local studies.

Hydrogeology of the Nubian Basin

The Nubian Aquifer System includes two major sedimentary series. The first series consists of continental clastic sediments, mainly sandstone, ranging in age from Cambrian to Lower Cretaceous. The second series includes marine sediments, composed, generally, of clays, marls and limestones. They range in age from Upper Cretaceous to Eocene. They are overlain by an upper continental formation, of Neogene age, which is important locally as a source of fresh ground-water. The Neogene sandstone aquifer exhibits, however facies variation in the northern parts of Libya and Egypt where it passes laterally into carbonate facies.

Several sub-basins and uplifts have been recognized in the area underlain by the Nubian

Figure 5.5.3.1.1 Structural highs and lowes in the Nubian Basin (Source: Thorweihe and Heinl, 1996)



Aquifer System (Fig. 5.5.3.1.1). These structural features have developed since the Paleozoic times through uplifting, block-faulting and downwarping.

The structural highs separate a number of major basins which include:

1. The Dakhla Basin;
2. The Kufra Basin;
3. The North-western Basin (Egypt).

To the south of the Uweinat-Safsaf-Kharga uplift, slow rate of subsidence has resulted in the deposition of limited thickness of continental sediments in the Aswan Platform and Northern Sudan Platform. Sedimentation began in the Santonian in the former basin and was initiated in the Permian in the latter basin. Extensive sedimentation and relatively higher rate of subsidence occurred during the Cretaceous in sub-basins formed in the Northern Sudan platform. These are the Dongola sub-basin, Abyad sub-basin and Salima sub-basin (Iskander et al., 1994, OSS, 1996).

Sedimentation in deeply subsiding basins occurred over a large area in Northwest Sudan, Chad, Libya and Egypt. Uplifts and downwarping have influenced the depositional environment. In general., thick predominately, continental clastic deposits of Paleozoic and Mesozoic age accumulated in the Kufra and Dakhla basins, whereas marine carbonates predominate in the northern 'coastal' basins of Egypt and Libya. After the Eocene, continental environment was established. Post-Eocene deposits consists chiefly of sands and sandstone. The continental 'Miocene' sediments which form an upper fresh groundwater reservoir pass northward into carbonate

formations with evaporites. This change in facies corresponds to a change in the quality of water, which becomes brackish and eventually saline.

The rocks of the Nubian Aquifer System vary in thickness from featheredge in outcrop areas to more than 3,000 m in the central part of the Kufra and Dakhla basin and range in age from Cambrian to Neogene. About 15 formations were recognized in eastern Libya and 12 formations in western Egypt. In Sudan and Chad the Nubian succession is much thinner comprising only few lithological formations.

The inclusion of higher lithostratigraphic units in the Nubian Aquifer System was considered essential for modeling of the system and for the investigation of the influence of upper aquifers on the regional aquifer system in terms of quality and quantity if a regional aquifer are designated by the letter A and a regional confining unit by the letter C the following regional hydrogeological units could be recognized:

A1 Miocene sandstone aquifer;
C1 Tertiary carbonate aquitard;
A2 Mesozoic (Nubian) sandstone aquifer;
C2 Mesozoic clay-silt aquiclude;
A3 Upper Paleozoic-Mesozoic sandstone aquifer;
C3 Paleozoic shale aquiclude;
A4 Lower Paleozoic (cambro-Ordovician) sandstone aquifer;
Basement.

These components of the Nubian Aquifer System constitute the principle elements of the hydrogeological framework and since available information indicate a hydraulic continuity within this framework, they could be utilized for the development of a conceptional model.

The groundwater of the Nubian Basin is generally characterized by its high quality. The total dissolved solids range from 100 to 1,000 ppm. Salinity increases northward. The freshwater saline interface passes through Qattara depression. In Libya the TDS of the deep Nubian aquifers ranges from 160 to 480 mg/l and from 1,000 to 4,000 mg/l in the shallow aquifers (Salem, 1991).

The Flow System

Regional flow is controlled by major uplifts developed in the basement and resulted in the sub-division of the 'Great Nubian Basin' into several sub-basins. Groundwater that flows in the transition zone from North Sudan Sub-basins to the Dakhla basin in Egypt can only pass through the Misaha trough between Jabal Uweinat and Bir Safsaf (Fig. 5.5.3.1.1). Thorweihe and Heinl (1996) estimated that only 380×10^6 m^3 passes yearly in Egypt. Similarly the outflow from the Kufra basin to the Dakhla basin across the transition zone developed through an uplift in the basement is estimated at 10–160 mcm/yr (Wright et al., 1982).

Analysis of recharge conditions must relate not only to current climatic periods, but also to previous climatic conditions. The overwhelming part of the region underlain by the Nubian aquifer system is hyper-arid. The average precipitation in Kharga and Dakhla is 0.3 mm/year. Present rainfall over east-central Libya is less than 25 mm. In the elevated parts of the Ennedi Mountains, in Chad, the mean annual precipitation is about 200 mm and in the Tibesti Mountain the precipitation amounts to 100 mm. In Northern Sudan runoff occurs in Wadi Howar and Wadi al Hawad (Edmunds et al., 1987). Using geochemical techniques Edmunds estimated direct recharge to the aquifer in the Butana (Khartoum) area with around 200 mm precipitation at 0.3 to 3.45 mm/yr.

Radiocarbon age dating indicates that groundwater formed in the Pleistocene in pluvial periods older than 20,000 years and in the Holocene between 14 000 and 4 000 P.B. However, the bulk of groundwater mass probably stems from humid climatic cycles ranging over 100,000s or

1,000,000s of years. With the Helium-Argon method the age of water in the deeper zones was determined to be some 1–2 million years (Himida, 1969).

The Nubian aquifer system is a continuous regional system. However groundwater flow is limited by relatively small gradients, accordingly, most of the recharged water flows to discharge areas nearby. Only a minor part reaches more distant areas at low levels. The regional flow across the system is very small compared with the flow within subs-basins.

However, the quantitative estimates of recharge, the quantities of water transmitted through the system and the relative importance of modern and paleorecharge in groundwater formation should be examined in the light of several controlling factors. These include hydrogeologic, structural and climatic factors.

Based on the estimates of the regional hydraulic parameters (gradient 3×10^{-4}, hydraulic conductivity 10^{-5} m/sec, and effective porosity 10%), the groundwater flow velocity was estimated at 1 m/yr. Thus the groundwater needs about one millions years to pass through the system from recharge areas at the southern boundary to the Qattara discharge area. During this time climatic changes including several humid periods occurred and provided recharge for 'local groundwater formation'.

Simulation of the regional flow in the Nubian Aquifer System showed that groundwater mainly formed by local Paleorecharge (Thorweihe and Heinl, 1996). The natural discharge of the whole system decreased from 2,400 mcm/yr 8,000 years ago to 500 mcm today. Groundwater thus flows between areas of former 'Paleo-' recharge to discharge areas. Groundwater was formed to a great extent during the post-pluvial periods in the unconfined parts of the aquifer. These parts of the aquifer system has been involved in a depleting process for several thousands years.

Isotopic investigations have made an important contribution to develop understanding of the groundwater flow system and support better groundwater resources management. If the configuration of the potentiometric surface is considered an indication of an effective regional groundwater flow, this flow runs in a north and northeast direction and therewith more or less along the iso-contours of stable isotopes. For this reason a possible regional groundwater flow in the study area is inferred on the basis of stable isotope contents in D and ^{18}O.

An important feature of the Nubian aquifer system is the occurrence of a sequence of oases within the extensive confined area. This discharge pattern is known as the 'New Valley' and is believed to be controlled by facture zones associated with stractural high areas (Lloyd, 1990).

Several models of different scales and techniques have been constructed in the past decades; analog, finite element and finite difference models. At the regional (basin) level only one model has been developed by the Technical University of Berlin. Different models constructed in each of the participating countries are sub-regional or local models. Because the regional and sub-regional models were developed to simulate aquifer systems of tens or hundreds of thousands square kilometers, the discretization of the systems is relatively coarse. Accordingly the model block area is too large for these models to be used to address specific groundwater problems. Local models with a smaller block size (4 km^2 or even less) are generally required.

The regional model is a two-dimensional horizontal finite element model was used for the simulation of the Nubian aquifer system. The finite element grid covered an area of about 2 million km^2 (Fig. 5.5.3.1.1), thus a long distance flow from Chad to Qattara depression in Egypt was nodeled as well as the transition from semi-arid climate to present day hyper-arid conditions (Thorweihe and Heinl, 1996).

Two phases, long-term due to climatic change (8000 BP to present day) and short term (1960–80) were simulated in the same model. Only different steps (100 years, 52 days) were used.

The model was based on hydraulic conductivities obtained from pumping tests carried out only in the Mesozoic sediments in the aquifer system. The hydraulic parameters for the Paleozoic deposits have not been defined. The hydraulic conductivity of these sediments has been deter-

mined through evident comparison with Mesozoic sediments of similar composition (Thorweihe and Heinl, 1996) (Fig. 5.5.3.1.1). The numeric simulation of the groundwater flow has used the interpreted values of the hydraulic conductivity in a resolution of one order of magnitude, and also the interpreted values of the transmissivity of individual lithological units in the various hydrogeological provinces.

The first simulation supposed filled-up conditions, i.e., considered that the aquifer has been filled during pluvial periods. Simulation of long-term decline due to climatic change indicated a drop of water level during the last 8,000 years of about 60 m to 100 m in each 1,000 years.

The simulated drawdown showed different behavior in elevated and low areas. In the Tibesti Mountains the groundwater level dropped more than 100 m. On the plateau the groundwater level dropped 60 m in 1,000 years. In the depression appreciable drawn does not occur as long as they remain natural discharge areas. However simulation indicated diminished discharge. The natural discharge of the whole system decreased during 8,000 years from 2,400 million m^3/yr to 500 mln. m^3/yr. Withdrawal in 1980 was about 500 mln. m^2/yr (Thorweihe and Heinl, 1986). This is negligible compared to the total water mass estimated at 150,000 km^3 (with effective pare volume at 7 to 10%), and the same order of magnitude as the natural groundwater discharge planned extraction in Egypt (E-Uweinat, New Valley) and Libya (Sarir, Tazerbo, Kufra) is estimated in 1986 at 5 km^3/yr (Therweihe and Heinl ,1996). The impact of this extraction has been simulated for the period 1990–2070. The model predicts a maximum drawdown of 130 m in Bahriya and Farafra, and 100 m in E-Uweinat. The five projects in Kufra, in Libya with a combined extraction 1,100 mln. m^3/year would form drawdown cone with a maximum depth of 50 m. This is much less than the E-Uweinat project because the aquifer is much thicker in Kufra and the extraction is distributed over a large area.

5.5.3.2 The Sahara Basin

The Sahara basin covers an area of about 780,000 km^2. It is underlain by two major aquifers:

1. the Lower aquifer: the 'Continental Intercalaire (CI), composed of continental sediments.
2. the Upper aquifer: the 'Complex Terminal (CT), multilayered aquifer consisting of sandstones and limestones.

The Sahara basin includes two sub-basins separated by the M'zab high. The western Timimoune basin occupies about 280,000 km^2 and is covered by the sand dunes of the Great Western Erg. The Eastern Mya basin extends over area of about 500,000 km^2 and is covered by the Great Oriental Erg (Khouri and Droubi, 1990; Nouiouat, 1993). The Lower aquifer consists of continental sandstone alternating with orgillaceous layers. It extends from the Hoggar highlands in the south to the Saharan Atlas in the north. The thickness of the Lower aquifer ranges between 200 and 1,000 m. It decreases northeastward to 125 m at Gharso Chott.

The lower confining unit consist of orgillaceous and marly formations of Devonian-Teriassic age. The upper confining units consist of evaporites and clays of Cenomanian age.

The lower and upper aquifers are almost independent in the west, in Algeria. Towards the Mediterranean coast they are interconnected or merge to form one aquifer system. The Sahara aquifer system is generally considered a nonrenewable aquifer system (OSS, 1995). Groundwater movement is towards the south and southwest in the western sub-basin. In the eastern sub-basin groundwater flows towards discharge areas, mainly desert depressions, 'Chotts' in Algeria (Chott Melrbir) and Tunisia (Chott Djerid). Discharge occurs through traditional canat systems (Foggaras). Some 570 foggaras discharge about 90 mln. m^3/yr.

Groundwater reserve is estimated 60,000 km^3 (Zitoun and Droubi, 1992). In Algeria production from the Sahara basin commenced in the middle of the 19th century, mostly in Oued Rhir oasis. Exploitation of the aquifer systems was through artesian wells, withdrawal of water from

the aquifer system was about 150 mln. m^3 until 1940. Since then pumpage increased to about 260 mcm (OSS, 1995). In south Tunisia, exploitation of the upper Terminal Complex aquifer was exclusively from wells. Withdrawal increased from 0.3 m^3/s in 1900 to about 6 m^3/s in 1995 (OSS, 1995).

The impact of intensive development on the aquifer system was observed in discharge areas. In Algeria the flow of springs decreased from 200 l/s in 1900 to 6 l/s in 1970, whereas in Tunisia. The flow from Djerid and Nefzaoua springs decreased from 2.5 m^3/s in 1900 to virtually nil (less than 30 l/s) in 1990 (Mamou, 1990).

In the western basin, the total dissolved solids of groundwater in the Lower aquifer ranges from 0.5 to 1 g/l. It increases and eastwards to 5 g/l. The concentration of dissolved solids water in the upper aquifer is about 2 g/l in southern areas of the Great Eastern Erg and in the North of Ouergla. Increase of concentration from 2 to 5 g/l occur in Tozeur in the north of the Great Oriental Erg and Ourgla and reaches 8 g/l in discharge areas (Hassi Messaoud, El Hadjima).

5.5.3.3 The Chad Basin

The Chad basin is a huge depression underlying 250,000 km^2, extending between Tebesti and Hoggor Precambrian massifs in the north and the Ouaddai and Adamaoue massifs in the south. It communicates with several large basins: the Niger basin in the west, the Murzuk basin in the north and the Benue basin in the southwest. The degree of interconnention with these basins is not, however, clearly defined.

The recurrent faulting and rifting is reflected in great variation in the depth of the basement and in the development of of uplifts and grabens or tectonic basins. The latter negative structures include:

1. Termit and Tedifet graben,
2. Djado basin,
3. Bilma basin,
4. Agadem basin.

Uplifts or positive structures include the Damergon shelf, which separates the Chad basin from the Niger basin. In this region a detrital series was deposited which constitutes the Tegama or Continental Intercalaire aquifer composed mainly of sandstone. In the Termit – Tefidet graben, the continental Intercalaire is represented by the Tefidet group. The Termit and Agadem basin, further east are filled with sandstone and clay formations. These include the Termit sandstone and agadem formation consisting of fine-grained sandstone and gypsiferous clays. In this region there are little hydrogeological data, although favorable hydrogeological conditions seem to exist.

The Lake Chad Basin is underlain, mainly, by Pliocene and Quaternary formations. These detrital formations outcrop to the east of Lake Chad. The Bodele formation outcrops north of the lake and the Chari-Baguirimi formation underlies areas located south of the lake. It is composed of sand, clay and gravel. Bahr el Ghazal series, occurring to the north east of the lake consist of sands, clays and limestones. The upper phreatic Quaternary aquifer consists of sandy, deltaic and lacustrime deposits. It is a regionally extensive aquifer extending from Chad to eastern Niger, northwestern Nigeria, northern Cameroon and the Central African Republic.

Recharge to the phreatic aquifer is from precipitation and occurs chiefly in the Chari-Salamat region and in the areas bordering the Guera and Batha massifs in the eastern zones. Recharge also occurs in the Piedmont zone in the south. Surface water runs from mountainous areas and Piedmont zones and infiltrates into the phreatic aquifer.

The potentiometric surface of the upper aquifer system is characterized by the existence of several anomalies: dome shaped and sunken or depressed areas; these anomalies were observed in several countries in West Africa: Senegal, Mauritania, Burkina Faso and Mali. The largest

depression is formed in Chad, in Bodele area where the lowest point of the depressed zone lies at 160 m above sea level and at 120 m below the level of Lake Chad. Many interpretations were put forward to explain this phemonon. The most possible attributes their formation to the influence of evaporation (OSS, 1992; Nouiouat, 1993).

The Pliocene aquifer system underlies 130,000 km^2 in Chad and could be tapped at a depth of about 300 m in the center of the basin. In the lake Chad basin it occurs under confined conditions, and constitutes an important source of freshwater. The Pliocene confined aquifer is a regional aquifer system. Trammissivities based on pumping tests, carried out in the area adjacent to lake Chad, range between 10^{-3} and 10^{-2} m^2/s. Groundwater is slightly mineralized. The concentration of dissolved solids ranges between 500 and 1,500 mg/l.

The continental Terminal aquifer system consists of sandstone and argillaceous sands. The aquifer occupies in Chad two separate areas: in the north it underlies 130,000 km^2 and lies at a depth of 80–100 m. It is exploited by traditional wells whose depth may reach 100 m. In the south, the aquifer system covers an area of about 160,000 km^2 in Middle Chari and Tandjile. The aquifer is only slightly developed. It can be taped at a depth 350 in the centre of the basin. It is, however, heavily exploited in the region of Maiduguri, in Nigeria.

5.5.3.4 The Niger Basin

The Niger basin extends for about 1,000 km from the Hoggar Pre-Cambrian massif, in the North to the Nigerian Shield in the south, and extends over 800 km from east to west. In the east it communicates with the Chad basin through Damergou shelf, a subsurface extension of the Air massif, and to the west it communicates with the Taoudenni basin through the Sudan graben.

Situated in the southern Sahara and northern Sahelian belts, the Niger basin is a relatively deep basin filled with a thick sequence of sedimentary rocks ranging in age from Paleozoic to Quaternary. The sedimentary succession consists predominantly of continental sandstones overlain by Cretaceous limestones. The higher stratigraphic horizons (Campanian to Pliocene) consist of an alternation of sandstone, sands, clays and limestones. This complex range of detrital and carbonate sediments can be classified into four hydrogeological units or major aquifers (Noouiouat, 1993; Khouri and Droubi, 1990):

1. the Lower continental sandstone aquifer system;
2. the Tegama 'Continental Intercalaire' aquifer system;
3. the Upper Cretaceous carbonate aquifer system;
4. the Upper Continental aquifer system: 'Continental Terminal'.

The Lower continental sandstone aquifer system consists of two major aquifers: the Izeguandane aquifer and the Agades-dabla aquifer. Both aquifers are composed primarily of sandstone and overlain by clayey confining layer (the Irhazer clays). The aquifer system covers an area of about 50,000 km^2, and is recharged from wadi runoff in the large outcrop areas of the air. Recharge is however small compared to the large reserves estimated sat 1,500–3,000 mln. m^3. Groundwater is slightly mineralized ranging from 700 to 3,000 mg/l.

The Continental Intercalaire aquifer systems, consists of continental sediments, mainly sandstones; the Tegama sandstone and Farak series. It underlies some 488,000 km^2. It is a water-table auqifer in the eastern part of the basin and confined in the central and southern parts, where it is overlain by the Upper Cretaceous and the clay formation of the Rima Group. The Average thickness of the aquifer is 500 m in the greater part of Niger and ranges from 240 to 500 m in Nigeria. It reaches about 1,000 m in the western areas (Nouiouat, 1993) age.

The Upper Cretaceous formations are predominently low-permeability marine deposits. The sandy formations of the Maestrichtian are moderately productive and their waters have relatively low concentration of dissolved solids (600–3,000 mg/l).

The higher aquifer system, the Complex Terminal, consists of three aquifers, the lower aquifer consists of coarse sands with clay intercalations. Its thickness varies from 30 to 75 m, and the aquifer is confined over almost all its extent. The regional flow is southword and discharge occurs in the Dallol Basso lowlands. Groundwater is fresh, the concentration of dissolved solids is about 200 mg/l.

The Middle aquifer consists of fine and coarse sand the thickness ranges between 20 and 30 m. It occupies the central part of the Doutchi syncline, where it is confined. In the marginal zones the middle aquifer merges with other phreatic aquifers. The upper aquifer is a water-table aquifer consisting of sands and alluvium. It covers the Dautchi synclinal basin. The thickness of the aquifer varies from featheredge to 60 m. Recharge occurs in the periphery of the Doutchi syncline, leackage from the lower aquifers is probable. Transmissivity values are of the order of 10^{-3} to 10^{-2} m^2/s. Groundwater is generally fresh (100 mg/l) As is the case in Chad one notes the phenomena of domes and sinkholes in the phreatic aquifer.

5.5.3.5 The Toudeni Basin

The Toudeni basin is one of the largest basins in the world. It covers an area of about 1.8 mln. km^2. It extends between the extensive Precambrian massifs of Sierraleone- Liberia, in the south, Reguibat massif in the north, Touareg massif in the east and the folded structures of Mauritanides in the west.

Major aquifer systems in the Taudeni basin include:

1. *Fissured aquifer systems:*
   Precambrian aquifers,
   Infra-Cambrian and Paleozoic aquifers.
2. *Intergranual aquifer systems:*
   The Continental Intercalaire aquifer system,
   The Continental Terminal aquifer system.

The Precambrian basement form generally poor aquifers. Groundwater could be tapped however in fracture zones., The depth of groundwater varies from few meters to 100 m. In the northern arid parts of the basin well yields range between 0.08 and 1.1 l/s. In the southwest, in the Upper Niger, which receive high rainfall, well yields may reach 8 l/s. Water, is however, aggressive with pH values between 5.5 and 7.7. The concentration of dissolved solids is generally low, less than 500 mg/l.

The fractured infra-cambrian sandstones are aquiferous in their upper parts, down to a depth of some tens of metres. The water table lies at a depth of 10 to 25 m. The aquifers depth may reach 60 m. Mineralization is low, about 300 mg/l.

The Continental Terminal aquifer system underlies large areas in the North-Sahelian and Saharian zones. The hydrogeological conditions are known in the western areas and southern border of the Adrar des Iforas. On the border of Adrar des Iforas. Confined groundwater could be tapped at a depth of about 100 m. The depth of the potentiometric surface, ranges between 35 and 60 m. Productivity is generally low, even in wells drilled into a depth of 150–200m.

The Continental Terminal aquifer system consists of sands and sandstones. In the interior delta of the Niger river, the Continental Terminal aquifer is recharged from surface water. It is also hydraulically connected with the overlying Quaternary alluvium.

Groundwater in the flood plain, is developed in a traditional manner by a large number of wells ranging in depth between 20 and 60 m. The concentration of dissolved solids is low (80–100 mg/l) in the Niger Delta areas, where recharge is relatively high. It increases northwards to about 3,500 mg/l.

In the Sudanes Strait, water levels are generally more than 40 m. They increase westward and southward, in Gao ara to a depth exceeding 100 m.

To conclude, recharge in the Taudenni basin is very low, or negligible, in the northern part, but relatively high in the south. The Niger river plays an important role in this respect. Recharge of the Paleozoic sandstone occurs mainly in southern part of the basin, whereas replenishment of the Continental Intercalaire aquifer system occurs mainly in the central delta of the Niger River. Concentration of dissolved solids in groundwater increases, generally, from the peripheral zones towards the center of the basins and, in the alluvial aquifer, from upper reaches to the lower reaches of the Niger river.

5.5.3.6 The Congo Basin

The Congo basin underlies over 1 mln. km^2 in parts of Zaire, Congo and Angola. Due to the large amount of surface water in the Congo river basin (1,300 km^3/yr, Shiklomanov, 1995), little attention was given to groundwater and therefore the present state of knowledge in this context is limited compared to basins in the arid parts of Africa. Only recently it was realized that provision of safe drinking water requires greater dependence on groundwater, even in areas endowed with abundant surface water.

The groundwater basin, a depression covering about 750,000 km^2 is far less areally extensive that the surface water basin (3.5 mln. km^2). It is bounded in the east by the mountainous terrain of the African rift, in the south by Kasai and Shaba plateaus and in the west by the Mayumbe hills. The basin is crossed by the equator. Annual precipitation ranges between 1,200 and 2,000 mm (UN, 1989). Rainfall decreases with distance from the equator.

The Congo aquifer system consists of three aquifers. They include:

1. Congo-Zaire and Ubengi alluvial aquifer,
2. the Tertiary and Quaternary aquifer,
3. the Karroo aquifer.

The upper alluvial aquifer is composed of coarse alluvial sediments, mainly sand, gravel and alternating with eolian sediments. It is a highly productive aquifer, recharge is from precipitation and the Congo river system. Favorable areas include the Isange de Libenge and the alluvial plain between N'Jili river and Galiemo Bay in Kinshasa. These areas are exploited by shallow wells, which produce high yield (Zitoun, 1993). In Congo the aquifer is limited in thickness and does not, therefore, present a particular hydrogeological interest.

The Tertiary-Quaternary aquifer underlies Betekes Plateau in Congo, and part of the Brazzoville area. It consists of sandy loam of Neogene age and soft sandstone of Paleogene age. The substratum is formed by argillites and arkozic sandstone of Inkizi. The productive levels in the aquifer consist of fine-grained sand, gravel and sandstone. The thickness of the aquifer is variable, reaching 100 m in Italoto. Direct recharge occurs from precipitation. Indirect recharge from streams is small compared to direct recharge. The aquifer sustains the flow of many rivers and tributaries. Groundwater is very low in dissolved solids. Concentration in water from Batekes sand is about 30 mg/l. Because of their acidic pH, the water supply systems require an equilibrium treatment (Zitoun, 1993).

The Tertiary formations of Kwango in the southwest consist of sandstones sands, clays and argillites. They form deep and shallow aquifers. In south and east Kassai, the aquifer consits of residual sands and eolian sandstone.

The Mesozoic (Karroo) sandstone aquifer underlies the central basin in Bokungu. It underlies the Tertiary sands in Kwango and Kisangani. The sandstone aquifer has very low productivity in Bokungu. In Congo, the Mesozoic aquifer is represented by the Stanley-Pool series consisting of

mudstone, white sandstone, and kaolinite sandstone. These sandstones form a moderately productive aquifer.

Some 2,000 wells were drilled during the 1960s and early 1970s for water supply of towns and villages in several regions in the Congo basins. These include Katanga, Kinshasa, Kassai, Kivu and many others. During the 1980s both deep and large diameter wells were drilled for the water supply of Inkisi, Shaba, Bas'Zaire, Equateur, Hant-Zaire, Kasai oriental and Kassai Occidental. There yield range between 15 and 80 m^3/h. Some high yielding wells reach 300 m^3/h.

In conclusion, after a slow start, the groundwater programs, in the Congo basin, seem to be developing rapidly, especially during the International Decade for Water Supply and Sanitation. However much attention is given to engineering aspects, such as well drilling and construction. Data collection systems and hydrogeological studies need to be strengthened in order provide adequate information for planning water resources development and improving water supplies for both the rural and urban communities (UN, 1989).

5.5.3.7 The Kalahari Basin

The Kalahari regional aquifer systems underlie a vast semi-arid region in parts of Angola, Zambia, Zimbabwe, Namibia and Botswana. The Kalahari basin is divided into two sub-basins: the Upper Kalahari and Lower Kalahari basins, by the Gobabis-Ghanzi technic high consisting of Pre-cambrian, Infra-Cambrian and Paleozoic rocks.

The Upper Kalahari Basin is drained by the Upper Zambezi, the Okavango and Kwando river systems. The Zambezi River flows into the Indian Ocean, whereas the Okavango river empties in a desert depression forming an inland delta. These river systems contribute to aquifer recharges and influence groundwater quality. Two regional aquifer systems have been recognized in the Kalahari basin:

- the Upper aquifer: the Kalahari aquifer system;
- the Lower aquifer: the Karoo aquifer system.

The Upper Kalahari Basin

The Kalahari aquifer system is composed, in this basin, of sand with clay either interbedded with sand or mixed with it in various proportions. In Angola the Kalahari aquifer systems is composed of clayey sand. Further south, in Zambia, sand is the dominant component. Productivity increases and the aquifer system becomes multi-layered, composed of fine to medium grained sand, gravel, marl and clay.

In Zimbabwe, the Kalahari aquifer system occurs in the Sabi, Londi, Limpopo and Zambezi valleys. The sandy beds of the oldest alluvium are water bearing, but, in general, transmissivity is poor. Nevertheless there is an important resources which could be used for irrigation.

The Lower aquifers are composed of continental deposits of Upper Carboniferous to Cretaceous age.

Information on these aquifers is limited in the countries that share the Upper Kalahari Basin, particularly in Angola and Zambia. In Zimbabwe, the Karoo sandstone constitutes an important regional aquifer system, and has moderate to high productivity. The overlying Cretaceous sandstone, has lower productivity (Table 5.5.3.7.1).

The Karroo aquifer system, consists of, in Zambia, of low permeability formations. Sand-stones and conglomerates which occur in the sedimentary succession are productive rocks. The eastern parts of the basin is underlain the Katanga aquifer system, consisting of limestones and dolomite traversed by a network of fissures and coves. The karstic aquifers have high trans-missivities, Thus forming Zambia's best aquifers. The transmissivity for the dolomitic limestones

Table 5.5.3.7.1 The Kalahari aquifer system in the Upper Kalahari Basin

Country	*Lithology*	*Productivity*
Angola	Argillaceous	Low
Malawi	Sands clayey sand	Low
Zimbabwe	Sands	Medium
Zambia	Sands and clays	Medium

Source: UN, 1989.

is about 800–1,000 m^3/day (UN, 1989). The upper part of the Katanga carbonate aquifer is relatively more productive. Wells tapping the limestones and dolomites yield up to 35–50 l/s. Wells in the dolomitic limestones, used for irrigation, generally yield 10–20 l/s (UN, 1989).

The Lower Kalahari Basin

The Lower Kalahari Basin occupies the greater part of Botswana and the eastern parts of Namibia. The Karroo aquifer forms a regional aquifer system in Botswana. The aquifer system is overlain in the west of Botswana and east of Namibia by the Kalahari aquifer system, which consists of sands, gravels and sandy alluvium. The sandy alluvium formation constitutes a major source of water supply for the rural and pastoral population, due, mainly to its accessibility.

The Karroo aquifer system consists of several sandstone formations separated by confining units: aquicludes or aquitards. The Karroo aquifer system, includes, in Botswana, three aquifers: the Cave sandstone aquifer, the Ecca sandstone aquifer and the Stromberg aquifer which includes basalts in addition sandstones and marls. However there are other geological formation which form productive aquifers in Lower Kalahari Basin (Table. 5.5.3.7.2). The different types of aquifer systems have been classified, in Botswana, as follows (UN, 1989).

Table 5.5.3.7.2 Types of aquifer systems in the Lower Kalahari Basin

Aquifer type	*Formation*
Porous	Kalahari sands, recent and old alluvium
Fractured/Porous	Karroo sandstones and basalts
Karstic	Transvaal dolomites
Fractured	Waterberg quartzites, Kanye volcanics, crystalline basement

In general, the Ecca and Cave sandstone aquifers are areally extensive and continuous aquifer systems. They are characterized by their large reserves, but groundwater development is constrained by low recharge and poor transmissivities. The quality of groundwater is generally fair to good, except in the Okavango Delta, the Makgadikgadi Pans and Southern Botswana, where concentration of dissolved solids exceed 5 g/l (Zitoun, 1993).

Due to prevailing aridity Botswana cannot meets future water demand. Current estimates of demand (80 to 150 mln. m^3/yr) is less than water availability from different aquifers, estimated at 66 mcm/yr (UN, 1989).

The Namibian part of Lower Kalahari Basin is called the Salt Block. The confined aquifer system underlies 15,000 km^2 of grasslands. It consists of the Auob and Nossob sandstones and the Dwyka series. The aquifer system is overlain in the east by the Kalahari saline aquifer. The casings of wells tapping the Auob and Nossob aquifers in the 'Salt Block' are subject to intense corrosion

by the highly mineralized water from the kalahari aquifer (Total dissolved solids may reach 80,000 ppm). Unless this problem is addressed, mixing of salty and freshwater could occur in wells. Groundwater development, under such unfavorable hydrogeological conditions is costly, and salinization may become a critical problem if mixing occur in uncemented wells, which have lower water production costs.

Accurate information on water resources is lacking. The Department of Water Affairs estimated the resource base at 500 mln. m^3. Of this total groundwater is estimated at 300 mln. m^3. Some estimates are of the order of 1,000 mln. m^3 (UN, 1989). It seems that the known potential is now completely developed, and further exploitation of groundwater could result in the depletion of reserves.

5.5.3.8 The Karroo Basin

The Karroo basin underlies 600,000 km^2 in South Africa. It is a large basin, 1,300 km long and 600 km wide. The Precambrian basement is overlain by a thick succession of sedimentary and metamorphic rocks, ranging in age from Cambrian to Cretaceous. Recent alluvial deposits which occur in the flood plain of perennial rivers or ephemeral streams are of limited areal extent. In some places occumulation of sands have been produced by the construction of an overflow dams across the bed of a water courses, which are gradually raised. The 'sand dams' create arteficial aquifers, which are locally exploited in rural areas for domestic use or for livestock (UN, 1989).

The Precambrian basement outcrops in the northwest, along the frontier with Namibia, in the north, close to the Botswana frontier and in the northeast, in Transvaal, along the frontier with Mozambique. The Late Precambrian outcrops west of Pretoria and northwest of Kimberley. It consists of basalt, conglomerate and quartzite followed by a thick (2,500 m) series of cherty dolomites, overlain by the Pretoria and Waterberg series (5,000 m) consisting of schists sandstones, dolomites and granites (Pretoria Granites).

The Paleozoic, Pre-Karroo formation outcrop in the peripheries of the Karroo basin. They include the Nama series and Cape series, composed of a sandstones, limestones quartzites and schists. The Pre-Karroo formation, about 6,000 m thick range in age from Cambrian to Lower Carboniferous. They are overlain by Karroo formations of Upper Carboniferous to Upper Triassic age. These sediments which cover more than half of South Africa, consist predominently of sandstones and schists. They include from bottom to top:

- *the Dwyka Series:* 800–1,000 m of schists and tillites of Upper Carboniferous age;
- *the Ecca Series:* 1,800 m, sandstones and schists of Lower Permian age;
- *the Beaufort Series:* 3,000 m of continental sandstone and orgillaceous schists of Permo-Triassic age;
- *the Stromberg Series:* some 650 to 1,100 m of Upper Triassic sandstones and schists which include the massive 'Cave sandstone'. The sedimentary sequence is overlain by the Drakensberg volcanic series, which range in thickness between 1,000 and 2,000 m.

Unlike the large basins of north Africa which form lowlands sloping gently towards the Mediterranean, the Karroo formations cover an area which consists basically of a plateau at least 1,000 m high. It terminates at the sea in narrow coastal plains. The Drakensberg, at the southern edge of the plateau, has several peaks over 3,000 m. The plateau is drained mostly by the Orange River which rises in the Drakensberg. The Limpopo River, which rises near Johannesburg, drains the Transvaal province of South Africa. The average rainfall is 475 mm. Rainfall decreases westwards to less than 400 mm, with only 50 mm on the Atlantic coast. Annual evaporation is 1,750 mm, typical of semi-arid regions (UN, 1989).

The porous Paleozoic-Mesozoic Karroo formations consists predominently of hard, indurated rocks. Their sediments have been subjected to the complex processes of lithification,

diagensis and low-grade metamorphism. The result has been the formation of comented sandstones and schists of low transmissivities. The storage capacities of these rocks are also low.

The fractured dolerite veins in the Karroo sediments constitute an intrusion system in the Triassic and Carboinfereous schists and sandstones. Large yields are available from these dolerite veins and their hardened zones of contact. The sub-horizontal sedimentary schists and sandstones of the Karroo basin have very low permeability and therefore are unproductive (UN, 1989, 1973; Zitoun, 1993). The Transvaal dolomitic series, which form the sub-stratum of the Karroo basin and outcrop in the northeast, constitute an important aquifer system. They contain large water resources in the interconnected dissolution channels. These karstic formations are broken into a number of separate compartments by impermeable veins of syenite. The reserves of the two main compartments, Oberholzer and Venterpost are estimated at 730 and 450 million m3 respectively (Zitoun, 1993). Studies of the fracture systems have been carried out to located favorable sites for large-diameter wells. Yields up to 400 m^3/h were obtained. The fractured zones are fault systems, often filled with poruns, permeable and unconsolidated deposits. These 'geological valleys', which are investigated by means of gravimetric surveys, form significant groundwater reservoirs which were developed during drought episodes (Table 5.5.3.8.1). It is possible, however, that their resources become depleted, because the drawoffs are far in excess of the natural recharge (Zitoun, 1993; UN, 1989).

Table 5.5.3.8.1 The Pre-Karroo and Karroo aquifers

Aquifer	*Age*	*Porosity (%)*	*Permeability (m/s)*
Pre-Karroo			
Table Mountain sandstone	Ordovician-Devonian	1.1	$1x10^{-9}$
Bokkeveld sandstone	Devonian	2.7 to 7	2×10^{-9} to 6×10^{-9}
Karroo			
Ecca	Permian	1.6 to 2.5	10^{-9} to 6×10^{-6}
Beaufort	Permo-Triassic	1.2 to 11	under 10^{-9} to 10^{-8}
Molteno	Triassic	5 to 10	1.5×10^{-9} to 3×10^{-8}
Clarens	Upper Triassic	47 to 21	10^{-8} to 7×10^{-7}

Direct recharge from rainfall is estimated, over South Africa, at 16 to 37 billion m^3. Since the Karroo aquifer system underlies about 50% of South Africa, recharge to this aquifer system is of the order of 8 to 16 billion m^3. The rest goes to the dolomitic and Pre-cambrian aquifers. Only part of this groundwater can be exploited at a sustained rate.

About 100 towns are, however, supplied exclusively from groundwater and 15 others are dependent partially on groundwater resources.

Groundwater is the sole resource for the vast arid areas of South Africa. It supplies about 15% of all water consumed in the country, which has by 1990 about one million wells. Since some 20,000 to 30,000 wells are drilled every year, the number of wells may have reached 1.25 to 1.35 million wells. At the rate of growth of groundwater installations, it is possible that about 5 billion m^3 will be withdrawn by 2010–20 (UN, 1989).

The reason why more use is not made of groundwater in South Africa is that hydrogeological conditions are not very favorable. The Quaternary sediments which usually contain the best aquifers are of limited areal extent. In some parts of the country, groundwater from the Kalahari is too saline to be used. Lastly favorable areas in the Karroo basin are too far from the consumption centers.

The groundwater resources of South Africa tend to be overexploited in most areas, because

water demand has increased considerably in recent years, and re-current droughts have affected the country. This threat to groundwater availability is aggravated by impairment of the water quality by industrial development and increasing use of fertilizers and pesticide in agriculture.

5.5.3.9 The Coastal Basins

The coastal plains of Africa south of the Equator are usually more populated than the interior, especially the arid and semi-arid regions occupied by the Kalahari Desert. Groundwater is an important resource in these narrow coastal zones, which include the coastal basins of Gabon, Congo, Zaire, Angola, Mozambique and Madagascar.

The Gabon coastal basin covers an area of about 55,000 km^2. It is underlain by a multi-layered aquifer system composed of several members. The Lower aquifers include Infra-Cocobeach (Permian to Jurassic) and Cocobeach (Lower Cretaceous) aquifers, which could be subdivided into several members composed of continental sediments. These aquifers are overlain by the 'Saliferous' (Upper Aptian) which consists of evaporites interbedded with carbonate rocks. Higher aquifers which belong to Upper Cretaceous, Tertiary and Quaternary consist of marine sediments. It comprises seven members, the most important of which are the Madiela series, the Sibang, the Azile and Komandji series. They consist of alternations of limestones, dolomites sandstones and marls. Water quality is good (less than 500 mg/l) but mineralization increases with depth to about 700 mg/l and even to 5 g/l in the Sibang-Azile series which reaches 500 m in Libreville.

The Congo-Zaire coastal basin is about 100 km wide. Important aquifers includes Diosso sands (Plio-Quaternary) and the Cretaceous sandstones. Their permeability ranges from 10^{-8} to 10^{-5}. The upper unconfined groundwater is exploited by traditional wells. Discharge is low and their waters are fresh.

The Angola coastal plain is underlain by two aquifers: the unconfined Plio-Quaternary sand aquifer, and confined deeper aquifer. Water is drawn, traditionally from the sandy formations filling the fossil valleys.

The Width of the Angola coastal basin reaches about 200 km near Luanda. The aquifer system consists of alluvium and orgillaceous sandstones, which fill 'fossil valleys'.

The coastal basin of Mozambique covers about 30% of the total area of the country, which is about 783,000 km^2. The coastline is 2,800 km long. Several large rivers empty in this coastal strip, into the Indian Ocean. They include from north to south the Ruvuma, Louria, Zambezi, Save and Limpopo rivers. Their average total flow is about 95 billion m^3, of which 87 billion m^3 is the average discharge of the Zambezi alone. The southern coastal plain of Mozambique is underlain by an extensive unconfined aquifer, receiving considerable recharge from rainfall and the river systems. The water of this aquifer, has, however, high mineral content, except in few places where there are accumulations of surface sands. The Karstified Miocene limestone which underlies about 25,000 km^2 south of the Sove contain water of low mineral content which furnishes high unit yields (UN, 1989). Further south a continuous aquifer, consisting of recent sand dunes, can be exploited in a vast region. Data and information on the aquifer system, in the south, is scarce. Available information indicates that there is a fairly good potential, but there is a need to conduct hydrochemical surveys on a regional and more detailed local scale. Studies have been carried out with the view of exploiting the water of the alluvium for urban supplies. Potential aquifers in this regard, include the alluvial deposits of Umbeluzi, in the south, which could meet the needs of Maputo, and it may be possible to exploit the potential of the Pungue alluvium to supply Beira. The alluvial deposits of the central part of Zambezi delta may contain freshwater, except in the coastal zone where there is a risk of sea water intrusion.

The study of groundwater of Mozambique is still at the stage of reconnaissance. There is no

doubt that the groundwater in the coastal basin represents a resource of considerable potential. Remote sensing, geophysical and hydrogeological surveys are needed to delineate the limits of alluvial zones and freshwater saline water interface. These methods could also identify fracture zones in the Precambrian crystalline basement, which is not usually affected by the problems of salinization.

The western coastal basins of Madagascar covers an area of about 200,000 km^2. The eastern part of the island, some 400,000 km^2 is occupied by a precambrian plateau with an average altitude of about 2,000 m. The average annual rainfall in Madagascar is 1,700 mm. It ranges from 3,000 mm in the coast to low than 400 mm in the south. The potential evapotranspiration varies from 1,300 to 2,000 mm, and the real evapotranspiration is between 1,300 and 300 mm (UN, 1989). To the west of Madagascar, the crystalline basement is overlain by a thick sedimentary succession ranging in age from Upper Carboniferous to Quaternary.

Five groundwater basins have been recognized in the western coastal plains of Madagascar. These are from north to south: the Antsiranana basin, the Mahajanga basin, the Morondava basin, the Toliara basin and the Southern (Cap Saint-Marie) basin. Several aquifers have been recognized in these basins. The continental formations form a multi layered aquifer system: the Isalo aquifer (Triassic to Middle Jurassic) is a major auqifer, which consists of coarse sandstone and conglomerate. It occurs in the Toliara and Mahajanga basins, where groundwater is confined. In the Toliara basin yields up to 208 l/s are obtained. Other important aquifers composed of continental sandstone include the Ankarafantsika sandstone aquifer and the Tsiandava sandstone aquifer (Cretaceous). The former occurs in the Mahajanga basin. It is an artesian aquifer with yields, up to 60 l/s. The latter is also a confined system but wells tapping this aquifer have relatively poor yields.

The carbonate aquifer system includes karstic aquifers of Jurassic and Eocene age. The Jurassic limestone aquifer has not been adequately explored. The Eocene carbonate aquifer has been, however, subjected to extensive studies. It underlies the Mahajanga, the Morondova and Toliara regions. Measured permeability's, in the Mahajanga basin varies from 130 to 860 m/day. Transmissivity is 5 to 6×10^{-3} m^3/day. In the Morondava basin transmissivity is of order of 700 m^2/day (Zitoun, 1993).

The alluvial aquifer systems are of widespread occurrence in the coastal basins of Madagascar. In the Mahjanga basin two aquifers have been recognized: the 'sands aquifer' and the 'alluvial aquifer'. The latter has usually higher productivity in this basin, but it is relatively unimportant in the Morondova and Toliara basins. In the extreme south, several aquifers of Neogene and Quaternary age have been recognized: groundwater from these shallow aquifers, has, however, high concentrations of dissolved solids. Freshwater occurs only in the Beloha sands.

Groundwater is of great social and economic importance to Madagascar. By 1981, 23 small towns (10,000–80,000 inhabitants) were provided with water supplies from groundwater sources. Withdrawal amounted to about 12 million m^3. Little is known about rural water supplies. In the high plateau and east coast, a large part of rural population obtain its water from wells tapping the sands aquifers. Water from the sands aquifers is also tapped by various means to irrigate the rice fields in the alluvial valleys of the high plateaus. Industry and cattle farming in the Mahajunga, Morondova and Tulear regions depend on the groundwater withdrawn from aquifers underlying these regions. In the semi-arid region of the far south, groundwater is often the only resource available to people and livestock.

Given the increase of water demand, and limitation on use of surface water, withdrawal from groundwater is expected to increase in Madagascar. Efforts should focus an institutional development in order to establish adequate structures for the development and management of groundwater resources. Special attention needs to be given to the operation and maintenance of water supply installations in Madagascar and other rural areas in Africa.

5.5.4 Groundwater use

Groundwater use in Africa varies from country to country and region to region (Fig. 5.5.10) in accordance to climate, water availability, financial resources and socio-economic development. In general groundwater is over-developed in northern Africa, i.e in the Arab countries which occupy the semi-arid-arid and hyper arid belt, north of the Sahara. In the Sudano-Sahelian region, groundwater is under-developed due to natural, demographic and economic factors. Population density is low in the large groundwater basins, which underlie this region, whereas in the greater part of the more populated areas, aquifers occur, predominantly in the crystalline basement. These aquifers are discontinuous, shallow and their productivity depends on the development of fissure and fracture systems. Their resources are very low, but recharge is relatively high.

In the humid equational and tropical regions, groundwater is under developed, because rainfall and surface water is abundant in major rivers and their tributaries. Countries in these regions have recently realized that provision of safe drinking water to small towns and rural areas could only be guaranteed by utilizing groundwater sources, provided that certain presentations are taken during well siting and construction. In the arid and semi-arid region of southern Africa, there is an urgent need for groundwater development, for rural water supply. The main constraint in this region is poverty and lack of adequate knowledge on groundwater availability and quality. In some countries, in this region, however, groundwater assessment and development received considerable attention.

In Botswana over two-thirds of the needs of urban and rural population, industry and livestock are met from groundwater sources. In South Africa, over one million of wells have been drilled to meet over 15% of water demand, although hydrogeological conditions are, often, not favorable. Water quality plays an important role, in Africa, not only because of its health impact but also because it affects agricultural development and the cost of water supply for human and industrial use.

Sea water intrusion, over development, and natural factors have contributed to the increase of concentration of dissolved solids in coastal aquifers and closed basins in the arid or semi-arid interior. In the coastal zone which extends from Nouadhibou to Nouakchott and even further south to the lower Senegal river, an extensive saline groundwater body have developed in a subsiding basin. The water table is below zero in almost all parts of the coastal aquifers, reaching 35 m east of Nouakchott. A similar hydrochemical condition exist in the alluvial coastal aquifer of Somalia, Kenya and Mozambique. In these phreatic aquifer systems fresh groundwater does exist but the main problems which impede use is the delineation of freshwater and saltwater zones.

Along the Mediterranean many of the regional aquifer systems discharge in the coastal plain or in depressions near the coastal zone. An extensive saltwater body has developed from upper Egypt to eastern Libya. It underlies the Nile delta and the Cairo area. The freshwater saline water interface passes through the Qattara depression, and crosses the Libyan-Egyptian border, turning to southwesterly direction until it reaches Tazerbo area. Thus, the main problem to be addressed for insuring a sustained use of groundwater in the Sirte basin in Libya and the Northwestern basin in Egypt, is the position of the salt water- freshwater interface, and the encroachment of salt-water in the coastal areas where sediments are tightly confined and flow in the Nubian regional aquifer system becomes sluggish. Accordingly the concentration of dissolved solids increases considerably (Khouri, 1996).

Over-development has also caused a substantial deterioration of groundwater quality in the Jefara coastal plain shared between Libya and Tunisia. Water quality problem are also of common occurrence in southern Tunisia, Groundwater use in such vulnerable areas in Africa needs improved management of quantity and quality to stabilize the freshwater-saltwater boundaries or, at least, minimize saltwater encroachment from the sea or from inland sources.

Groundwater contamination is an equally import issue which need addressing in Africa. A groundwater quality study in the rural areas of West Africa, based on field trials of a World Bank Hand Pumps project comprising Burkina Faso, Côte d'Ivoire, Ghana, Mali, Niger as well as a 3,000 well drilling program in Ghana, indicated that hand pump equipped drilled wells showed a similar degree of pollution as dug wells. Case studies, showed that the main causes of pollution is inadequate well construction, poorly installed or inadequately designed hand pumps. Sources of pollution include human settlements, fertilizers and pesticides.

With the exception of the countries of North Africa, and few countries in West and South Africa, adequate and reliable information on water use is lacking or scarce in Africa. Much data is available on surface water use, because rivers are usually regulated and their waters are exploited by water development and management authority. Groundwater, in Africa, as is the case in many regions in the world, is exploited mainly by individuals, especially farmers who use over 80% of total water withdrawn from groundwater sources.

Table 5.5.4.1 shows the distribution of withdrawal by region. The northern region represents half of total withdrawal. The semi-arid and arid belt of North Africa (Northern and Sahelian zone) represents 67% of total withdrawal. Water withdrawn from the southern and eastern region makes 17% and the least amount withdrawn is 5% from central and Gulf of Guinea regions.

Groundwater withdrawal has not been adequately assessed in Africa. Available data indicate that it is highest in the northern and southern region, but it is always much less than surface water withdrawal as can bee seen from the Table 5.5.4.2.

Margat (1995) has attempted to estimate the relative importance of surface and groundwater in meeting water demand during the period 1985–90 (Table 5.5.4.3). He reached similar

Table 5.5.4.1 Water withdrawal at the regional level in Africa

Region	*Area (1,000 km²)*	*Internal water resources (km³)*	*Withdrawal by sector*			*Total (mcm)*	*Percentage of total*
			Agriculture (mcm)	*Domestic (mcm)*	*Industry (mcm)*		
Northern	5,753	50	65,000 (85%)	55,00 (7%)	5,800 (8%)	76,300 (100%)	50.9
Sudano-Sahelian	8,591	170	22,600 (94%)	1,200 (5%)	300 (1%)	24,100 (100%)	16.1
Gulf of Guinea	2,106	952	3,800 (62%)	1,600 (26%)	700 (12%)	6,100 (100%)	4.1
Central	5,329	1,946	600 (43%)	600 (43%)	200 (14%)	1,400 (100%)	0.9
Eastern	2,916	259	5,400 (83%)	900 (14%)	200 (3%)	6,500 (100%)	4.3
Southern	4,739	274	14,100 (75%)	3,000 (16%)	1,800 (9%)	18,900 (100%)	12.6
Islands	591	340	16,400 (99%)	200 (1%)	20 (–)	16,620 (100%)	11.1
Total	30,025	3,991	127,900 (85%)	1,300 (9%)	9,020 (6%)	149,920 (100%)	3.8

Source: FAO, 1995.

Table 5.5.4.2 Groundwater withdrawal in the Northern Region

Country	*Groundwater withdrawal (b.c.m)*	*Total withdrawal (b.c.m.)*
Algeria	2.0	5.4
Egypt	3.0	63.1
Libya	4.8	5.2
Morocco	5.0	11.0
Tunisia	1.8	2.9

Source: Allan, 1993, ACSAD, 1997.

Table 5.54.3 Water supply sources in North Africa for 1985–90 period (%)

Region/Country	*Surface water*	*Groundwater*
Northern		
Algeria	54	36
Egypt	86.1	4.5
Morocco	73	26.6
Tunisia	42	47
Sudano-Sahelian		
Cape Verde	20	80
Mali	92	8
Mauritania	53	47
Niger	91	9
Senegal	82	18
Chad	47	53
Sudan	98	2
Somalia	96.5	3.5

Source: Margat 1993.

conclusions with regard to the Northern countries. In regards to the Sahelian and Eastern regions, he reported high values for groundwater withdrawal in Cape Verde, Mauritania and Chad.

In regards to distribution of withdrawal by sectors, for the continent as a whole about 85% of water withdrawals is used in agriculture, but sectorial water use, agriculture, communities and industries varies considerably from region to region. The arid, northern region, has the highest level of water withdrawal for agriculture. By contrast the humid, central and Gulf of Guinea have show the lowest agricultural withdrawal.

Table 5.5.4.3 shows groundwater and surface water availability at the regional and country level. In the northern region groundwater forms about 25% of internal water resources.

It is over developed in Libya and large arid basins of Algeria, Tunisia and Egypt. Groundwater constitutes about 36% of the renewable water resources of the Sudano-Sahelian zone and about 25% of the resource base of the Eastern region. With the exception of the northern region, withdrawal, throughout Africa in general, and groundwater development in particular, is very low due to lack of agricultural wells, irrigation schemes and urban drinking water networks.

Irrigation water demand could be met from both surface and groundwater resources. Surface water is used more extensively at the present time, especially for agricultural purpose. Present national plans which aims at extending and improving domestic water supplies will give more attention to groundwater use. In the long term, an integrated use of surface and

groundwater resources will be required to protect the resource base and enhance socio-economic development.

Table 5.5.4.1 shows the distribution of withdrawal by region. The northern region represents half of total withdrawal. The semi-arid and arid belt of North Africa (Northern and Sahelian zone) represents 67% of total withdrawal. Water withdrawn from the southern and eastern region makes 17% and the least amount withdrawn is 5% from central and Gulf of Guinea regions.

5.6 Groundwater resources and their use in Australia, New Zealand and Papua New Guinea

The locations of Australia, New Zealand and Papua New Guinea are shown in Figure 5.6.1. The hydrogeology of Australia was last summarized in a hydrogeological map and accompanying text in 1987 (Lau et al., 1987). Since then research has added to our knowledge of a number of major sedimentary basins (Fig. 5.6.2) and some of this work is summarized in this section. The groundwater resources of Australia were last assessed in the *1985 Review of Australia's Water Resources* (DPIE, 1987). The account of New Zealand's hydrogeology and groundwater resources by Len Brown in this section is the first documentation of this topic in an international publication, and is based on Brown and Gregg (1994). The geothermal resources of New Zealand were reviewed by Thompson et al. (1995). The account of the hydrogeology and groundwater resources of Papua New Guinea by Jim Lytham and Elizabeth Michael in this section is the first documentation of this topic since the 1970s (Carter, 1979), and is also the first such documentation in an international publication.

Figure 5.6.1 Locations of Australia, New Zealand and Papua New Guinea

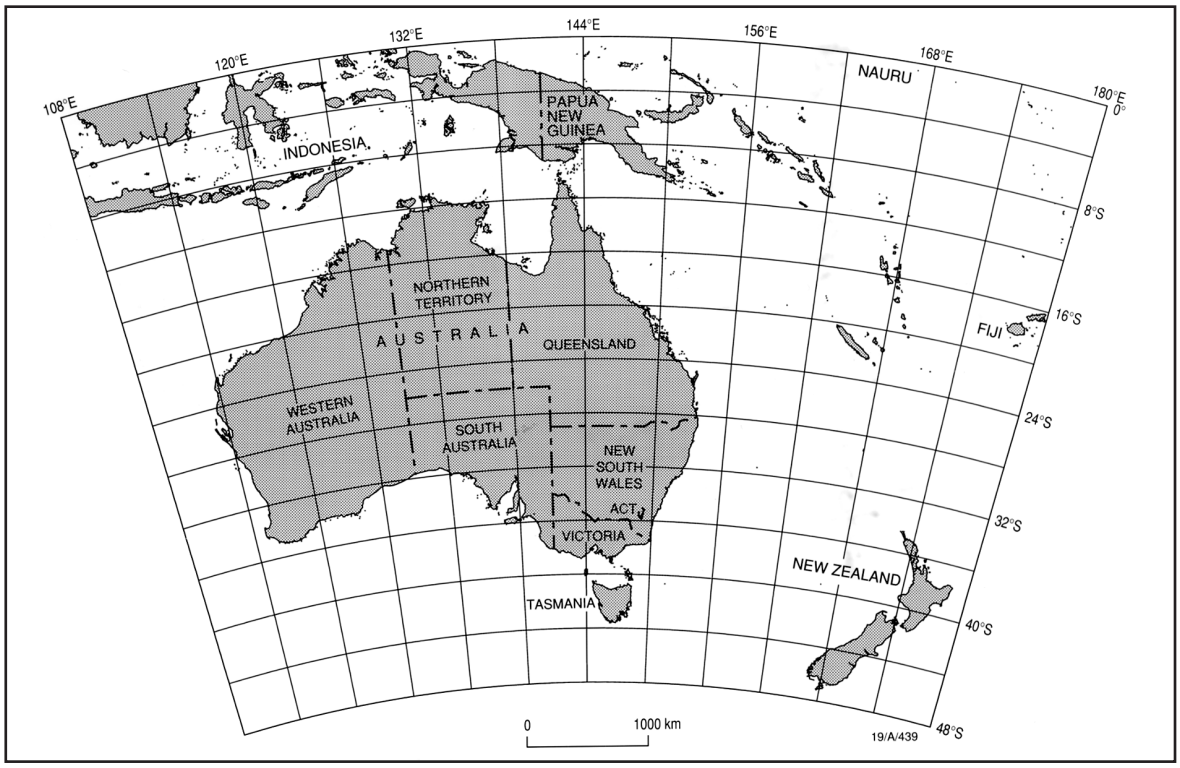
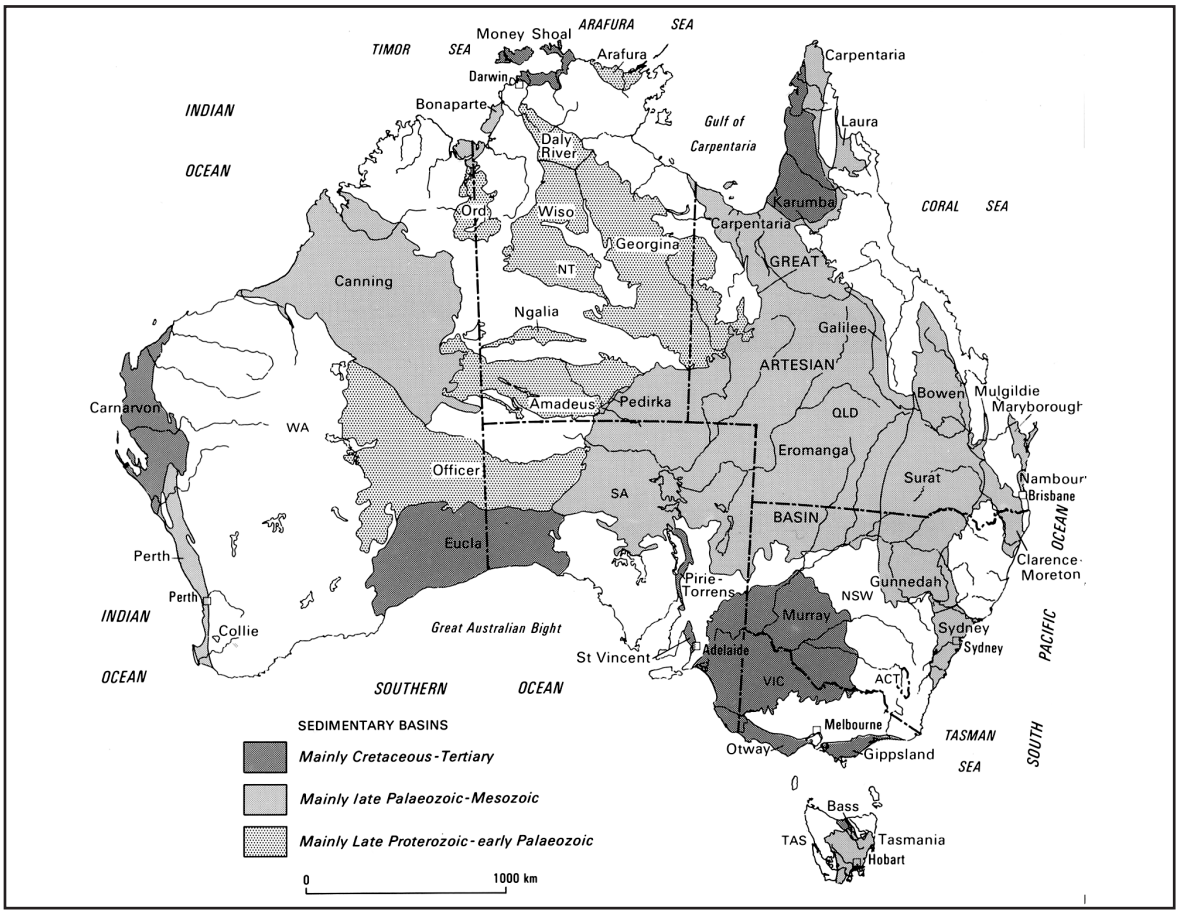


Figure 5.6.2 Number of major sedimentary basins



5.6.1 Main aquifers of Australia

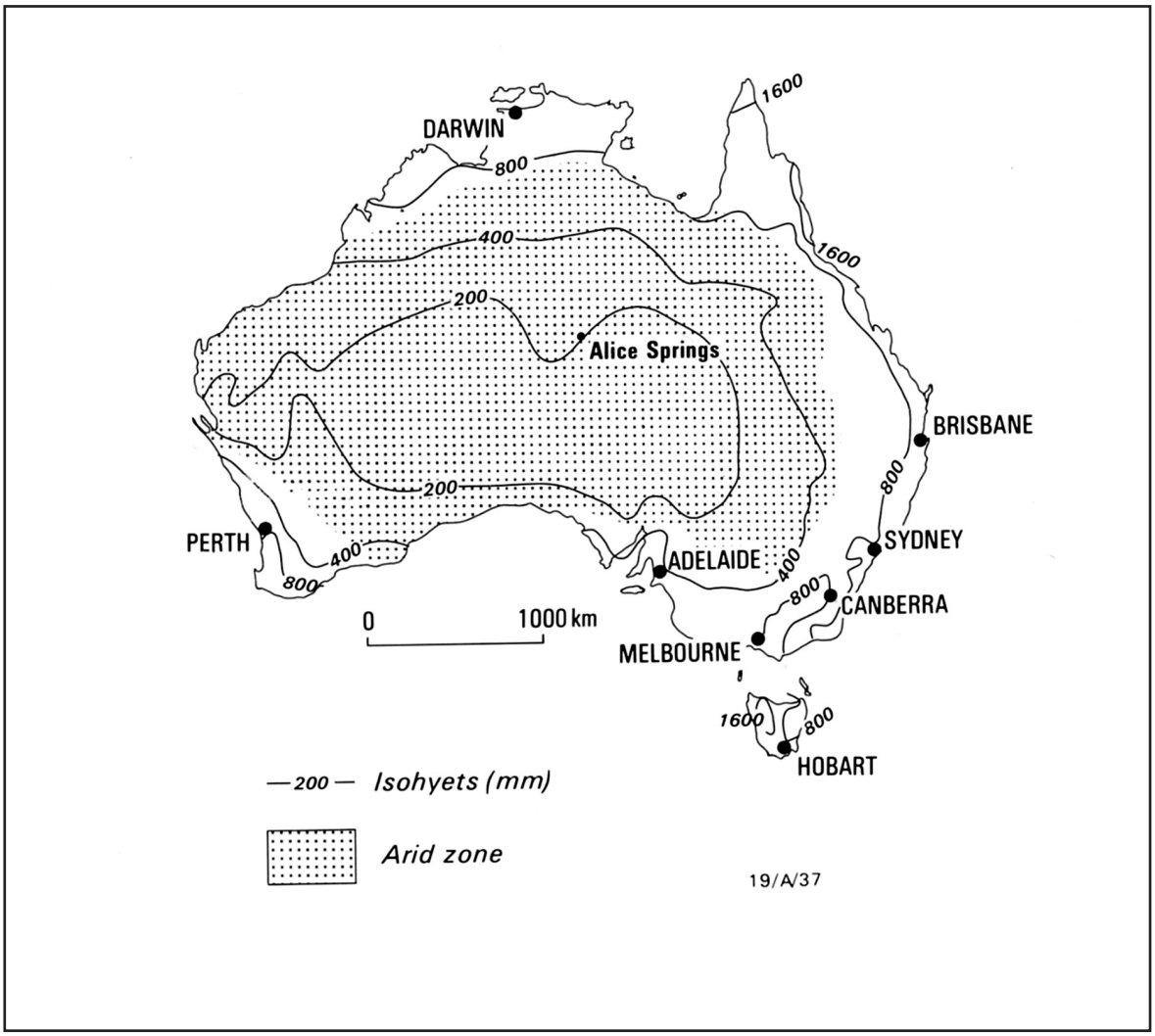
The Australian continent (area about 7.7 x 10^6 km^2) is geologically mature, and has generally low topographic relief. The highest peak, Mt Kosciuscko, elevation 2,228 m, is part of the Great Dividing Range which runs the entire length of the eastern seaboard. This drainage divide separates streams that flow eastwards to the Pacific Ocean, from those that flow to large inland drainage basins, including the Murray-Darling basin and the Lake Eyre basin. Over large areas of central and southern Australia there are no permanent streams.

The aridity of much of the Australian continent is a significant factor in the occurrence and assessment of the groundwater resources. Figure 5.6.3 shows the mean annual rainfall. The highest rainfall occurs in areas of higher topography in eastern and southern Australia; and in the monsoonal and cyclonic areas of northern Australia. A large part of western and central Australia is arid, with mean annual rainfall below 250 mm, and variable seasonal distribution. Evaporation generally increases from south to north across the continent, and also inland from the coast. Annual values of pan evaporation exceed 4,000 mm in parts of western and central Australia. For most of the continent, annual evaporation is many times the mean annual rainfall.

The total surface runoff from the Australian continent is about 440,000 x 10^6 m^3/yr, with a large proportion of this in streams flowing to the Gulf of Carpentaria, and in Tasmania (Brown, 1983). Surface runoff from Australia is low compared with other parts of the world, and also has pronounced seasonal and annual variations owing to the influence of the El Niño – Southern Oscillation effect on Australia's climate.

Australia's most highly productive freshwater aquifers are the surficial sedimentary

Figure 5.6.3 Mean annual rainfall



aquifers in the wetter regions of the continent where there is annual groundwater recharge. Some of these aquifers are now highly stressed (Table 5.6.1.1).

The Tertiary-Quaternary alluvium associated with inland rivers forms major aquifers in eastern Australia. There are highly productive alluvial aquifers in the valleys of the Condamine, Namoi (Merrick et al., 1986), Lachlan, Loddon, Campaspe, Goulburn , Murrumbidgee and Murray Rivers (Macumber, 1986) and these aquifers sustain important irrigated agricultural districts in southeast Australia. In general the upper reaches of these valleys have shallow alluvium which is hydraulically connected to the river flow; downstream the valleys broaden and mature, with extensive alluvium often more than 100 m thick and providing important groundwater sources. Where the rivers leave the highland valleys to enter the riverine plains, there are large alluvial fans containing fresh groundwater. Permeability tends to decrease from the apex of the fan outwards. Outside these alluvial fan areas, the groundwater salinity tends to increase down valley.

The Quaternary alluvial sediments in eastern coastal river valleys form aquifers of varying groundwater potential. The coastal rivers are relatively short compared with the inland rivers; their alluvium is limited in extent and thickness and, towards the coast, there is commonly a transition to estuarine sediments. The significant alluvial aquifers in the coastal valleys are up to 35 m thick. The largest of these alluvial deposits and also the most intensively developed for groundwater, is in the valley of the Hunter River, New South Wales, where yields from irrigation

Table 5.6.1.1 Major Australian groundwater systems under stress

System	Aquifertype	Abstraction ($x\ 10^6\ m^3$)	Natural recharge ($x\ 10^6\ m^3$)	Induced recharge ($x\ 10^6\ m^3$)	Management strategy
Burdekin Delta, Queensland	Deltaic sediments	331	323	200	Artificial recharge; water allocation
Namoi Valley, New South Wales	Alluvium	37	35	0	Controlled depletion; water allocation
Bundaberg, Queeensland	Tertiary sediments	50	61	0	Surface water substitution; water allocation
Lockyer Valley, Queensland	Alluvium	47	25	6	Recharge weirs; controls on groundwater use
Callide Valley, Queensland	Alluvium	28	12	10	Increased surface storage for release to recharge weirs
Padthaway, South Australia	Limestone	32	32	0	Water allocation

wells are 10–40 l/s. Similar high well yields are obtained from alluvia of the Callide, Pioneer, Burnett, Brisbane and Lockyer Rivers in eastern Queensland.

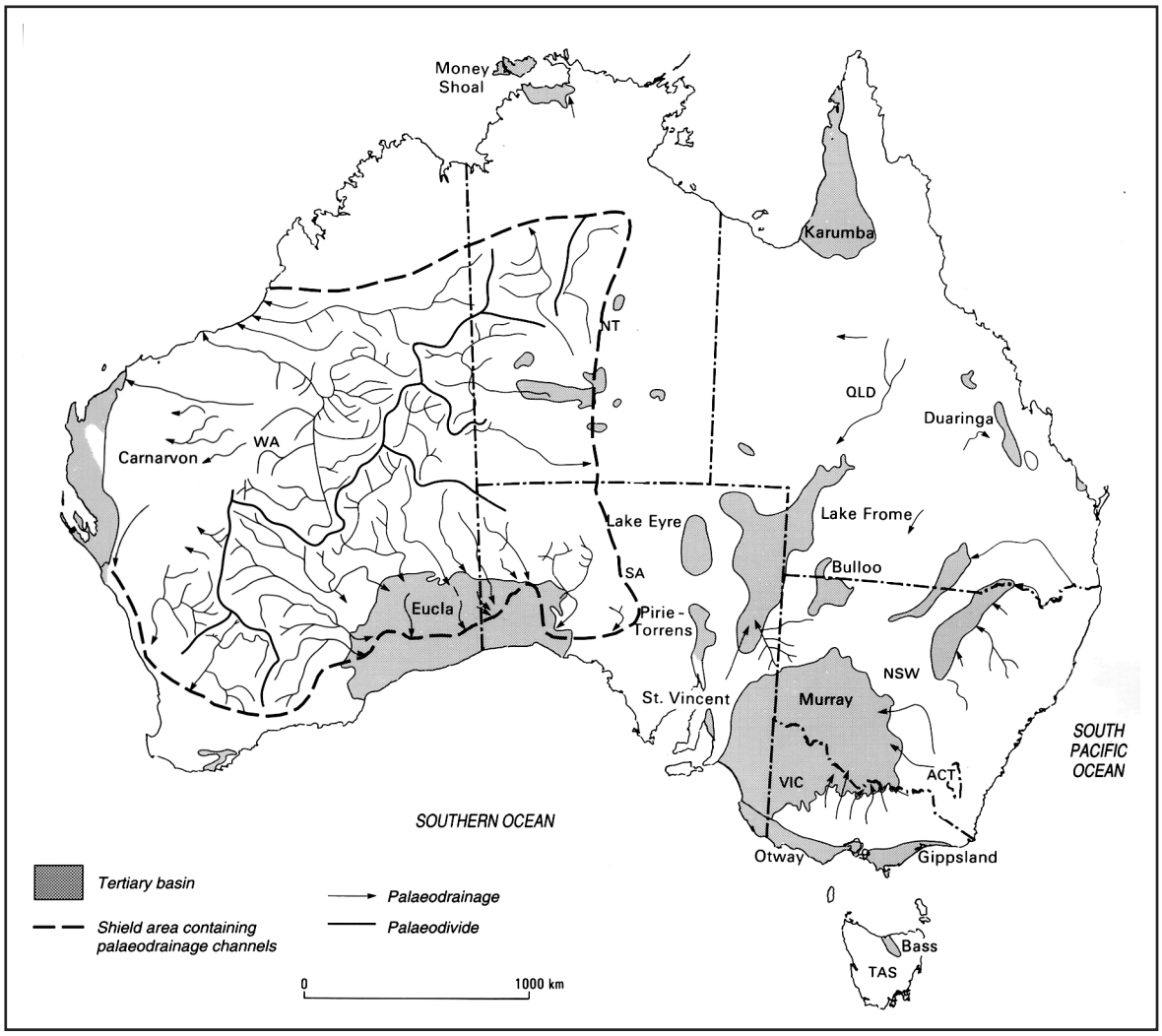
Estuarine and deltaic sediments occupy extensive areas along the east coast of Australia. The Burdekin River Delta in central Queensland is the site of very large groundwater abstraction for irrigation ($330 \times 10^6\ m^3$) and the aquifer is replenished by artificial recharge to prevent saline intrusion. The Quaternary Botany Sands aquifer in Sydney is heavily pumped for industrial use but the groundwater is acidic and sulphate-rich owing to intercalated peat beds (Lavitt et al., 1997). Coastal and deltaic alluvium also form an important aquifer at Bundaberg in central Queensland, where $50 \times 10^6\ m^3$ is abstracted for irrigation. Many estuarine deposits are underlain by saline groundwaters owing to Holocene sea level changes (Arakel, 1986), and brines are extracted for industrial use in the Fitzroy River delta, central Queensland.

Quaternary sand dunes are important reservoirs of fresh groundwater along the east coast of Australia. The sand dune aquifers are commonly 20–30 m thick and are recharged annually by rainfall, maintaining a freshwater lens. An example is the Tomago Sandbeds, New South Wales, from which about 25% of Newcastle's city water supply is obtained. The Tomago Sandbeds comprise an inner barrier dune system 30 km long and 2–5 km wide. The topographic surface is 5–8 m above sea level, and the sands extend to an average depth of 18 m (Hartwell and Viswanathan, 1983). There are significant groundwater resources beneath the high sandy islands of southern Queensland. These aquifers are susceptible to overpumping and saltwater intrusion.

There are important groundwater resources in sands and gravels of the Cainozoic Basins of arid Central Australia (Senior et al., 1995). These basins contain Tertiary sediments up to 300 m thick, with a thin veneer of Quaternary. Australia's main arid-zone irrigation scheme is based on groundwater extracted from the Ti-tree Basin, in the Northern Territory. The Ti-Tree Basin covers 5,000 km^2; and about half of it contains groundwater with less than 1,000 mg/l TDS (Calf et al., 1991; McDonald, 1988). Recharge in the modern climatic regime occurs through river bed 'floodouts' although diffuse recharge by direct infiltration of rainfall took place episodically in the Holocene.

A dendritic system of palaeodrainage channels is a prominent feature of older terrain in the Australian arid zone (Fig. 5.6.4), including much of Western Australia, the western part of South Australia, and the southwest part of the Northern Territory (Van de Graaf et al., 1977). Incision of

Figure 5.6.4 Dendritic system of palaeodrainage channels; a prominent feature of older terrain in the Australian arid zone



the palaeodrainage system predates the separation of Gondwanaland which began in the Jurassic or possibly earlier (Clarke, 1994). In post-Eocene times the palaeodrainage valleys retreated into chains of lakes, as increasing aridity accompanied the separation of Australia from Antarctica.

In Western Australia, there are significant aquifers in the Tertiary alluvium of the palaeodrainages, and in the associated Quaternary calcrete deposits. An example is the Millstream calcrete aquifer in the Fortescue River valley from which 10 x 10^6 m^3 is extracted annually for use in the mining ports of Dampier and Karratha. The calcrete is dolomitic and is up to 30 m thick (Commander, 1983). The groundwater contains 900 mg/l TDS and is used conjunctively with surface water from a dam in order to improve the water quality. This addition of surface water also conserves the groundwater resource which is constrained by infrequent recharge and a need to maintain spring flow for ecological reasons. Calcrete aquifers also provide water supplies for other small towns and settlements in Western Australia and the Northern Territory (Jacobson and Arakel, 1987). Hypersaline groundwaters in palaeochannel sediments are used for the treatment of gold ore in Western Australia (Boyes and Hall, 1991).

Many surficial aquifers in the Australian arid zone have significant natural groundwater quality problems, including high salinity and the occurrence of nitrate and other deleterious elements (Hostetler et al., 1998).

A summary is given below of several large sedimentary basins where significant advances in knowledge have been documented since 1987. The locations are shown in Figure 5.6.2.

Amadeus Basin

The Amadeus Basin, in central Australia, is a complex region of folded and faulted rocks of late Proterozoic to Carboniferous age, overlain in places by Cainozoic sediments up to 300 m thick (Fig. 5.6.5). The region (160,000 km^2) is arid and totally dependent on groundwater.

The northern half of the basin is a synclinal province containing continuous sandstone units forming a multi-layered groundwater system. Three Palaeozoic sandstone formations, the Hermannsburg Sandstone, the Mereenie Sandstone and the Pacoota Sandstone are important aquifers. Modelling of this basin has indicated flow times along a section 250 km long and 6,000 m deep to be several million years (Brown et al., 1990), and this remarkable system may reflect palaeorecharge conditions in the early Tertiary. The great antiquity of some groundwaters in this region is borne out by the preliminary results of chlorine-36 dating (Jacobson et al., 1994).

The Mereenie Sandstone aquifer is the most reliable source of good quality groundwater over some 26,000 km^2 of the Basin and supplies the town of Alice Springs with 12 x 10^6 m^3/yr. However this groundwater is mainly derived from regional storage (Jolly and Chin, 1992) and water levels are falling by more than one metre annually, so that a second borefield will be needed early in the twenty-first century. Infiltration of rainwater through fissures has been the main mechanism for recharge of the Mereenie Sandstone aquifer. Dating of groundwater using radiocarbon indicates that the freshwater resources of the aquifer were mainly recharged in wetter climates of the Late Pleistocene (Jacobson et al., 1989; Calf, 1978).

In the synclinal province, groundwater flows generally southeast (Fig. 5.6.5). Sudden drops of the order of 50 m in the potentiometric surface are associated with thrust faults. The Pacoota Sandstone is structurally segmented and hydrocarbon traps occur in two localities, with the hydrocarbons overlying overpressured groundwater (Lloyd and Jacobson, 1987).

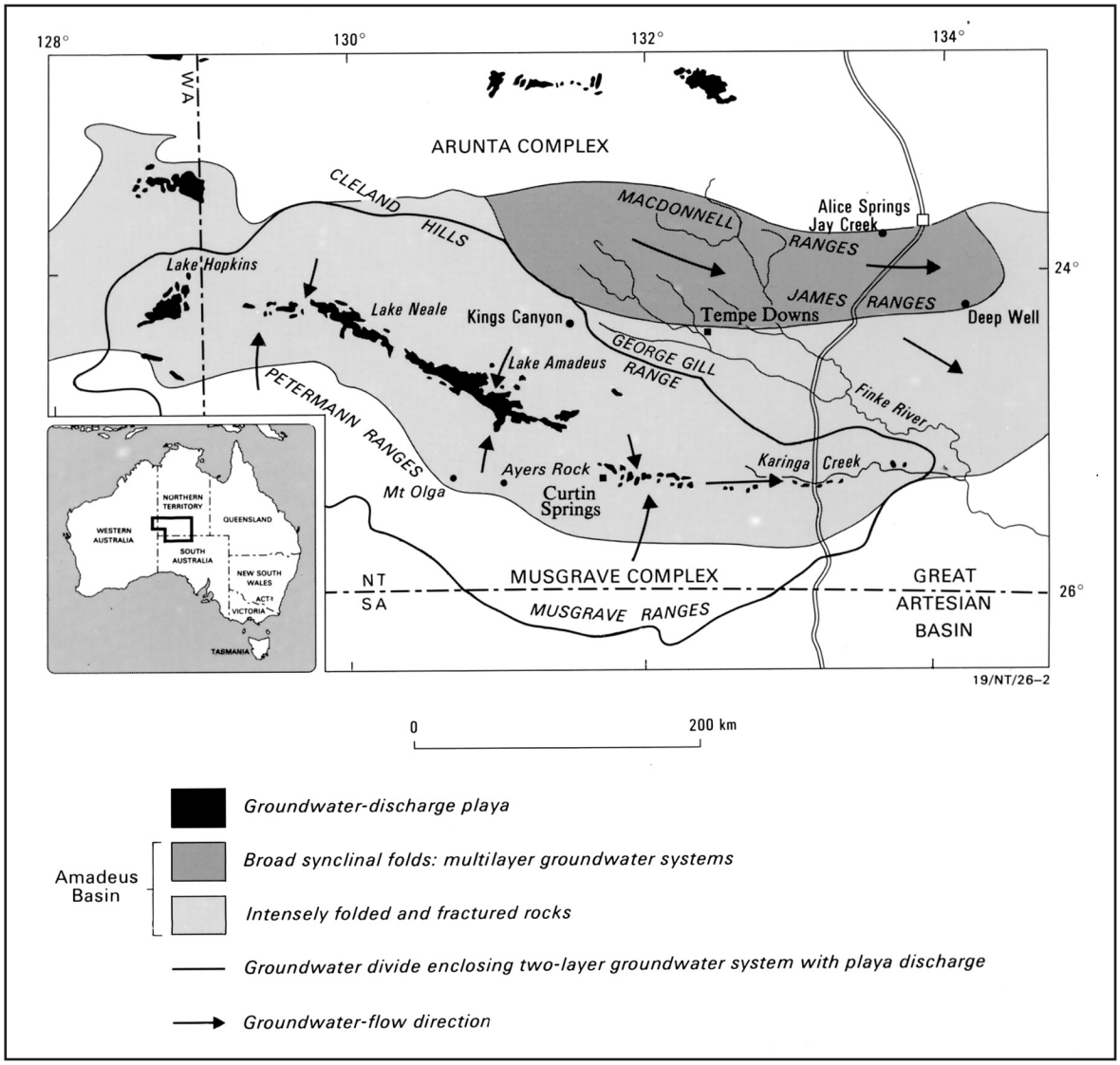
In the southern half of the basin, shallow aquifers in the Cainozoic sediments, which are up to 100 m thick, overlie the older, fractured Proterozoic rocks to form a two-component system. This two-layer system discharges to a chain of playas 500 km long that includes Lake Amadeus. The Yulara tourist resort is supplied from these Cainozoic aquifers, within a buried valley system (English, 1998). Although there is some hydrographic evidence of modern recharge related to 1 in 20-year rainfall events (Barnes et al., 1994), the groundwater is brackish and is desalinated from 1,800 to 400 mg/l TDS.

Fresh groundwater (containing less than 1,500 mg/l TDS) is more readily obtainable by drilling in the northern synclinal province, particularly along the northern margin where the Macdonnell Ranges provided a focus for rainfall and recharge in the Late Pleistocene. Groundwater salinity generally increases southward into the fractured rock provinces where brackish water, containing 1,500–7,000 mg/l TDS, is the best available water and the mainstay of the beef cattle industry. Hypersaline brines, containing more than 100,000 mg/l TDS are concentrated by the major groundwater discharge zone in the south of the basin, which comprises a chain of playas 500 km long (Fig. 5.6.5). Some of these playas contain K and Mg salts and have economic potential as a source of industrial minerals (Jacobson et al., 1989).

Canning Basin

The Canning Basin, in the northwest of the continent, has an onshore area of some 430,000 km^2 and contains Ordovician to Cretaceous sedimentary rocks which are up to 4,000 m thick (Fig. 5.6.6). At present, little groundwater is used in this sparsely populated basin which underlies

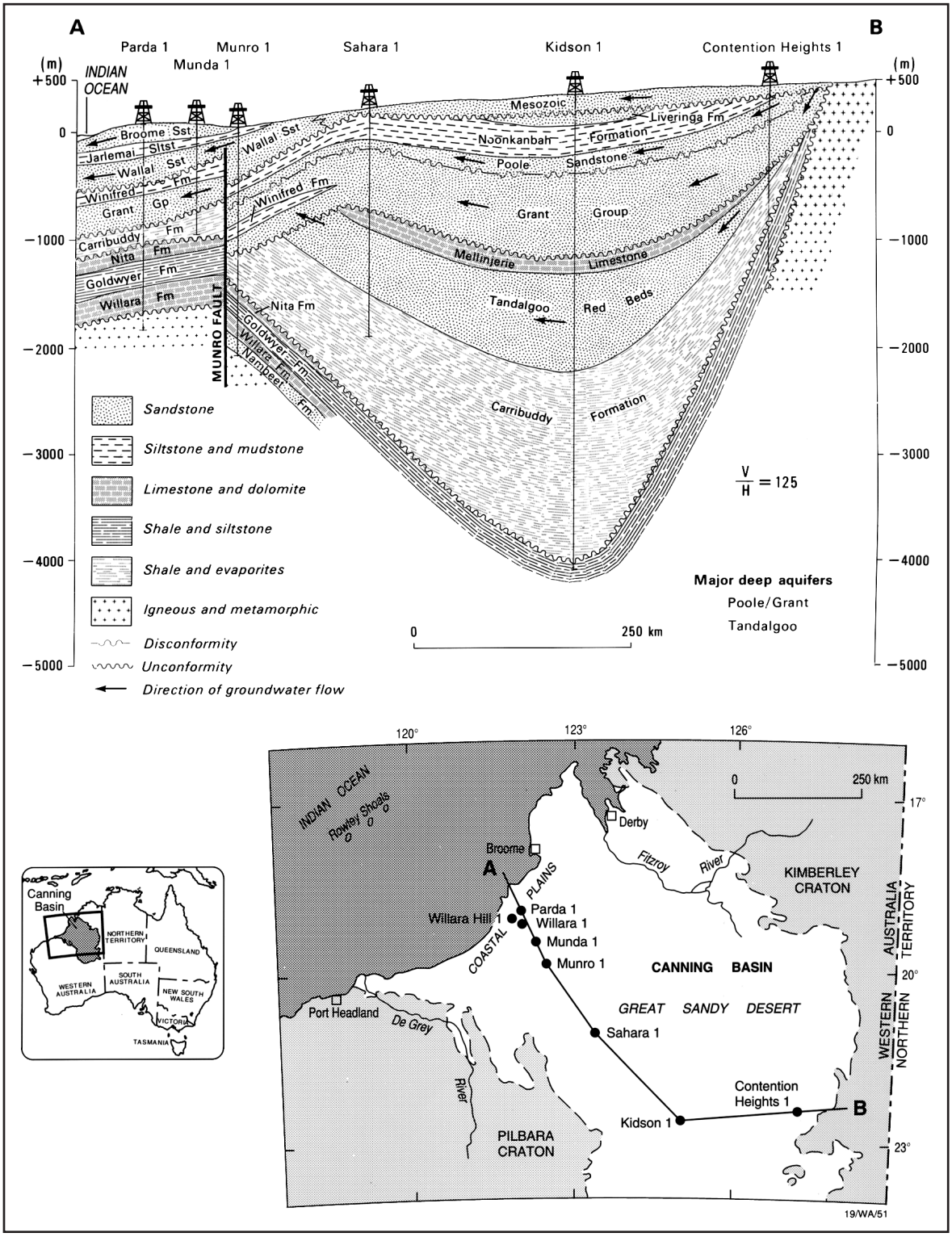
Figure 5.6.5 The Amadeus Basin, in central Australia,



the Great Sandy Desert, but the substantial resources may be used in the future. In the southwest corner of the basin investigation has shown that a major confined aquifer system in the Jurassic Wallal Sandstone underlies an unconfined aquifer in the Jurassic-Cretaceous Callawa Formation (Leech, 1979). Groundwater quality is good in the confined aquifer but poor in the unconfined aquifer. On the northwest coast, the Cretaceous Broome Sandstone is a high yielding aquifer at Broome where it contains fresh water overlying saline water (Laws, 1991).

Ghassemi et al. (1992) studied the deeper Palaeozoic aquifers in the Canning Basin, using oil exploration well data. They reported that 'the major Palaeozoic aquifers are the Early Permian Poole Sandstone, the Late Carboniferous to Early Permian Grant Group, and the Devonian Tandalgoo Sandstone. These aquifers have a complex structure owing to tectonic and erosional effects, and they are interconnected with the younger and shallower aquifers. The general direction of groundwater flow in the Palaeozoic aquifers is from the southeast towards the west and northwest. Groundwater velocity is in the range of 0.2 to 0.5 m/yr, and temperature ranges from 30 to 83 °C. Groundwater salinity is low at the margins of the basin, but increases with depth and along the flow lines.' These deep aquifers are as yet untapped but are potentially important groundwater resources.

Figure 5.6.6 The Canning Basin, in the northwest of the continent



Great Artesian Basin

The 'Great Artesian Basin' covers 1.7 x 10^6 km^2 and is one of the largest groundwater basins in the world. It underlies parts of Queensland, New South Wales, South Australia and the Northern Territory. It comprises several sedimentary basins: the Carpentaria, Eromanga and Surat Basins;

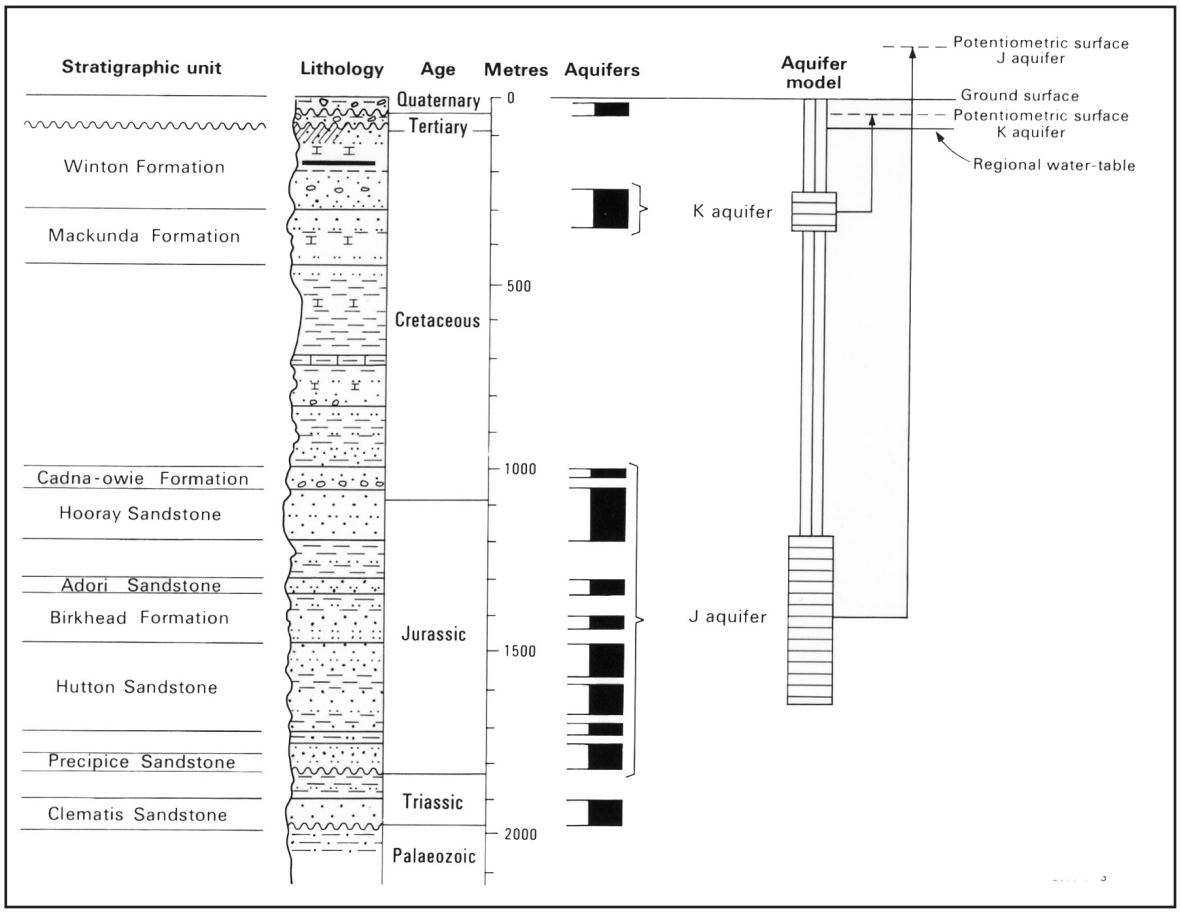
and the upper parts of the underlying Bowen and Galilee Basins. It is a multi-layered confined aquifer system, with the main aquifers occurring in Mesozoic sandstone (Habermehl, 1980) which is interbedded with mudstone (Fig. 5.6.7). The basin is up to 3,000 m thick and forms a very large synclinal structure, uplifted and exposed along its eastern marginal zone and tilted southwest. Recharge is mainly by rainfall on the eastern margin. The potentiometric surfaces of the lower, mainly Jurassic sandstone, aquifers are above ground level in most areas of the basin. The potentiometric surfaces of the upper, mainly Cretaceous sandstone, aquifers are below the ground surface throughout most of the basin.

More than 4,000 flowing artesian bores have been drilled to depths of up to 2,000 m and individual bore flows exceeding 100 l/s have been recorded (Habermehl, 1980). The total discharge is about 500×10^6 m^3/yr to water bores. Many of these bores flow uncontrolled and water is wasted by seepage and evaporation; some have ceased to flow because of dimishing pressure head. Conservation of this groundwater is now a matter of concern, and a major project to rehabilitate the uncontrolled artesian bores is under way (Palmer and MacNamara, 1991; Hazell, 1991). There are also about 20,000 non-flowing artesian bores, mainly in the higher aquifers.

The best quality groundwater occurs in the lower, mainly Jurassic, aquifer system which generally contains 500 to 1,000 mg/l TDS; these are mainly sodium bicarbonate waters with salinity increasing towards the centre of the Basin (Habermehl, 1980). The upper, mainly Cretaceous, aquifer is more saline. High fluoride concentrations are a problem for domestic water supplies in parts of the Basin.

The temperatures of groundwater in the Great Artesian Basin range up to 121 °C, and the

Figure 5.6.7 **Multi-layered confined aquifer system, with the main aquifers occurring in Mesozoic sandstone**



mean geothermal gradient in the basin is 48 °C/km (Polak and Horsfall, 1979). Hot water is used as an energy source on a small scale in the Basin. There are significant prospects of generating geothermal energy from hot rock in one of the component basins, the Eromanga Basin (Wyborn, 1995).

In the Great Artesian Basin groundwater ages up to 2 million years have been measured using the radioisotope chlorine-36 (Airey et al., 1983; Bentley et al., 1986) and are comparable with hydraulically calculated groundwater flow times.

The natural discharge of this very large basin is to springs around the basin margin, including a number of travertine mound springs (Habermehl, 1982). The Dalhousie Springs in South Australia form an important oasis, with many endemic animals. This complex includes 100 springs and mounds spread over an area of 70 km^2 (Zeidler and Ponder, 1989). Diffuse natural discharge from the Great Artesian Basin has been calculated by Woods et al. (1991) to be about 1.4 x 10^6 m^3/day. This compares with the measured discharge from bores of 1.5 x 10^6 m^3/day and from springs, of 0.13 x 10^6 m^3/day.

The largest single groundwater withdrawal from the Basin is 4 x 10^6 m^3/yr for a large mine in South Australia (Waterhouse and Armstrong, 1991). Drawdown at this site is regulated to protect natural spring discharge and associated wetland features. The other main use of the groundwater is for livestock watering, and the occurrence of the deep artesian water has enabled the pastoral industry to occupy otherwise arid areas. A numerical simulation model was developed for this large basin (Seidel, 1980) and is now being upgraded by the Australian Geological Survey Organisation.

The Carpentaria Basin is a northern extension of the Great Artesian Basin (Fig. 5.6.2). Its major widespread aquifer, the Jurassic Gilbert River Formation, has flowing artesian bores (Lait, 1991). However this aquifer has significant water quality problems, being corrosive, with a high fluoride content. There are important groundwater resources in the Late Cretaceous and Tertiary sediments that overlie the Carpentaria Basin.

Murray Basin

The Murray Basin is a Cainozoic sedimentary basin, extending over 300,000 km^2 in southeast Australia (Fig. 5.6.5). It is an important agricultural region but suffers from a serious and growing problem of land and water salinisation caused by rising water tables. This is due to the clearing of native vegetation for dryland agriculture in the recharge zones of the basin over the 150 years of European settlement, and also because of the irrigation of poorly drained soils. The Murray River, Australia's largest river in terms of flow, drains the basin and is affected by increased salinity, to the detriment of important urban and rural water supplies along its course.

The Murray Basin is essentially a closed groundwater system. The Cainozoic sand and limestone aquifers are recharged by streamflow at the basin margins and by direct infiltration of rainfall. Groundwater discharges into the Murray River and to numerous playas (Fig. 5.6.8), many of which have been re-activated by rising water tables. The occurrence of groundwater discharge zones in the Murray Basin is influenced by subsurface permeability barriers which disrupt groundwater flow and cause upwards groundwater movement (Telfer, 1991; Lindsay and Barnett, 1989).

Aquifer/aquitard relationships in the Murray Basin are shown schematically in Figure 5.6.9. The main fluvial sand unit of the Palaeocene-Early Oligocene sequence is the Renmark Group, which is up to 300 m thick (Brown and Stephenson, 1991). The Late Oligocene- Middle Miocene sequence contains shallow-marine limestones collectively known as the Murray Group, and marginal-marine clays and marls of the Geera Clay and Winnambool Formation. In the eastern part of the basin, the Renmark Group extends up into the Miocene and partly envelops the Geera

Figure 5.6.8 Groundwater discharges into the Murray River and to numerous playas

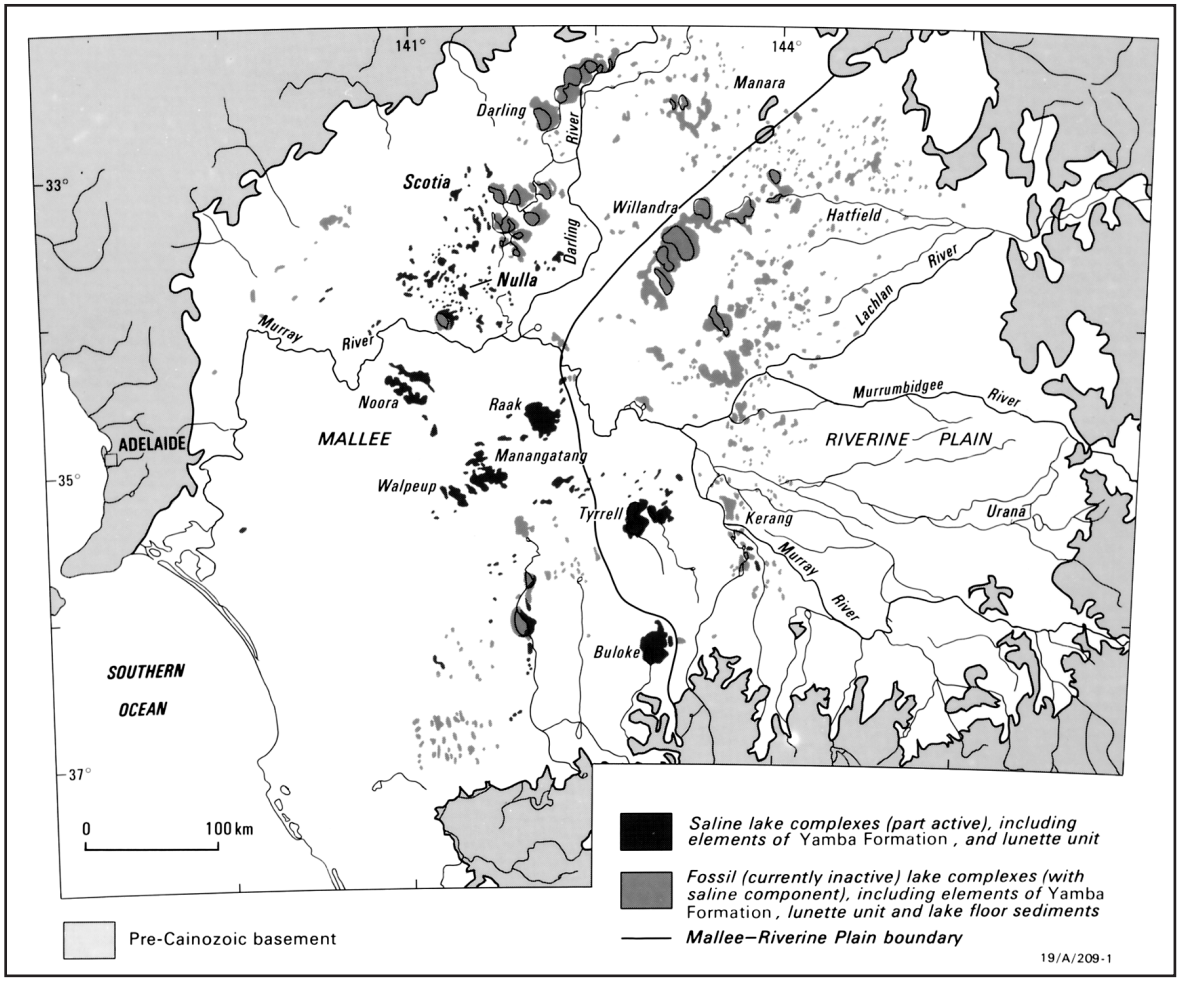
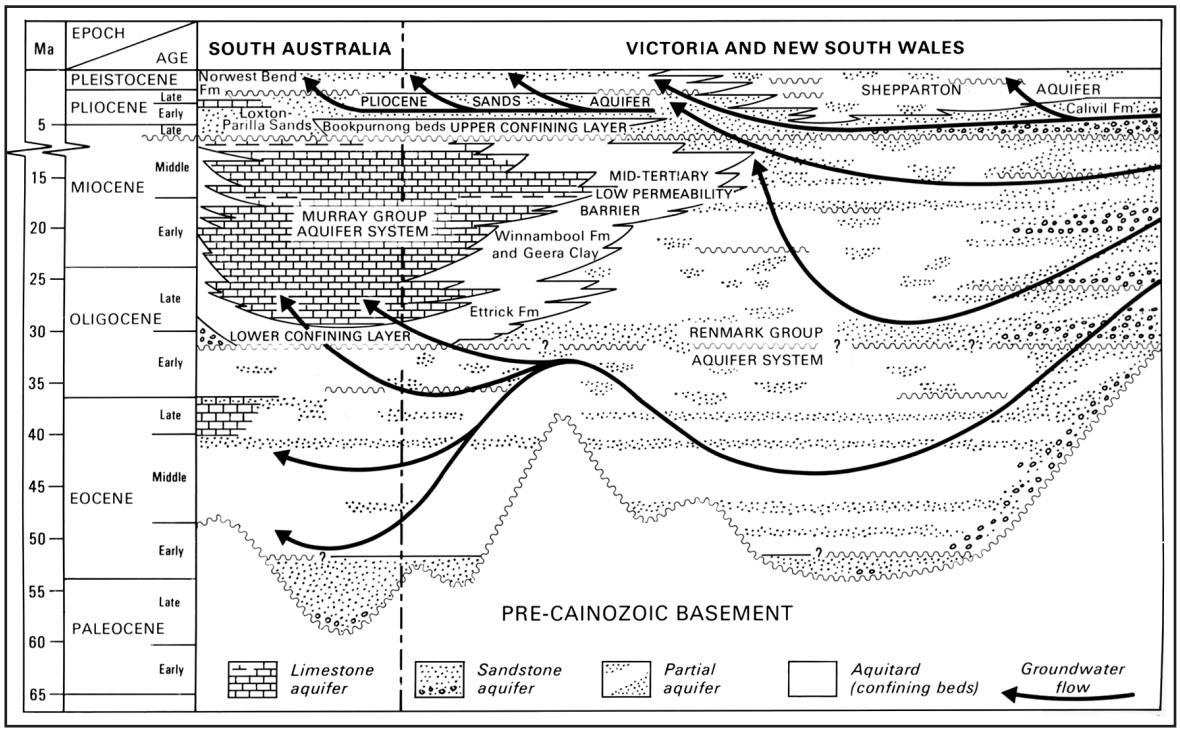


Figure 5.6.9 Aquifer/aquitard relationships in the Murray Basin



Clay. The Late Miocene-Pliocene sequence contains an important Pliocene marine sand unit, the Loxton-Parilla Sands, in the west, and a widespread Pliocene fluviatile unit, the Calivil Formation, in the east. These units are overlain, in the east of the basin, by the Shepparton Formation, comprising clay, silt and sand, of Pliocene to Quaternary age.

The main aquifers are the Renmark Group, the Murray Group Limestone, the Pliocene Sand aquifer (which is a composite of the Loxton-Parilla Sands and the Calivil Formation), and the Shepparton Formation (Evans et al., 1990). The Renmark Group forms the basal aquifer throughout the basin. It is recharged around the basin margin, and groundwater flow is inwards, towards the west-central depocentre of the basin, where it leaks upwards into the Murray Group aquifer (Fig. 5.6.9).

The Murray Group Limestone aquifer is best developed south of the River Murray where it is an important freshwater source. The aquifer is more saline immediately north of the river, where it may be partly recharged by upwards leakage from the Renmark Group. The Murray Group groundwater flows towards the Murray River, where its discharge is the main cause of significantly increasing river salinity in South Australia. The travel time along a 300 km flowline is estimated at 150,000 years (Davie et al., 1989).

The Pliocene Sand aquifer is widespread in the basin; it is generally unconfined in the west, but is partly confined by Quaternary units in the east. It is recharged around the basin margin by infiltrating rainfall where the aquifer is unconfined; by downwards leakage from the overlying Shepparton Formation; and by channel bed leakage from streams in the Riverine Plain. The aquifer contains fresh water at the eastern margins but is saline elsewhere. The Pliocene Sand aquifer in the west of the basin has a similar chemical composition to that of seawater in many respects (Macumber, 1991).

The main aquitard in the Murray Basin is a composite of mid-Tertiary low permeability clays and marls (Winnambool Formation, Geera Clay) that extend in an arc about 100 km wide through the centre of the basin (Evans and Kellett, 1989). This low-permeability barrier disrupts lateral groundwater flow in the middle and upper parts of the Renmark Group, and controls the distribution of groundwater discharge zones (Brown and Radke, 1989). In the west and south, the Renmark Group is separated from the Murray Group Limestone by a lower confining layer, the Ettrick Formation (Evans et al., 1990). The eastern part of the Murray Group Limestone is separated from the Pliocene Sand by an upper confining layer, the Bookpurnong Beds.

The regional aquifers of the Murray Basin can be divided areally into three distinct provinces: the Riverine province in the east (Fig. 5.6.8); the Mallee-Limestone province in the southwest; and the Scotia province in the northwest (Evans and Kellett, 1989). The Riverine province contains highly productive alluvial fan aquifers. The most productive individual water bore in Australia is sited in these fan deposits at Coleambally, New South Wales; it produces 400 l/s of water, which is used for irrigating wheat.

The Scotia groundwater province in western New South Wales contains numerous groundwater discharge complexes (Jacobson et al., 1994; Ferguson et al., 1992). In this province, groundwater flows from north to south, in the shallow unconfined Pliocene Sand aquifer, in the Murray Group limestone, and in the deeper, confined Renmark Group aquifer. These aquifers are separated by low-permeability units: the Geera Clay, Winnambool Formation and Bookpurnong Beds. Recharge to the major aquifers is from ephemeral streams on the northwest margin of the basin, and from the Darling River, and recharge to the Pliocene Sand is also by direct infiltration of rainfall.

The climate in the west-central part of the Basin, the Mallee region (Fig. 5.6.8), is semi-arid, with annual rainfall about 300 mm, and pan evaporation about 2,200 mm. Under these conditions, the amount of groundwater recharge ranges from 0.04–0.08 mm/yr beneath sand dunes with native vegetation (Allison and Hughes, 1983) to 3–10 mm/yr beneath cleared and cropped land

(Cook and Walker, 1989). This increase in recharge resulting from land clearing has caused water tables to rise and has led to severe dryland salinity problems. The fundamental reason for the basin-wide rise in water tables is the increased hydraulic pressure generated by land clearing along the foothills of the Great Dividing Range, which is the main regional recharge zone.

The natural salinity of groundwaters in the Basin is variable, ranging up to 300 g/l TDS. In general, the better quality water is found around the basin margins, with salinity increasing down flow towards the basin centre. Man-induced changes to the hydrologic regime have increased salinity by remobilising existing salt stores or by concentrating salt in the near surface zone by evaporation.

Otway Basin

The Otway Basin extends 24,000 km^2 across the Victoria-South Australia border, and contains two major aquifer systems each with groundwater salinity less than 1,000 mg/l TDS. The confined aquifers of the Early Tertiary Wangerrip Group are separated from the overlying Quaternary-Upper Tertiary aquifers by an Upper Tertiary aquitard (Love et al., 1993). The confined aquifers are high-yielding and supply several towns including Geelong. A regional flow system with interaquifer mixing has been recognized from hydraulic head distribution, environmental isotopes and hydrochemical data (Love et al., 1993). The Blue Lake at Mt Gambier is fed by water from both aquifers. In the Port Philip Sub-basin the principal aquifer is the confined Fyansford Formation-Brighton Group system, comprising mainly Tertiary sands.

An important unconfined aquifer, the Gambier Limestone, overlies parts of both the Murray Basin and the Otway Basin, as well as the Padthaway Ridge that divides these two basins. The limestone is up to 300 m thick and is of Eocene to Miocene age (Brown and Stephenson, 1991). The regional groundwater flow is coastwards, N–S near Mt Gambier and E–W near Naracoorte (Waterhouse, 1977). Using lysimeters Holmes and Colville (1970*a*,*b*) determined the annual water balance for grassland areas as: rainfall 632 mm, evaporation 588 mm, recharge 63 mm. In forested areas, evapotranspiration was much greater and recharge was negligible. Using environmental chloride and tritium, Allison and Hughes (1978) determined annual recharge as between 50 and 250 mm in cleared areas, depending on local soil types. Discharge from the system is to coastal and submarine springs and to coastal lakes, some of which are hypersaline through evaporation (Burne and Ferguson, 1983).

Most water bores in the Gambier Limestone have salinity less than 600 mg/l TDS, and these groundwaters are mainly of the Ca-Na bicarbonate type. However, a considerable part of the Gambier Limestone aquifer contains high nitrate groundwaters (> 45 mg/l NO_3) and these have been the subject of considerable investigation (Forth, 1981). Sources of nitrate are both 'diffuse' and 'point-source'. The diffuse source is mainly livestock urine leached from leguminous pasture (Dillon, 1988), and this is the legacy of a century of grazing. The point sources include dairies, cheese factories, and abattoirs.

Quaternary limestone of the Bridgewater and Padthaway Formations forms an important aquifer used for irrigation at Padthaway. Stresses on this aquifer have been reflected in deteriorating water quality, as salt is recycled into the aquifer (Harris and Stadter, 1987), and management controls have been introduced.

Love et al. (1994) evaluated the palaeohydrology of the confined Dilwyn Sand aquifer (Wangerrip Group). Hydraulic data indicated a mean residence time of about 49,000 years for groundwater flowing to the sea, whereas the radiocarbon data indicated a mean residence time of about 12,800 years. Love et al. (1994) suggested that the radiocarbon data reflects lower sea level in the last glacial period resulting in increased hydraulic gradients and a decrease in groundwater

residence time. The present-day water levels, which determine the hydraulically calculated travel time, are related to the present, relatively high, sea level.

Perth Basin

The Perth Basin extends for 800 km along the west coast of Australia (Fig. 5.6.2) and ranges from 15 to 90 km wide onshore; its areal extent is about 60,000 km^2. The basin contains some 15,000 m of sediments deposited in a graben. Fresh groundwater occurs in the upper 2,000 m of the sequence. The most important aquifers are the Quaternary Kwinana Group (or 'superficial formations'), and Mesozoic sandstones in two major structural troughs (Commander et al., 1991). The Kwinana Group, ranging from coastal limestones to interbedded sand and gravel at the foot of the Darling Range, is an unconfined aquifer. The Mesozoic sandstones include: the Cretaceous Leederville Formation, the Jurassic-Cretaceous Yarragadee Formation and the Jurassic Cockleshell Gully Formation. These three sandstones are confined aquifers which are sometimes hydraulically connected, but generally form discrete flow systems. Hydrodynamic studies by Thorpe and Davidson (1991) show that groundwater flows westwards in these aquifers at 1–12 m/yr to discharge into the ocean, and that recharge rates are low.

The Perth Basin contains a large groundwater storage, estimated as 1,000 x 10^9 m^3 and renewable groundwater resources of the order of 2,000 x 10^6 m^3/yr (Commander et al., 1991). Current abstraction from the Basin is about 300 x 10^6 m^3/yr and this is believed to be well within sustainable limits (Davidson, 1995) even though groundwater from the basin is of increasing importance to the Perth region and to inland towns. The water supply for Perth (population 1.2 million) is obtained from surface water reservoirs on the Darling Plateau and from both confined and unconfined groundwater. The groundwater is withdrawn from artesian bores in the Mesozoic sandstones and from the Quaternary 'superficial formations'. The groundwater from the 'superficial formations' requires treatment to remove dissolved iron, turbidity, and organic colouration before it can be used for public water supply. However, without treatment it is a readily available and suitable source for park and garden reticulation, industry and irrigation. There are an estimated 60,000 private water bores in the Perth urban area.

The confined aquifers provide about 10% of the total Perth water use, and their management strategy has been outlined by Banyard and Davidson (1991). The policy is to limit private abstraction to users for whom the confined aquifer is the only possible source; to reserve good quality water for users that depend on it; to limit abstraction to the equivalent of modern recharge; to limit decline in hydraulic head in order to prevent seawater intrusion; and to permit 'mining' of the resource only when recharge and storage are too small to satisfy water demand. A case study south of Perth has shown that the Leederville Formation aquifer has a low hydraulic gradient, and that the aquifer is 'full' but that additional recharge could be induced by additional pumping (Wharton, 1991). However seawater has intruded the Yarragadee Formation aquifer at Bunbury, south of Perth (McNulty, 1991).

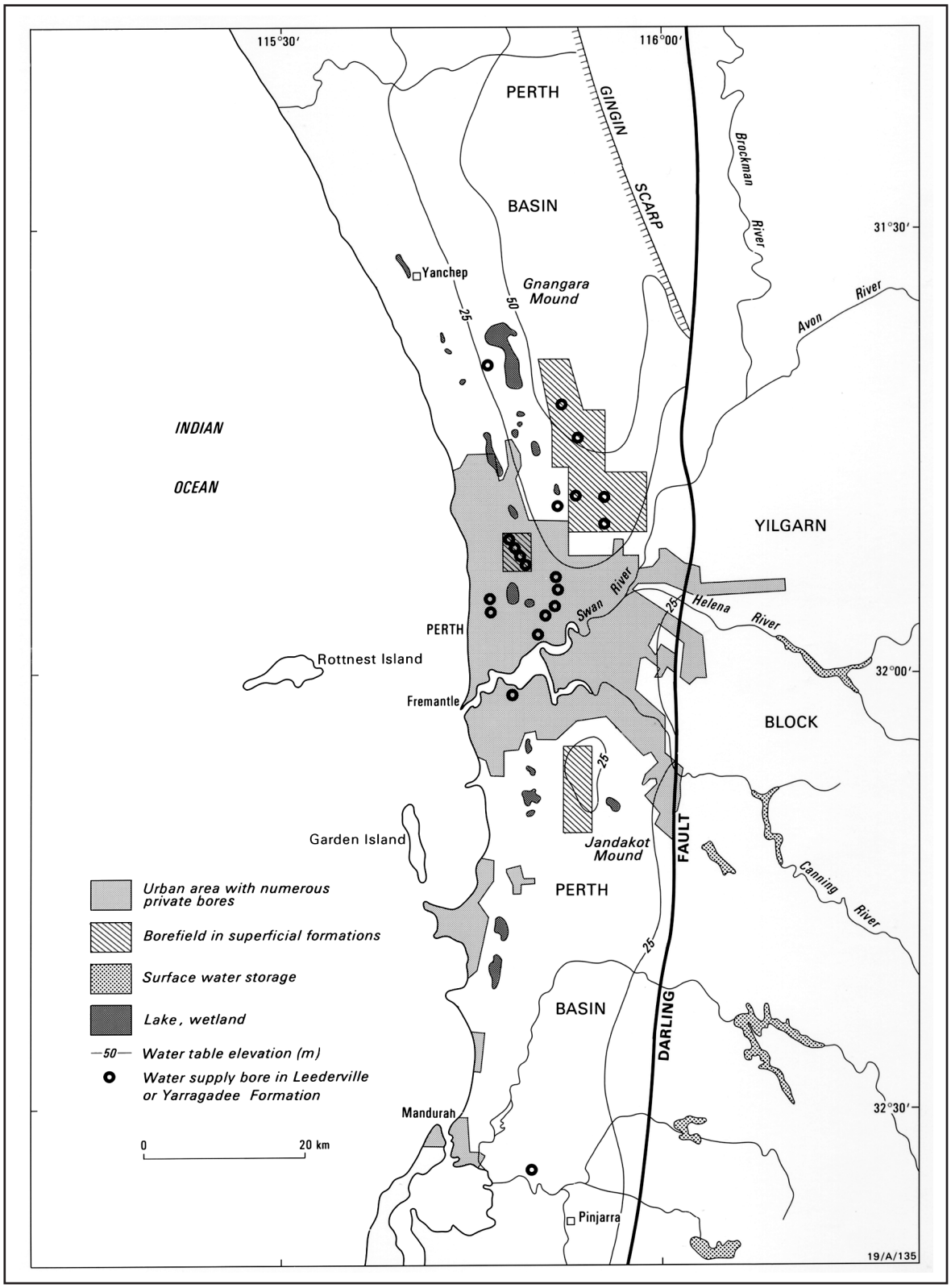
A significant number of pollution incidents has occurred in the Quaternary aquifers of the Perth Basin and a regional overview of vulnerability to pollution has been given by Appleyard (1991). Maintaining water levels in wetlands that are hydraulically connected with the Quaternary aquifers is also a major concern (Fig. 5.6.10).

Two areas in the Perth Basin have geothermal gradients above 40 °C/km and there is some potential for geothermal energy development (Bestow, 1991).

Eucla Basin

The Eucla Basin covers an area of 230,000 km^2 in South Australia and Western Australia (Fig. 5.6.2)

Figure 5.6.10 Maintaining water levels in wetlands that are hydraulically connected with the Quaternary aquifers is also a major concern



and contains downwarped shallow-marine sediments up to 600 m thick, which range in age from Early Cretaceous to mid-Miocene. The basin contains two aquifer systems. An upper unconfined aquifer comprises several Tertiary limestone units as well as the Tertiary basal sandstone. A lower,

confined aquifer consists of Early Cretaceous sandstones, the Madura Formation and the Loongana Sandstone (Lowry, 1970; Shepherd, 1983), as well as weathered granitic bedrock (Commander, 1991). Groundwater salinity is generally greater than 1,400 mg/l in both aquifers, with the fresher water in the northern margin of the unconfined aquifer. There is a large area of brackish water in the confined aquifer in the centre of the basin, and groundwater is desalinated for aboriginal community water supplies in this region.

There are important karst features in the limestone, which forms the Nullarbor Plain, one of the largest arid-zone karst areas in the world (Gillieson et al., 1994). The water table is up to 100 m deep, with spectacular underground lakes several kilometres long in some caves.

Officer Basin

The Officer Basin covers 275,000 km^2 of South Australia and Western Australia (Fig. 5.6.2). It contains a thick, gently folded sequence of Late Proterozoic sedimentary rocks overlain by a relatively thin, flat-lying Cambrian to Cretaceous sequence. The main porous aquifers are considered to be the Wanna Beds and the Lennis Sandstone, the Paterson Formation, and the Samuel Formation (Lau et al., 1995). The basin sediments are overlain by an extensive palaeodrainage system which contains useful calcrete aquifers.

Groundwater flows south to discharge at the surface in playa complexes and at depth to the Eucla Basin. Groundwater storage in the Cambrian-Ordovician unit is reduced both by stratigraphic thinning and by decreasing porosity and permeability toward the base of the sequence. The Wirrildar Beds are impermeable mudstones which project above the potentiometric surface and act as a partial barrier to horizontal groundwater flow from the Officer Basin to the Eucla Basin.

In the South Australian portion of the Officer Basin significant groundwater resources have so far been found only on the northern margin at the petroleum exploration well Birksgate No. 1, and in a broad area centred on Mintabie (Read, 1990). It is believed that recharge to the Basin has occurred mainly in this northern area and that groundwater salinity increases downgradient.

In the Western Australian half of the Officer Basin, fresh groundwater is relatively widespread especially in the Permian Paterson Formation, which possibly consists of glacial alluvial-fan sediments (Commander, 1991; Iasky, 1990). Commander (personal communication, 1994) considers that recharge occurs on the interfluves of palaeodrainages and that most bores sited on interfluves and away from playas ought to obtain fresh water.

Four major fractured-rock groundwater provinces have been recognized in Australia (Fig. 5.6.11) on the basis of major structural elements and climate (Lau et al., 1987).

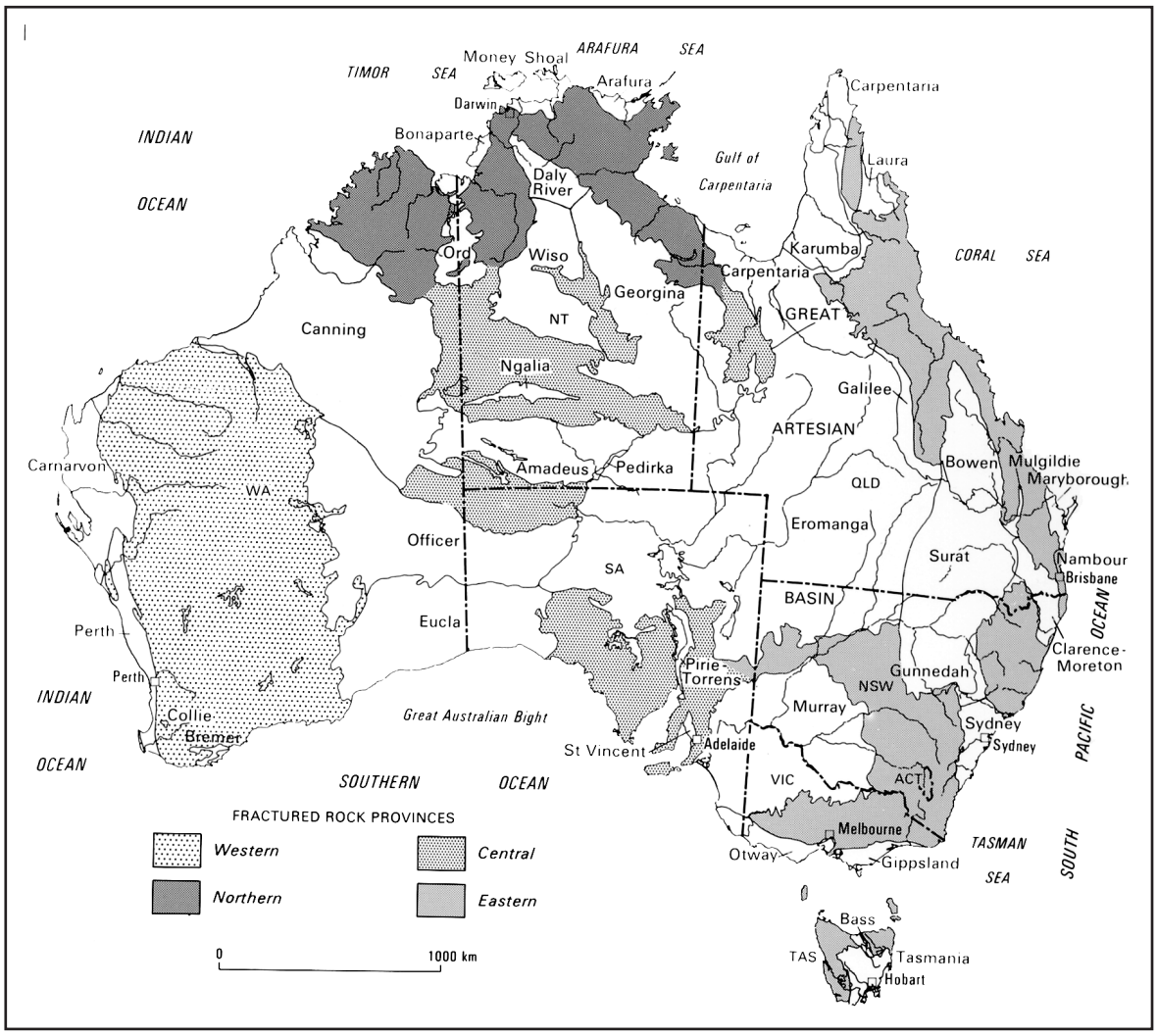
The Western Province

The Western Fractured-Rock Aquifer Province (Fig. 5.6.11) consists of two major Archaean metamorphic blocks separated by Proterozoic mobile belts; the latter are overlain and flanked by relatively undeformed Proterozoic platform cover. The two Archaean blocks, the Yilgarn and Pilbara Blocks, consist of complexes of granite, greenstone and high-grade metamorphic rocks. The Proterozoic mobile belts contain sedimentary and metamorphic rocks, and granite.

Within this province, topography changes from a low deeply weathered plain in the south to the dissected plateaux and ranges of the Hamersley and Bangemall Basins in the north. The climate changes from one of regular winter rainfall in the southwest to one of irregular summer rainfall, in the north. An annual rainfall deficit exists over the province, and perennial streams occur only in the southwest corner.

Deep laterite profiles occur on the Yilgarn Block and generally enhance the storage charac-

Figure 5.6.11 Four major fractured-rock groundwater provinces recognized in Australia



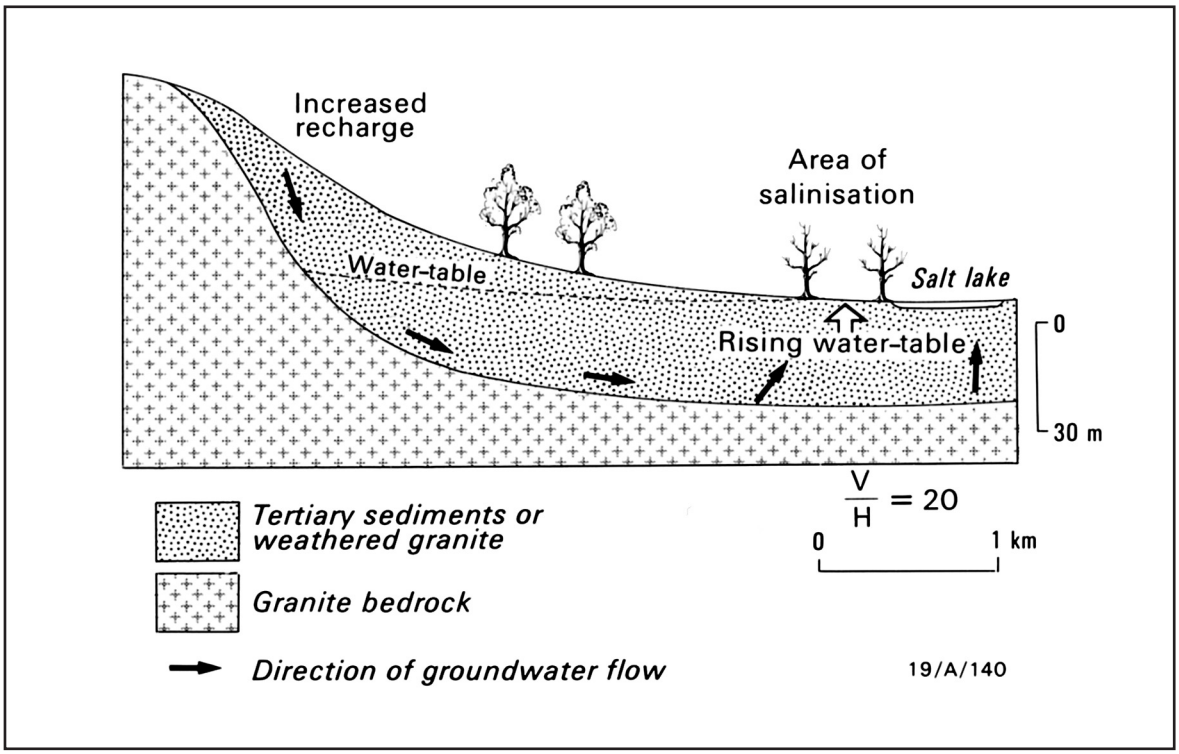
teristics of the fractured rock aquifers (Whincup and Domahidy, 1982). In the southwest of this province a widespread but ephemeral shallow aquifer recharges a permanent, deeper, fractured rock aquifer through vertical root channels (Johnston et al., 1983). Increasing salinity affects many streams in the southwest of this province and a large amount of agricultural land has been salinized (George et al., 1997). This major problem has been caused by clearing of native vegetation for agriculture leading to rising water tables over a timescale of several decades (Fig. 5.6.12).

The Northern Province

The Northern Fractured-Rock Aquifer Province (Fig. 5.6.11) comprises several large pre-Cambrian structural units, and Cambrian and younger platform cover, in the high rainfall area of northern Australia. The overlying units include flatlying Cambrian volcanics, particularly the Antrim Plateau Volcanics of the Victoria River district which attain a maximum thickness of 1,000 m. The Antrim Plateau volcanics underlie the cattle-grazing lands of the Victoria River District, and aquifers within this unit include vesicular basalt zones as well as interbedded sandstones (Randal, 1973).

In the Pine Creek Geosyncline, the Proterozoic Coomalie Dolomite and its overlying

Figure 5.6.12 Native vegetation for agriculture leading to rising water tables over a timescale of several decades



Cretaceous sediments contain high yielding bores which augment Darwin's surface water supply (Verma and Qureshi, 1982). Fractured Proterozoic schist provides high groundwater yields for pipeline supply to the Jabiru regional centre. In the Kimberley Basin, Proterozoic sandstones produce high bore yields for the mining towns of Yampi Sound (Bar-Joseph, 1985).

Within the Northern province the annual rainfall ranges from 400 mm in the headwaters of the Victoria River to 1,200 mm at Gove, and occurs mainly in summer. The annual evaporation averages 3,000 mm. The perennial streams are fed by groundwater, and five major rivers, the Fitzroy, Ord, Victoria, Daly and Roper Rivers, drain to the sea.

The Central Province

The Central Fractured-Rock Aquifer Province (Fig. 5.6.11) contains rocks of mainly Precambrian age in the arid regions of central and southern Australia. These rocks include the Archaean granites and metamorphic rocks of the Gawler Block; metamorphosed Early Proterozoic geosynclinal sediments and granite in the Broken Hill, Arunta, Granites-Tanami and Tennant Creek Blocks; basalt, metasediments and granite in the Arunta, Musgrave and Broken Hill Blocks; and Late Proterozoic-Cambrian platform sediments in the Adelaide Fold Belt and the Stuart Shelf. Topographic relief is generally less than 500 m except in the central Australian ranges and the Flinders-Mount Lofty Ranges of South Australia.

Development of two wellfields at the mining town of Leigh Creek (Waterhouse and Read, 1982) provides a case-study of fractured rock aquifers in the Adelaide Fold Belt. Groundwater was required to augment erratic surface water supplies from a nearby dam. Water of up to 5,000 mg/l TDS was acceptable as feed water for a reverse osmosis plant for domestic supply; water of poorer quality was acceptable for industrial use. Both wellfields were sited on favourable lithologies near rivers which were thought to provide recharge, either directly, or indirectly through ephemeral aquifers in river bed alluvium. Better quality water (TDS 1,500 mg/l) and a

deep watertable characterize the Emu Creek wellfield in which geological structure is complex, disrupted by a major thrust fault. Poorer quality water (TDS 6,000 mg/l) and a shallow watertable with intermittent groundwater discharge characterize the Windy Creek wellfield in which geological structure is simple and permeability of the target bed decreases downdip. Faulting has therefore created radically different groundwater conditions at two sites of similar surface hydrology and rock type.

At Kintore, in central Australia, groundwater is drawn from a Proterozoic fractured basalt aquifer; in this situation the complex structure does not allow prediction of aquifer geometry (Wischusen, 1994). Modern recharge occurs at this locality, focussed by an ephemeral stream, and the groundwater quality is about 800 mg/lTDS.

High salinity groundwaters are a major constraint on water supply development in the fractured rocks of the Arunta Block, Central Australia (Knott and McDonald, 1983) and in the fractured rock aquifers of South Australia (Cobb et al., 1982). Naturally occurring deleterious elements in groundwater, such as nitrate and fluoride, are also a significant constraint. Some relatively fresh groundwaters in fractured rock aquifers (less than 1,000 mg/l TDS) contain high nitrate concentrations (50–150 mg/l NO_3). The nitrate in these surficial aquifers is derived from surficial biological processes (Barnes et al., 1992). The fluoride commonly occurs in shallow aquifers in granitic rocks with little modern recharge, and long residence times. Recently it has become apparent that many shallow, fractured rock aquifers in central Australia also contain significant concentrations of toxic elements such as uranium, selenium and boron (Hostetler et al., 1998).

The Eastern Province

The Eastern Fractured-Rock Aquifer Province (Fig. 5.6.11) comprises Palaeozoic rocks of the high and moderate rainfall zone of eastern mainland Australia and Tasmania. Most of the area is above 200 m in altitude with parts of the Eastern Highlands above 1,000 m. Rainfall varies from summer-dominant in the north to winter-dominant in western Victoria and northern Tasmania. Western Tasmania receives annual rainfall of about 2,400 mm and northern Queensland receives about 3,200 mm. Drainage is eastward to the Pacific Ocean or southwest to the Southern Ocean via the Murray-Darling system.

The Eastern Province comprises rocks of various ages including deformed Middle Proterozoic sedimentary rocks and granite in the Coen and Georgetown Blocks; Late Proterozoic metasedimentary rocks and granite in the Lyenna and Rocky Cape Blocks of western Tasmania; and Palaeozoic sedimentary and low grade metamorphic rocks in the Lachlan Fold Belt.

In Canberra and its environs, in southeast Australia, groundwater occurs in fractured sedimentary and volcanic rock aquifers and granite of the Lachlan Fold Belt. This region has an annual rainfall of 650 mm and evaporation of 2,000 mm. Under these conditions, groundwater recharge is by the infiltration of rainfall into open rock fractures in hilly areas with skeletal soils. In the valleys, a high potentiometric surface is common, and in places causes upwards flow to the surface forming springs and swampy ground. This has resulted in seepage problems affecting urban development. Water bore yields in the fractured rock aquifers range from 0.1 to 5 l/s, with the higher yields obtained in fault zones. Groundwater salinity is in the range 200 to 2,000 mg/l TDS. Groundwater resources are developed for rural water supplies and for urban irrigation, although the main urban water supply is from surface water catchments.

Norfolk Island, in the southwest Pacific Ocean, has an area of 35 km^2 and rises to an elevation of 300 m (Abell and Falkland, 1991). It is a basaltic volcanic complex with a deep weathering profile. The island has an upper, water-table aquifer in weathered rock, and semi-confined aquifers in the underlying network of fractures. Groundwater recharge is about 30% of

the incident rainfall. Groundwater abstraction is about 0.2 x 10^6 m^3/yr, which is about half of the water used on the island, and there is scope for additional development of the deeper aquifers (Abell and Falkland, 1991).

In the rocky Torres Strait Islands between Australia and Papua New Guinea, severe water shortages in the dry season deleteriously affect the health of the islanders (Henderson et al. 1995), and have led to proposals for upgrading island water supplies. There are abundant groundwater resources on Badu Island, a large granite island, and extension of shallow wellfields or deeper drilling has been recommended as the best solution to the water supply problem. Other considerations for future water supply strategy in the Torres Strait Islands are that rainwater storage needs to be upgraded on an individual and community basis, and that dual supply systems need to be considered on smaller islands that have inadequate water resources.

There is an emerging problem of dryland salinity consequent on land clearing in the upland catchments of the Lachlan Fold Belt in southeast Australia (Acworth et al., 1997; Bradd et al., 1997).

5.6.2 Groundwater assessment

The last comprehensive review of Australia's groundwater resources was done in 1985 (Department of Primary Industries and Energy, 1987). The review considered divertible groundwater resources, defined as: 'the average annual volume of water which, using current technology, could be removed from developed or potential ... groundwater resources on a sustained basis, without causing adverse effects or long-term depletion of storages.' The divertible groundwater resources were further classified into major or minor depending on the magnitude of the resource. Thus, major divertible groundwater resources were defined as those capable of supplying sufficient water to sustain a small town or irrigation development, and this was assumed to be about 500,000 m^3/yr. Minor divertible groundwater resources were defined as those too small or scattered to be diverted for major water supplies.

Table 5.6.2.1 shows the major divertible groundwater resources of different salinity ranges by aquifer type. Table 5.6.2.2 shows the minor divertible groundwater resources of different salinity ranges by aquifer type. The total divertible groundwater resources of Australia are of the order of 30 x 10^9 m^3.

Table 5.6.2.1 Australia : major divertible groundwater resources (DPIE, 1987)

Aquifer type	*Area (10^3 km^2)*	*Fresh (10^6 m^3)*	*Marginal (10^6 m^3)*	*Brackish (10^6 m^3)*	*Saline (10^6 m^3)*	*Total (10^6 m^3)*	*Abstraction 1983–4 (10^6 m^3)*
Surficial	413	2,430	1,300	596	220	4,540	1,070
Sedimentary	3,380	2,280	5,390	1,140	581	9,390	1,100
Fractured	1,430	150	188	97	35	470	64
Total		4,860	6,880	1,830	836	14,400	2,240

Table 5.6.2.2 Australia : minor divertible groundwater resources (DPIE, 1987)

Aquifer type	*Area (10^3 km^2)*	*Fresh (10^6 m^3)*	*Marginal (10^6 m^3)*	*Brackish (10^6 m^3)*	*Saline (10^6 m^3)*	*Total (10^6 m^3)*	*Abstraction 1983–4 (10^6 m^3)*
Surficial	1,040	986	1,190	623	927	3,720	53
Sedimentary	2,860	1,520	2,080	1,170	716	5,490	109
Fractured	2,650	1,450	2,130	2,230	841	6,660	234
Total		3,960	5,400	4,020	2,480	15,900	396

5.6.3 Total groundwater use

The total amount of groundwater used in Australia annually was about 2,460 x 10^6 m^3 in 1983, equivalent to about 14% of the total amount of water used. Groundwater was drawn from about 500,000 water bores (tubewells). The greatest concentrations of water bores are near Perth and Adelaide, in southeast South Australia and western Victoria, and on the central Queensland coast.

In Australia, the surficial aquifers are generally the groundwater sources most intensively used for irrigation and for urban and industrial water supplies. The intensive use of groundwater in some areas, especially for irrigation, has led to the overdevelopment of some regional aquifers. This has occurred in at least 13 regions and is manifest as low water-tables or increased salinity (Jacobson and Lau, 1988). Most of these areas are now proclaimed as controlled zones under the relevant State legislation, and the extraction of groundwater is limited. In some of these areas artificial recharge is used to balance the excessive groundwater extraction: in others, groundwater and surface water are used conjunctively to ameliorate the effects of demand exceeding supply.

The potential for production of industrial brines has not yet been fully investigated and the geothermal resources of Australia are, as yet, little used.

The components of groundwater use are estimated to be: irrigation use 1,640 x 10^6 m^3; urban and industrial use 480 x 10^6 m^3; and other rural uses including livestock 340 x 10^6 m^3 (Jacobson et al., 1983). Throughout the country groundwater is used for small-scale agricultural and domestic water supplies, and several hundred small towns and communities depend on groundwater. Groundwater is vital to the pastoral industry (cattle and sheep) throughout large parts of Australia, and the mining industry is also heavily dependent on groundwater.

5.6.4 Groundwater pollution

An inventory of 144 documented groundwater contamination incidents in Australia was compiled by Jacobson and Lau (1994), mainly from published case studies and government sources. It is believed that there are many more incidents where information is in private hands and there may be many more undiscovered incidents (Knight, 1993). A wide range of contaminant sources is involved, including industrial effluent, sewage and landfill leachate.

Several important regional aquifers are affected by pollution, including: the Quaternary sand aquifers of the Perth Basin; the Gambier Limestone; Quaternary volcanic rocks and the Tertiary sand aquifers near Melbourne; the Botany Sands aquifer in Sydney; and fractured Silurian sedimentary rocks at Canberra (Jacobson, 1983). These are all shallow unconfined aquifers that underlie regions of intensive urban, industrial or agricultural development. Recent investigations have also shown widespread pollution of surficial aquifers by agrichemicals including pesticides, with up to 50% of some agricultural districts affected (Bauld, 1996).

The legislative and institutional framework for groundwater quality management varies in Australia, between and within states. This has led to a diversity of approach to groundwater quality management. Growing awareness of these issues within a number of national policy-setting fora has led to the development of Groundwater Protection Guidelines by the Australian Water Resources Council (1992). These are intended to provide a broad national framework within which state and local agencies can develop their own specific resource protection measures. In these Guidelines the goal of groundwater protection is stated as '... to protect the groundwater resources of the state ... to ... support their identified beneficial uses in an economically, socially and environmentally sustainable and acceptable manner'. This goal relies on an hierarchical framework of existing or potential beneficial uses for the water in an aquifer. The identified beneficial uses of groundwater comprise: human consumption and food production; agricultural,

industrial and mining uses; and ecosystem support. There is also a classification of no definable beneficial use, which allows for possible controlled degradation of the aquifer.

According to the Groundwater Protection Guidelines (AWRC, 1992), the designated beneficial use classification of an aquifer should be that of the most valuable potential use of that water. Once the beneficial use determination has been assigned, the obligation for protection of groundwater under this framework lies with the industry or activity which has the potential to contaminate the groundwater resource. The concept of beneficial use can be used further to define 'pollution' as occurring when the water quality has deteriorated to a point where the existing or potential beneficial uses are diminished.

The main components of the proposed groundwater protection strategy are: particular forms of government intervention, including consideration of the 'polluter pays' principle; and legislation, which includes groundwater management, land-use planning, and environmental protection legislation. Groundwater management strategies can include: the planning framework; vulnerability and vulnerability mapping; aquifer classification systems; levels of action for classified groundwaters; and well-head protection plans. Land use planning and environment protection strategies may also be developed under various legislative powers. Development of a regional groundwater protection plan requires public involvement, strategic assessment of groundwater resources, and definition of beneficial uses.

The Guidelines have been framed so that they can be adapted to different regulatory situations in the states. Implementation will require co-ordination between agencies with different functions. The national goal for the coming decade is to protect those groundwater resources that are used for drinking water or that support important ecosystems; and also to provide a beneficial use classification for all other aquifers.

The groundwater protection guidelines form part of the National Water Quality Management Strategy which was developed by the Australian and New Zealand Environment and Conservation Council and the Australian Water Resources Council (1992). This Strategy provides a framework within which State government agencies can institute complementary policies and programmes for water quality management. The Australian federal and state governments are currently negotiating an Intergovernmental Agreement on the Environment. It is expected that national standards for water quality, assessment of contaminated sites, and hazardous waste management will be developed under this Agreement.

In Australia, salinisation is part of the nation's most serious environmental problem, land degradation, and threatens the sustainability of agriculture and the quality of major surface water resources. About 5 million ha of land are affected, and the situation is worsening. A major concern is that a large part of Australia's major agricultural region, the Murray-Darling catchment, is affected by both irrigated and dryland salinisation. For instance, in the Mallee region of the Murray Basin, widespread clearing of native vegetation has increased recharge by up to two orders of magnitude, and rising water tables have salinized low-lying areas and increased saline groundwater inflows to the Murray River (Barnett, 1989). This has caused huge losses of agricultural production, and also a serious deterioration in the quality of Australia's largest river system.

The serious threat that salinisation poses to agriculture and ecosystems in the southwest of Western Australia (Fig. 5.6.4.1) has been outlined by George et al. (1997). They comment that:

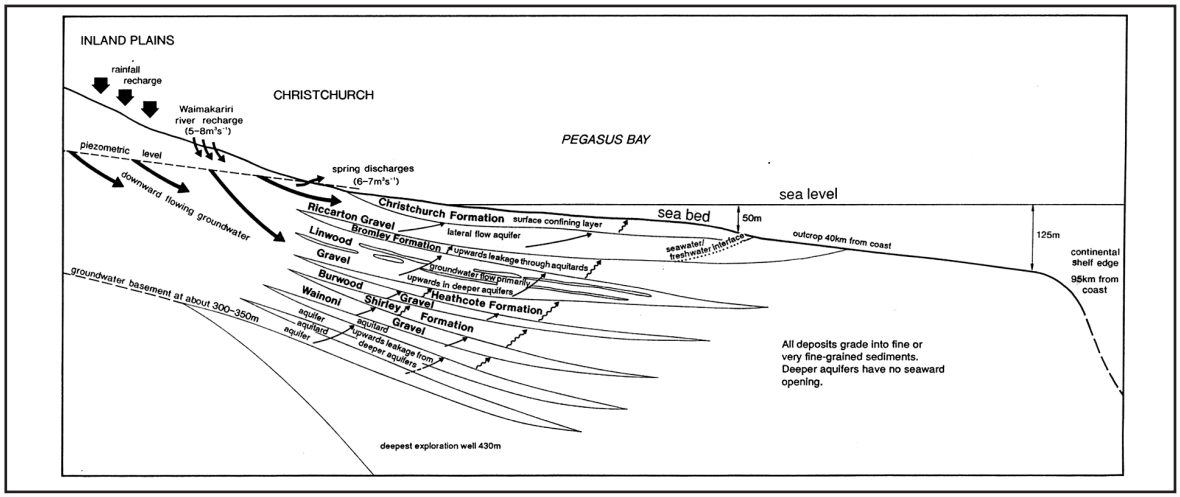
> In Western Australia an abundance of salt within the deeply-weathered soil profiles and the clearing of native vegetation have resulted in unparalleled hydrological changes and extensive salinisation. Groundwater levels have risen by over 30 m and aquifers occur in catchments where, before land clearing, none existed. Aquifers vary from structurally-controlled, poorly-connected and 'cell-like' at the local scale (weathered, fractured rock systems) to well-developed and interconnected at the

intermediate to regional scale (sedimentary, palaeochannel or major 'fault' systems). Currently more than 1.8 million ha (9.4%) of cleared farmland in Western Australia is salt-affected. The affected area is expected to double within the next twenty-five years and double again before reaching a new equilibrium.

Salinity in streams is increasing by 10 to 90 mg/l each year. As a result, large areas of remnant vegetation, and the biological diversity it contains, are threatened .... Salinity management must be based on a good knowledge of hydrogeological systems. Land managers must have access to cost-effective methods of treatment and packages of biophysical information which can be used to design and predict the impact of physical and economic management systems. There are few cost-effective methods and it is difficult to predict the effects of treatments on biophysical and economic factors. A complex hydrogeology has contributed to low predictability.

The fate of Western Australia's agriculture, water resources and natural environment depends on acknowledging the lessons of the past and investing in the future. Priority areas for hydrologic research must be identified and management methods that are currently available need to be incorporated into new, locally-based, 'higher water use' farming systems. (George et al., 1997)

Figure 5.6.4.1 Aquifer-aquiclude sequence underlying the city of Christchurch on the Canterbury Plains (Brown, 1994)



The use of groundwater simulation models and their linkage to options for salinity management strategies have been the subject of a detailed regional study in Western Australia by Gomboso et al. (1997). Mapping and assessing salinity hazard is an important ongoing task in Australia (e.g. Bradd et al., 1997; Tickell, 1997).

5.6.5 Groundwater management, artificial recharge

A number of significant surficial aquifers are stressed through overpumping (Table 5.6.1.1). The conjunctive use of surface water and groundwater, and artificial recharge, have been used to manage these aquifers.

The largest groundwater withdrawal in Australia is about 330×10^6 m^3/yr from the Burdekin River delta in North Queensland. This is achieved by artificial recharge totalling more than 200 m^3/yr. The artificial recharge scheme is supplied by water drawn from the Burdekin River, and uses natural and artificial channels, recharge pits and tidal barrages (Hillier, 1993).

Reduction of the groundwater overdraft in a Tertiary limestone aquifer in the Angas-Bremer

basin, South Australia, has been achieved by reducing allocations through a process of community consultations (Harris, 1993). Heavy withdrawals for irrigation (21 x 10^6 m^3/yr) had led to declining water levels and increased salinity.

In the Australian arid zone, the ubiquity of saline groundwater makes desalination an important option for small town supplies. In addition many of the 900 remote Aboriginal communities depend on groundwater, and a significant proportion of these small and generally arid settlements have serious problems with water supplies (Federal Race Discrimination Commissioner, 1994).

Major environmental issues related to groundwater discharge are emerging as a result of the intensified urbanisation of the Australian coastal zone, as well as agricultural development in the hinterland catchments. These issues include the eutrophication of coastal waters in southwest Australia owing to the discharge of nutrients from sewage, fertilizers and industrial effluent. This problem contains a substantial groundwater component; remedial strategies are being developed, including reduction of fertilizer use.

Acidic drainage from acid sulphate soils on Holocene coastal plains along the eastern Australian coastline is a major constraint on economic development and also a significant environmental impact. Drainage of these soils for urban and other development has resulted in the oxidation of pyrite and consequently the acidification of groundwater and estuarine water.

Significant degradation of the Great Barrier Reef has occurred through the export of nutrients from North Queensland catchments to the coastal zone. The nutrients are mainly derived from fertilizers used in sugar cane and other farming. This problem may contain a groundwater component.

Seawater intrusion is a problem in several important regional aquifers along the east and south coasts of Australia. Management strategies include the conjunctive use of surface water for irrigation, and artificial recharge of coastal aquifers (Hillier, 1993).

5.6.6 Future groundwater use and sustainability

The Council of Australian Governments has recently endorsed a program of reform of the 'water industry' in Australia which includes a proposed national framework for improved groundwater management (ARMCANZ, 1996). Key reforms are intended to: promote the efficient, sustainable use of groundwater; enable identification of the sustainable yield, allocation and use of aquifers; remove restrictions on groundwater use imposed by inefficiently designed or constructed wells; establish systems to support transferability of groundwater entitlements; improve integration of groundwater and surface water management; and expand a national driller's licensing scheme. In addition, there is provision for management and licensing of high yielding wells and there are requirements for drillers to provide well construction data for all wells drilled. Arrangements will be introduced to provide full recovery of direct costs of groundwater management.

A National Land and Water Audit is presently being developed as a foundation for future management of the nation's resources, including groundwater.

Several large groundwater basins cross State borders in Australia, and are the subject of inter-State agreements. The aquifers of the Murray Basin are partly controlled by the Murray-Darling Basin Ministerial Council which comprises ministers from the Commonwealth Government and each of the State governments that have an interest. The Great Artesian Basin is now coming under the review of a Consultative Council, which includes participating governments and other stakeholders. The limestone aquifers of the Otway Basin extend across the Victoria-South Australia border and their use in the border zone is controlled by an inter-state agreement.

5.6.7 Main aquifers, groundwater use and management of New Zealand

New Zealand is located in the southwest Pacific Ocean at one of the major tectonic plate boundaries of the world. Interaction between the plates has produced a 1,200 km long narrow northeast-southwest trending land of two main islands and several smaller islands of total area 270,000 km^2. Southwest of the South Island the Pacific plate is pushing over the Australian plate, while under the North Island the Pacific plate is being thrust beneath the Australian plate. Between these opposing subduction systems, the New Zealand landmass is being twisted and torn by complex tectonic processes with horizontal (faulting) and vertical (folding) movement. Buckling of the crust has uplifted an axial mountain range and magma ascends through crustal fractures to the surface to form volcanoes (Brown, 1992).

Erosion of the axial mountain range which is predominantly greywacke (indurated sandstone) and transport of the eroded debris by rivers, produces durable gravel clasts which build extensive fans, river channels, deltas and floodplains. Erosion and deposition processes have been enhanced by the alternating cold to temperate climate cycles of the Quaternary. Deposition has filled subsiding coastal basins with layered fluvial gravels which form aquifer systems; marine silts and sands deposited when the climate was warm and sea level high, form intervening aquicludes and aquitards underlying the plains. Figure 5.6.7.1 shows the aquifer-aquiclude sequence underlying the city of Christchurch on the Canterbury Plains (Brown, 1994).

Extensive areas of volcanic rock with fractures and porous rubbly interflow layers, form another important aquifer type. Older sedimentary rock sequences contain high yielding karstic limestone aquifers but the older sandstones, siltstones and mudstones are generally low yielding.

Metamorphic rocks form the 'basement' rocks underlying the mountain ranges of New Zealand. High water yields can be obtained where bores intercept fissure zones but generally these rocks are impermeable. The distribution of these regional hydrogeological units is shown on Figure 5.6.7.2.

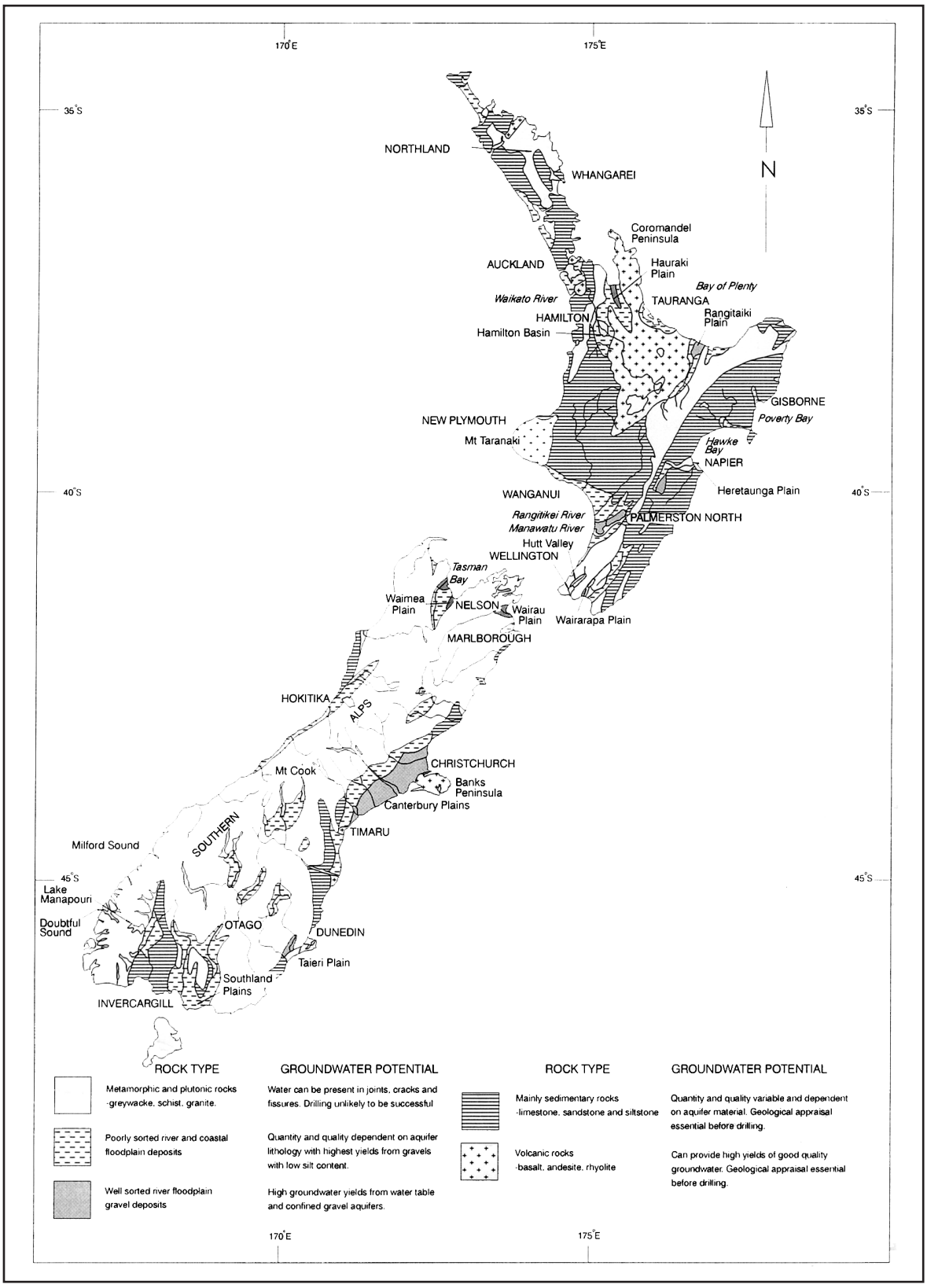
In addition to these aquifers New Zealand has many geothermal fields and areas of warm to hot groundwater (Thompson et al., 1995); these are shown in Figure 5.6.7.3. High temperature geothermal fields occur in the central North Island Rotorua-Taupo volcanic region where heat from magma in the crust drives hot fluid (water and minor gas) circulation and accumulation in reservoir rocks. Faults and fractures provide conduits for the upflow of superheated water. Hot groundwater and springs are associated with recently extinct volcanic fields (e.g. Auckland), the deep circulation of groundwater along permeable or active faults (e.g. South Island), and heating of groundwater by slow circulation through laterally extensive aquifers at depth (e.g. East Coast, North Island).

Hot springs are important for recreational and therapeutic bathing. New Zealand was one of the first countries to drill wells to tap and use geothermal energy for electricity generation with the commissioning of the 180 MW Wairakei power station in 1963. Since then several geothermal power stations and other applications utilizing the heating and drying properties of the steam and hot water, have been constructed. Tourism is a major industry based on the geothermal resources.

The river floodplain aquifers are the most important of the aquifer types as they underlie the extensive late Quaternary plains on the east coast of both the North and South Islands. The plains are flat lying, the fertile soils can be readily cultivated, and support intense agriculture and horticulture when water is available for irrigation to supplement unpredictable rain.

The Resource Management Act (RMA) of 1991 was designed to promote the sustainable management of natural and physical resources including groundwater. Under the RMA, resource management is a statutory responsibility of regional government. Regional Councils monitor aquifer systems to acquire knowledge of the hydrogeology, groundwater recharge source, flow path, rate of flow, and outflows (natural and abstractive) – so that response to imposed stresses of

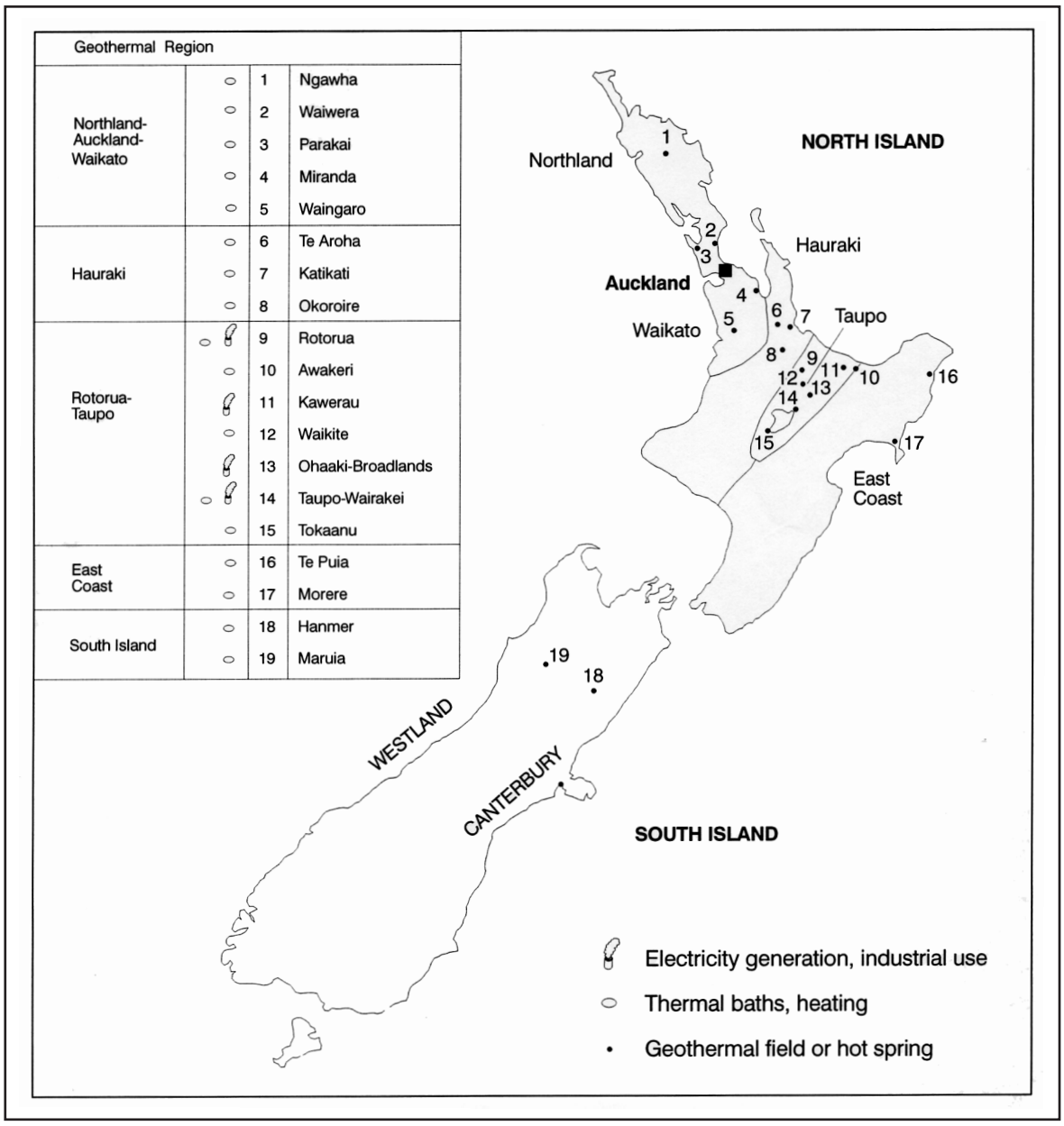
Figure 5.6.7.1 Distribution of regional hydrogeological units



over exploitation and pollution can be predicted, detected, and prevented. Sustainable management of the groundwater resources is the goal (Brown, 1994).

Until 1950 the New Zealand economy was agricultural, with 'dry farming' of sheep and

Figure 5.6.7.2 New Zealand geothermal fields and areas of warm to hot groundwater (Thompson et al., 1995)

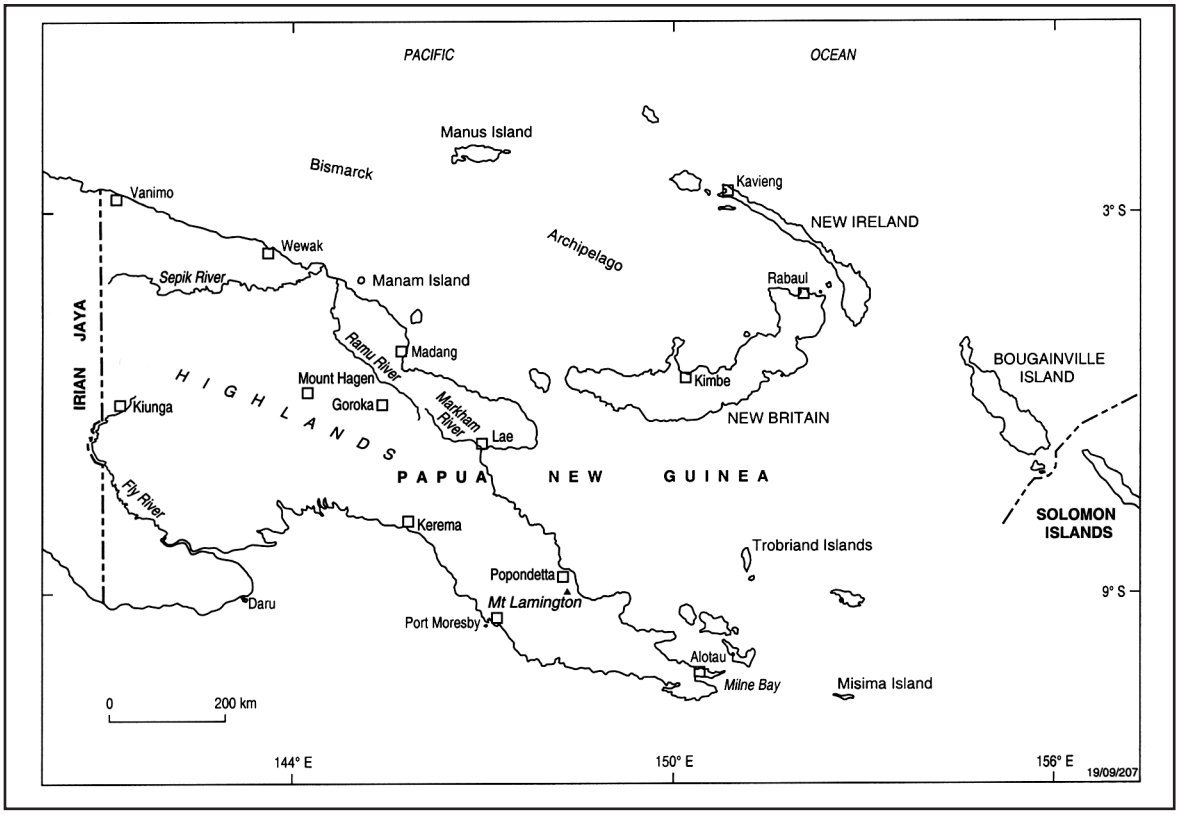


cattle the main land use. Over the last 50 years agriculture has become more diverse with the production of crops, fruit, vegetables and grapes, and more milk production from dairy farming. This has been achieved with irrigation including irrigation from groundwater. Industries including aluminium smelting, steel manufacture, paper mills, and fruit, vegetable, meat and dairy product processing plants, are also dependent on water supply from groundwater. Many New Zealand towns and cities obtain public water supplies from wells, and farms often use wells for domestic and livestock water supplies.

Several important regional aquifers have been investigated in recent years, including aquifers underlying the Canterbury Plains, the Waimea Plains in Nelson Province, the Wairau Plain in Marlborough Province, the Heretaunga Plains at Hawkes Bay (Dravid and Brown, 1997) and the Hutt Valley (Fig. 5.6.7.2).

The geothermal resources of New Zealand have been documented extensively (e.g. Thain,

Figure 5.6.7.3 PNG's borders



1995). Geothermally generated electric power totals about 300 MW annually, from four fields, the largest being Wairakei.

The Maori people used rivers, streams and springs for water supply and thermal springs for cooking. Freshwater and mineral water springs were often reserved for curative and medicinal use. Maori were very careful to keep water sources clean and were amazed by the European colonists' disregard for protecting water supply from pollution. The Europeans (1840 onwards) used springs and streams until the water was polluted and water borne diseases became a problem. Shallow wells were then dug but these were also prone to pollution from nearby cesspools. Pipe wells were driven into unconsolidated sediments and with the advent of the steam engine, rigs capable of drilling through layered and consolidated sediments were available to drill deep water bores.

At several locations, especially on the coastal plains, drilling encountered artesian aquifers with groundwater flowing from the well at above ground level. Flowing artesian aquifers provided excellent quality groundwater without the need for pumping and hundreds of wells were drilled for household and industry supplies. Groundwater levels declined as more and more wells were drilled with many wells flowing to waste.

In the first half of the twentieth century, wells were drilled throughout New Zealand for water supply for industry, town water supply and domestic and livestock use on farms with the only concern being the availability of a reliable aquifer supply source. Since the 1950s, the diversification of agriculture with irrigation has resulted in an increase in the number of wells drilled and the quantity of groundwater abstracted. Also technology advancement with the development of downhole electric pumps provided a convenient means of pumping large quantities of water from deep aquifers.

Now groundwater supplies about 800 x 10^6 m^3/yr or 42% of the total New Zealand annual

water consumption (Brown, 1992). In terms of population, groundwater provides the total water requirements of about 25% of New Zealanders and part of the water requirements of another 20%.

To mitigate against drought, irrigation is used on a small but important 2% (240,000 ha) of the total area of land used for agriculture. This irrigation use of groundwater accounts for 60% of total groundwater consumption in New Zealand. The main increase for groundwater demand in recent years has been from expansion of dairy farming with irrigation of pasture for maintaining milk production.

Water supply for cities and towns is the next most important use of groundwater. The cities of Napier, Hastings, Rotorua, Palmerston North, Lower Hutt, Blenheim and Christchurch, use groundwater as do the towns of Kaikohe, Tokoroa, Havelock North, Picton, Ashburton and Gore. Cities including Auckland, Wanganui, Palmerston North, Wellington, Nelson and Dunedin, are partly dependent on groundwater. At least 1.5 million city and town people rely on groundwater-based water supply and account for 30% of New Zealand groundwater use.

The meat processing industry is a major industrial consumer of groundwater. Processing plants throughout New Zealand have their own wells and water supply. Recent amalgamations of dairy factories with a few large factories replacing many small factories has resulted in reduced but concentrated groundwater demand. Other industrial demand for groundwater from steel and aluminium refining, paper manufacture, beer brewing, and fruit and vegetable processing, has remained relatively static for over a decade.

Another important groundwater use is for rural household and livestock water supplies, which do not need to be approved or registered with regional councils. It is estimated that rural water supply and industrial water use accounts for 10% of New Zealand's groundwater use.

Whether or not groundwater is used as a source of water supply depends on availability, reliability and cost of alternative supply sources, good quality, and the value of the product. For the east coast alluvial plains, groundwater is generally the only option because it provides a reliable, readily available, on site, good quality water supply source. Water supply for the city of Christchurch (population 350,000) is pumped directly from wells into the reticulation system without treatment. The ready availability of groundwater allows industry such as meat processing plants to be sited near production sources (i.e. farms). Cities such as Wellington which derive their water supply from both groundwater and surface water sources are better able to cope with shortages imposed by drought-affected surface water supplies. Surface water supplies are also vulnerable to damage from natural hazards such as volcanic eruption, earthquake and severe storms (Brown, 1995).

Volcanic rocks provide some of the highest yielding aquifers in New Zealand. Springs flowing from volcanic rocks are the source of Rotorua's water supply. Auckland's water was derived from groundwater beneath basalt flows until pollution from the Auckland became significant in 1908. The spring supply continued to be used until 1928 and is now retained as an emergency water supply to supplement surface reservoir supplies.

Monitoring of groundwater quality in New Zealand is routine where it is used for city, town, or water supply for concentrated groups of people (e.g. schools). There is now an awareness of the relationship between the intensity of land use and groundwater quality. The expansion of dairy farming has resulted in an increase in nitrate levels in shallow groundwater aquifers. Agriculture and horticulture operations with application of fertilsers, herbicides and pesticides is resulting in residues entering groundwater. Surface drainage, accidental spills and leaks are other causes of groundwater pollution. In the 1980s petrol leaking from underground storage tanks overlying the recharge zone of the Hutt Valley aquifer system resulted in an extensive clean-up operation to retrieve the petrol before it moved into the confined aquifer. At Masterton in the Wairarapa Valley a spill of timber preservative concentrate containing chrome and arsenic compounds contaminated groundwater up to 2 km downstream of the spillage. For several

months wells in the area could not be used for drinking water and potable water was delivered by tanker to those affected. Another industrial pollutant detected in New Zealand groundwater is chlorofluorocarbons (CFCs). These are used in refrigeration and air conditioning, and for pressurising aerosol cans, and are released to the atmosphere, absorbed by water and enter groundwater through recharge. CFCs in groundwater do have one useful function in that they can be used to age groundwater to complement tritium dating for determining groundwater flow rate and residence time in aquifers.

Contaminated sites pose a threat to groundwater quality. These include operating and closed landfills, industrial sites such as former coal gas production works, paper mills, timber treatment plants and storage depots with bad housekeeping resulting in regular spillage of contaminants. Waste or process water disposal from sites ranging in size from meat processing plants to cow milking sheds and household septic tanks, pollutes groundwater when the waste is discharged onto or into the ground.

Protection of groundwater from pollution is a requirement of the RMA. There is provision for the control of the use and storage of hazardous substances specifically to prevent their release into the environment. This is achieved by the implementation of industry Codes of Practice to ensure that appropriate environmental protection measures are installed for the manufacture, storage, transport and use of hazardous substances. The cleaning up of sites that are already contaminated and that pose a threat to groundwater quality is problematic in terms of who will meet the cost. The general principle applied is that of the market-based approach – the polluter pays. Often the original contaminator has moved on and it is not possible to identify an appropriate alternative. In these cases it may be required that the groundwater resource user pays, with the definition of 'user' depending on the specific circumstances (Beanland and Brown, 1994).

Increasing groundwater abstraction from aquifer systems can result in deteriorating groundwater quality as mineralized groundwater from adjacent and underlying aquifers, or sea water, enters the main aquifer system to replace abstracted groundwater. The Heretaunga Plains aquifer at Hawkes Bay has this problem with inflow of mineralized groundwater from adjacent limestone, sandstone and siltstone aquifers (Brown et al., 1998). The sandstone aquifers of North Otago, and the gravel aquifers of Poverty Bay, yield groundwater that can only be used after treatment to reduce the iron content. In New Zealand, groundwater and thermal systems commonly mix so that the chemical components in groundwater derived from thermal systems may preclude its use for specific purposes. For instance, groundwater with a high arsenic content may be unsuitable for domestic water supply or groundwater with a high boron content may be unsuitable for irrigation of certain crops.

Different regional councils have different priorities for managing groundwater resources for maintaining availability and quality. For groundwater quality, guidelines adapted by central government ministries (Ministry for the Environment) to control landuse practices are applied under the RMA. These guidelines include: constructing landfill sites with an impermeable base to stop leachate seeping into groundwater; and restricting subdivision of land to reduce concentrations of septic tanks. Other polluting landuse such as cattle feedlots, and industry disposing of process water by irrigation, are also carefully controlled and monitored. Guidelines for the transport, storage and use of a range of hazardous materials have also been formulated and applied.

The requirements for management of groundwater quantity aspects is generally not so clear as for many aquifer systems the sustainable yield is not yet known. Also for most aquifer systems the quantity of groundwater abstracted is not measured. The policy of installation of meters on wells for all major users of groundwater including irrigators is gradually being promoted by regional councils. There is debate as to whether naturally flowing artesian wells should be maintained or whether more groundwater abstraction should be allowed resulting in all well owners installing pumps. Groundwater abstraction is often linked with surface water flows. For

the city of Christchurch, groundwater-sourced springs provide the base flow of rivers and streams that flow through the city. During the summer, spring flow decreases with increasing groundwater abstraction, and river and stream flows decrease. The local Christchurch rivers and streams are a major scenic and tourist attraction and the preservation of the spring flow may impose restrictions on groundwater abstraction (Brown and Weeber, 1992).

The delineation of Catchment Water Management Plans or Groundwater Management Areas by Regional Councils is a management practise applied where a specific area may have a specific groundwater problem. In Wellington Harbour at the Hutt Valley coast, dredging near the mouth of the Hutt River caused a pressure decline in coastal wells when the aquifer confining bed was penetrated. Pressure was restored by refilling the hole with excavation material and river sediment, but the loosening of the overburden has weakened the confining beds, and leaks have been observed in this area since that time. The realisation of the sensitive nature of the aquifer confining bed has resulted in a plan that controls all drilling and excavation 8 m below the surface in the Hutt Valley, and all drilling and excavation in the harbour.

As infiltration from the beds of the floodplain rivers is the main source of groundwater recharge for the floodplain gravel aquifers, changes to the river bed can affect the recharge process. During the 1960s the Hutt River was eroding into its bed in an area where surface flow losses were measured. This was in response to gravel extraction from the river bed. Also silt and clay from wash water from quarries and gravel extraction plants was discharged into the river. In the Lower Hutt valley a steady decline of artesian head of wells (1 m in 4 years) had been measured. The decline in groundwater level was attributed to the lowering of the river bed and the impeding of influent seepage from the river by silt and clay. Controls were imposed on gravel extraction and on the discharge of washing water. Groundwater levels returned to normal in a few years.

The regional council periodically 'rakes' the Hutt River bed in the recharge zone to remove fine sediments and assist river seepage for recharging groundwater. A scheme designed to artificially recharge groundwater in the aquifer underlying the Heretaunga Plains, Hawkes Bay, diverts river water into infiltration ponds immediately adjacent to where the river flow naturally recharges the aquifer through gravel channels. There have been experiments on the Canterbury Plains inland of Christchurch which suggest that artificial groundwater recharge could be a useful augmentation management option.

Other groundwater management options such as the implementation of well spacing criteria, specification of depth requirements for wells in specified areas and transfer of water consents from area to area within an aquifer system, are being considered.

Groundwater discharge from aquifers offshore as springs on the seabed is known from fluvial gravel, limestone and volcanic rock aquifers. The first systematic attempt to measure the flow from submarine springs for an aquifer is being undertaken in Wellington Harbour for the Hutt Valley aquifer. In Hawke Bay offshore from the Heretaunga Plains, fresh water springs were located during a bathimetric survey in 1951. There has been concern about saltwater intrusion into confined aquifers beneath the Waimea Plains, Nelson, where summer groundwater abstraction reduced well heads below sea level. Recently a moratorium has been placed on additional groundwater allocations and rationing is imposed when coastal groundwater levels drop below a certain level. The Hutt Valley urban water supply was redesigned after a survey which indicated that coastal well fields created the potential for localized saltwater intrusion. New water supply wells were drilled 3–4 km inland and spread across the valley to reduce the impact of concentrated abstraction.

Seasonal saltwater intrusion has been noted in coastal aquifers at Tasman Bay, Nelson and at Heretaunga Plains, Hawkes Bay. At Hawkes Bay, wells in a coastal village at the eastern margin of the Heretaunga Plains, tapping a shallow, unconfined coarse sand aquifer showed increasing

high levels of various ions during a hot dry summer suggesting seawater intrusion. The water quality subsequently improved over the winter.

It is anticipated that the current trend of increasing groundwater use for crop irrigation will continue. This is driven by the overseas demand for the wide variety of fruit and vegetable products that it is possible to grow in New Zealand when a reliable water supply is available. Also continued expansion of vineyards for wine production and of dairy farming will require more groundwater supplies. Urban and industrial water supply demand is only likely to increase slowly with the application of 'user pays' policies and the installation of individual property water meters. Increased use of groundwater for irrigation will impact most on the east coast floodplain aquifer systems. Equitable allocation of the resource will affect the water requirements of all water users and assignment policies will need to consider cost benefit to the regions and the people living there as a whole.

Maintenance of groundwater quality in aquifer systems throughout New Zealand is the other critical factor determining the future sustainability of the country's groundwater resources (Brown et al., 1998). Groundwater quality is affected by both depletion of the groundwater resource, and by land use and point source pollution. Depressed water levels and pressures associated with concentrated groundwater abstraction results in the inflow of replacement groundwater which can be of inferior quality. The associated intensified land use compounds the problem as groundwater flow rates decline, and dilution and dispersion of contaminants becomes less effective. Integrated land and water use management practices will go some of the way to reducing the problem. The decision of when to irrigate and how much water to apply and at what rate on a given piece of land, for a particular crop, will need careful consideration by water users and resource managers if groundwater is to be conserved, competition for a dwindling resource is to be prevented, and quality maintained.

5.6.8 Main aquifers, groundwater use and management of Papua New Guinea

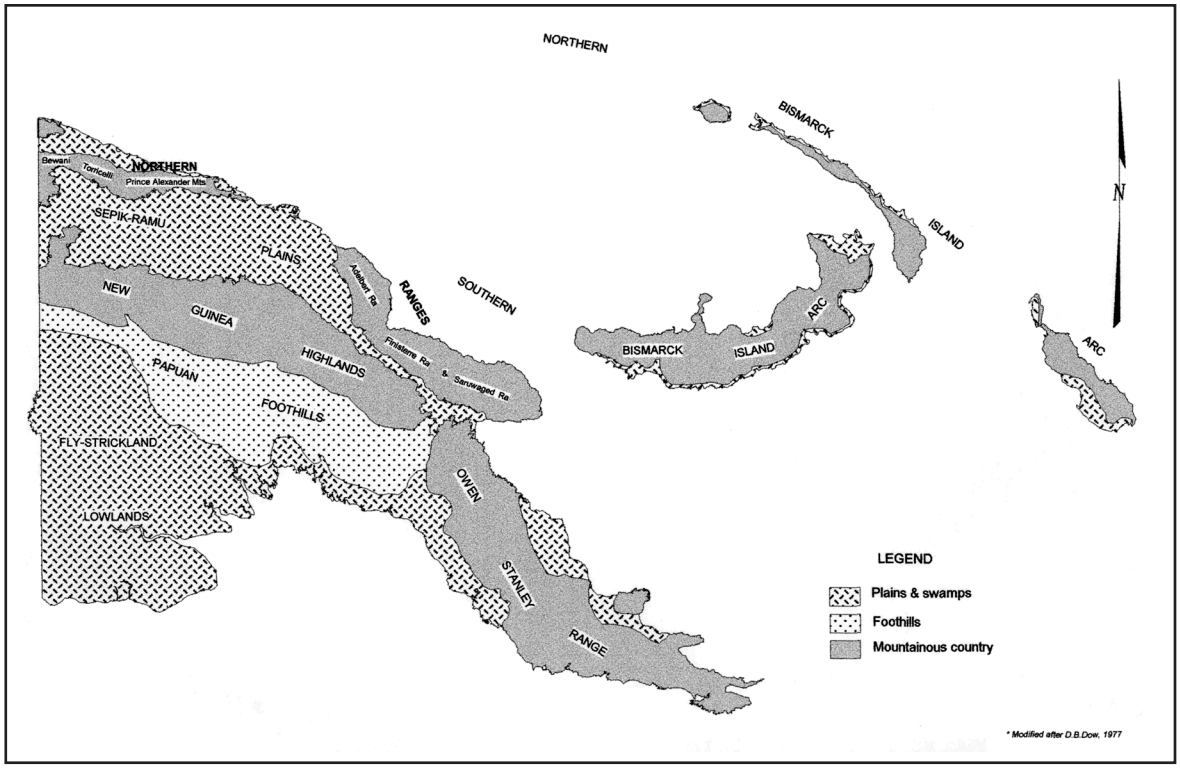
Papua New Guinea (PNG) comprises the eastern half of the island of New Guinea plus the major islands of the Bismarck Archipelago and the northernmost Solomon Island group as well as some 600 smaller islands. PNG's borders extend from the equator to 12°S and 141° to 161°E (Fig. 5.6.8.1) with a total land area of about 465,000 km^2 and a marine jurisidiction zone exceeding 2 million km^2.

PNG is perhaps unique among the developing countries of the South Pacific, with its large land mass and relatively low population (about 4 million). However, it faces the same problems that affect other developing countries in the region: a rapidly expanding population with increasing demands on its water resources including groundwater. Historically, investment in, and development of the country's water sector has been given a low priority.

The country can be divided into a number of geomorphological regions (Fig. 5.6.8.2) which generally closely follow the main structural regions. A deeply dissected, central mountain belt divides the mainland and also extends eastwards across the Bismarck Archipelago. Some of the 600 smaller islands are volcanic but many are low-lying coral atolls. There is an extensive lowland coastal strip where the majority of the coastal population resides.

The country has a wide range of climates but is generally classified as rainy tropical. Most of it has a mean annual rainfall between 2,000 and 3,500 mm, ranging from 1,000 mm along the coastal strip to 10,000 mm in the Western Highlands. Most areas of the country experience marked seasonal variations in rainfall, with the main exceptions along the Southern Fold Mountain Belt, and in the Wewak area and the outer islands. PNG experiences serious droughts which are

Figure 5.6.8.1 Main geomorphological regions of Papua New Guinea



irregular but recurring, and are related to El Niño events. The 1982–3, 1986–7, 1992–3 and 1997–8 droughts severely affected many parts of the country (Berhane and Tutton, 1997).

Mean annual temperatures range from 28 to 38°C in lowland areas with lower temperatures (24–26 °C) in the highlands with only small seasonal variations; temperature variations can be directly related to altitude. The prevailing warm and humid climate combined with fertile soils gives rise to a rich diverse vegetation and about three quarters of PNG is still covered by rain forest.

The geology of Papua New Guinea is complex; it is located on the junction between three major tectonic plates, the Indo-Australian, Pacific and Solomon Plates. The rocks which make up PNG are mainly Triassic-Quaternary in age.

The country can be subdivided into five main hydrogeological units (Fig. 5.6.8.3) based on their groundwater potential (Jacobson and Kidd, 1974) which is affected by factors such as lithology, porosity and fracturing. Other sub-divisions can be made, for instance, it is possible to include volcaniclastic deposits and differentiate between the various intrusive and metamorphic rocks. There are large areas of PNG where exploitation of groundwater is precluded by steep topography, deep water tables and total inaccessibility. More than 2,200 water bores have been drilled in PNG over the past 40 years.

This general term includes all the metamorphic, intrusive igneous rocks (basic and intermediate), and some sedimentary formations present in the mobile belt. These formations occur in a large part of the mainland of PNG including the Highlands and Papua, and extend east to the islands. These formations are characterized by low primary porosity and permeability; groundwater is present mainly in joints and fractures. Until recently these formations were generally considered to have low aquifer potential and no attempt was made to exploit them. However recent drilling in the Port Moresby area and at the Misima Island mine have shown that the groundwater resources of bedrock formations can be important.

The Port Moresby Beds are present throughout the National Capital District and consist of

Figure 5.6.8.2 Hydrogeological zonation of Papua New Guinea

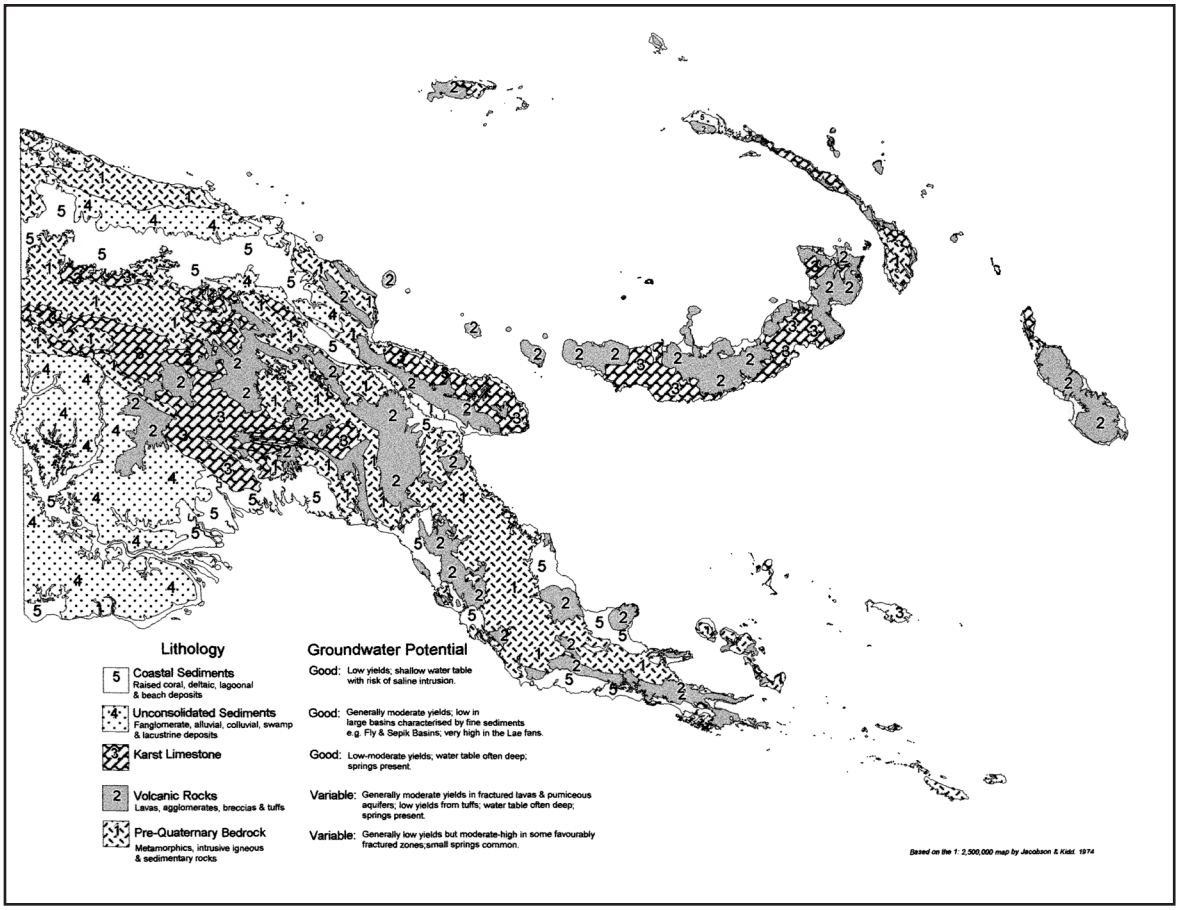
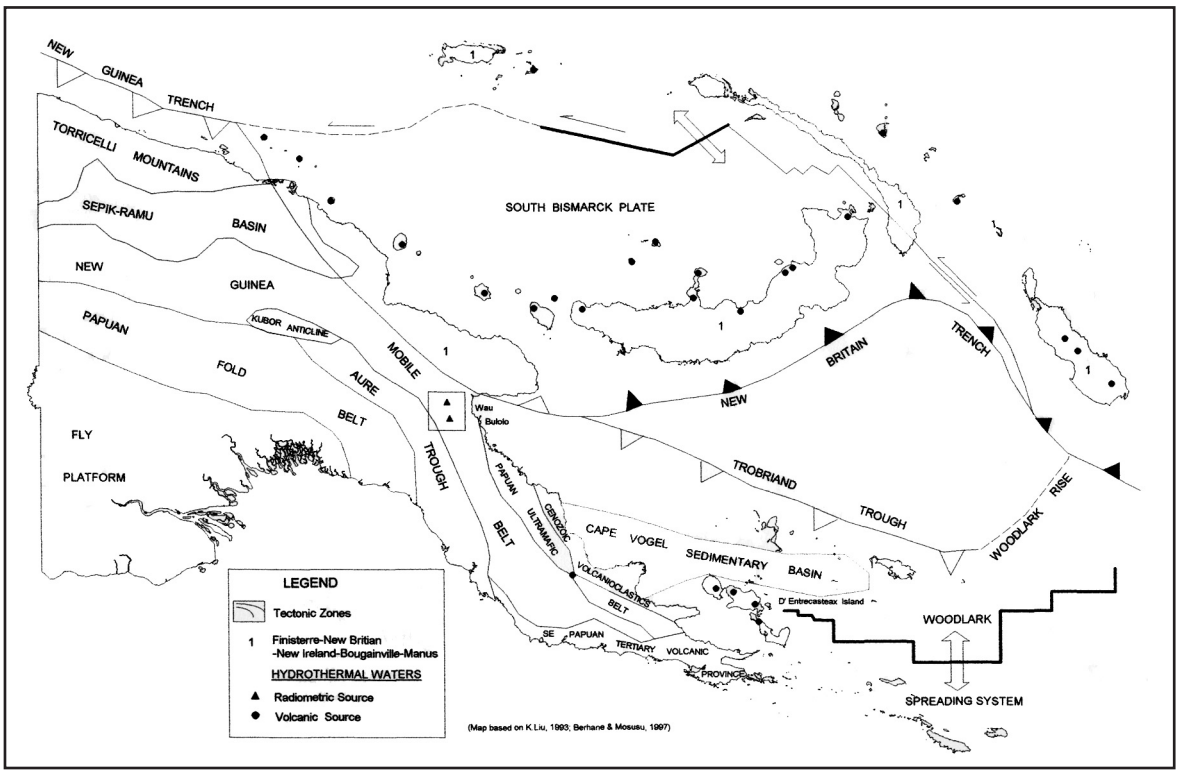


Figure 5.6.8.3 Location of hydrothermal watersources in Papua New Guinea and their tectonic settings



calcareous mudstone, siliceous mudstone, chert and shale with associated limestone, volcanic tuff and gabbro. The rocks have been folded, faulted and sheared and groundwater occurs in the fissures and joints. These aquifers are confined when overlain by alluvial deposits in the valleys, or are semi-confined when exposed on the hills. Discharge rates measured in 93 boreholes gave a mean flow rate of 1.9 l/s; specific capacities are in the range 0.03–3.3 l/s/m with a mean of 1.1 l/s/m. Estimates of the transmissivity of these aquifers are in the range 125–214 m^2/day and storativity 2.4×10^{-4} to 4.5×10^{-4}.

About 150 boreholes have been drilled at the Misima Island and of these 44 have some pump test information including 15 in bedrock formations. The bedrock here consists of green and black schist interbanded with fractured and sheared porphyry. The discharge rates range from 0.4–51.7 l/s (mean 18.2 l/s) with a mean specific capacity of 3.4 l/s/m. Some of the highest bore yields were restricted to narrow fracture zones. Specific yields were in the range 0.02–0.2.

Volcanic deposits occur in all the three main structural provinces of PNG, although occupying only a small total area. Some volcanic centres are active for instance Rabaul, Mt Lamington and Manam Island (Fig. 5.6.8.1). The composition of the volcanics can vary from basalt to andesite and they occur as lavas and pyroclastics. The lavas, which are well-jointed and fractured, have good aquifer potential but finer pyroclastics can weather to clay-rich material which may have poor aquifer properties. The Kuriva area, 40 km north of Port Moresby, is underlain by weathered, jointed agglomerate with poor aquifer potential; it has a 45% failure rate for boreholes, and low yields. However the volcanic ash deposits at Rabaul in East New Britain and Kimbe in West New Britain have moderately good aquifer potential.

In the Rabaul town area, bore yields from volcanic ash deposits range up to 17.7 l/s (mean 3.3 l/s); specific capacities range from 0.1–21.7 l/s/m (mean 3.8 l/s/m). At the Kokopo wellfield, 20 km southeast of Rabaul, which is currently under development, the volcanics consist of weathered ash in the form of clayey silt, sand and sandy gravel. The aquifer is considered to be semi-confined to unconfined due to the overlying, less permeable silty clay layers. The reported discharge rate at one site was 7.1 l/s with a specific capacity of 0.2 l/s/m; the transmissivity was 30 m^2/day with a storage coefficient/specific yield of 3×10^{-3}.

At Kimbe, West New Britain, semi-permeable sandy clay and silty clay overlie reworked pumiceous sand which forms a confined aquifer. A borefield has been developed for town water supply. Bore yields range from 1.4 to 8 l/s (mean 3.5 l/s); specific capacities range from 0.3 to 2.4 l/s/m (mean 0.9 l/s/m); and transmissivity is in the range 64 to 230 m^2/day.

A feature of volcanic areas is the prevalence of springs which can develop at the basal contact of unconsolidated pumiceous tuffs overlying massive agglomerate, lava or bedrock or at the base of open-jointed lava flows overlying buried soil or finer grained tuff layers (Jacobson and Kidd, 1974). Volcanic spring discharge rates are generally low, < 0.1 l/s, but may be adequate for a village water supply. An exception is Tomakavin Spring, south of Mt Varzin, East New Britain, with a reported flow of 22,000 m^3/day.

There are extensive areas of karst limestone on mainland PNG and also in some of the larger islands including New Britain, New Ireland and Bougainville (Fig. 5.6.8.1). The karst areas are characterized by caves and sinkholes and have poorly developed surface drainage. Springs are also a feature of the karst areas although high discharge rates have not been reported. In spite of their potential as aquifers, the karst areas of the Southern Highlands have not been investigated as they occur in remote areas where demand for water is low. Some boreholes have been drilled in karst areas of the Highlands in connection with petroleum exploration.

Unconsolidated sediments are the most important source of groundwater in PNG. These sediments include alluvial, lacustrine and fan deposits which have formed in the main river valleys and major depressions. Jacobson and Kidd (1974) suggested that in the larger basins the sediments are finer grained, mainly silt and sand with some gravel, whereas in the smaller

mountain-rimmed basins and tectonic depressions, including the Markham Valley, coarser sediments predominate. The thickness of sediments in the major basins and tectonic depressions is unknown but is considerable. Distinct aquifer horizons are not generally developed in the tectonic depressions due to rapid vertical and lateral changes in the deposition of sediments.

The groundwater potential of these extensive areas of unconsolidated sediments has not yet been investigated in detail. Information on aquifers in unconsolidated sediments is available in several regions, including the Fly-Strickland Platform area, the Sepik – Ramu Basin, the Vanimo Basin, Alotau, Popondetta, the Markham Valley, and Lae. Based on current information, the Markham Valley and Lae have good aquifer potential, similarly the upper regions of the Fly River in the Kiunga area.

In the Fly-Strickland Platform area the sediments consist mainly of clay and mudstone with some sand and gravel; typically borehole success rates are low and also yields are low (0–0.6 l/s); specific capacities are in the range 0.4–0.7 l/s/m. Salinity is an additional problem in the area. At Daru, a small island which is underlain by limestone, bore yields are higher (0.9–7.8 l/s) with specific capacities ranging from 2.1–7.5 l/s/m. At Kiunga, the township water supply is from alluvium adjacent to the upper Fly River. The aquifer consists of sands overlain by clay with lignite bands. Bore yields range from 1.2–10 l/s (mean 7.8 l/s); specific capacities are in the range 0.5–1.0 l/s (mean 0.7 l/s).

In the Sepik-Ramu Basin, most investigations have been concentrated in the coastal sediments of the Wewak area which are predominantly argillaceous with occasional coral limestone. Typically the area is characterized by low success rates and low bore yields (0–2.4 l/s) while inland success rates were also low in predominantly argillaceous sediments. In the Ramu Basin, a wellfield supplies the Ramu Sugar Estate which has a factory and also a population of 7,000. Clay and sandy clay overlies a series of water-bearing sand, gravel and clay beds. The aquifer is confined and capable of discharge rates up to 42 l/s. Specific capacity was reported at 2.2 l/s/m.

Vanimo lies in a small sedimentary basin to the north of the Sepik-Ramu Basin. The abandoned wellfield consisted of a prominent sand aquifer (12 m thick) overlain by clays. Aquifer yields ranged from 1.3–3.6 l/s (mean 3 l/s); specific capacities were in the range 0.9–3.5 m/s/m (mean 1.25 l/s/m), with mean transmissivity 315 m^2/day and storativity 5.6 x 10^{-4}.

The Alotau wellfield in Milne Bay, lies close to the coast in unconsolidated alluvial fan deposits. The aquifer is confined, consisting of sandy gravels with thin clayey layers and overlain by sandy clays. Discharge rates are in the range 4.2–9.5 l/s and specific capacities 0.5–19 l/s/m.

In the Popondetta area, the aquifers are thin, irregular, sand and gravels in a sequence of poorly sorted alluvial deposits. The system is considered to be multi-layered, leaky and confined. Reported discharge rates are 1.9–5 l/s. Recent pump testing indicates a transmissivity of 82 m^2/day with a storativity of 2.8 x 10^{-5}.

The Markham Valley is a major structural depression filled by a thick sequence of alluvial fan material derived mainly from the Sarawaged Range on the northern flank of the valley. More than 200 boreholes have been drilled and indicate that the aquifers are generally gravels overlain and confined by clayey formations (Van der Made, 1991). Discharge rates range from 2 to 5 l/s with specific capacities 0.5–7.4 l/s/m. Transmissivities range from 291 to 1,439 m^2/day; the lower transmissivities in this range correspond with clayey gravel aquifers and the higher transmissivities with gravels.

The city of Lae lies on the coastal plain and is underlain by a thick accumulation of unconsolidated coarse alluvial fan deposits derived partly from the Sarawaged Range in the north, and partly from finer sediments (sand, silt and clays) of the Markham River in the west. The thickness of the alluvium exceeds 100 m and is probably considerably more. The aquifers consist of sand and gravel with some conglomerate and silt. Specific capacities of boreholes range from 1.3 to 16.8 l/s/m in the town, and from 10.7 to 80 l/s/m in the new wellfield at Taraka northeast of

Lae (Berhane et al., 1996). The Taraka wellfield boreholes have very high yields, 100–160 l/s, far in excess of any other aquifer in Papua New Guinea. Transmissivities range from 2,300–18,000 m^2/day with a mean of 5,000 m^2/day; storativity (confined) ranges from 7×10^{-3} to 2.9×10^{-4} and storativity (unconfined) ranges from 1.9×10^{-3} to 5.5×10^{-3}.

A narrow, low lying strip of coastal sediments is widely developed around mainland PNG and in the islands, and extends up to several hundred metres inland. Two main sedimentary environments are present: fluvial and littoral. The fluvial deposits of the coastal strip are unconsolidated sediments consisting of gravel, sand and clay/mud. Most of the groundwater resources in the coastal strip occur in these fluvial sediments. The littoral deposits are also unconsolidated but because of their proximity to the sea are susceptible to saline intrusion; beach ridges and plains consist of sand with shelly horizons which may or may not contain freshwater. Away from the coast the littoral deposits grade into fluvial formations.

Of the littoral deposits, estuarine plains and deltas are extensively developed along the southern coastline of PNG, while raised coral reefs are more common in the islands. The raised coral reefs outcrop from a few metres to more than 100 m above sea level in the islands of Milne Bay Province and in Bougainville where they form prominent cliffs. The raised reefs consist of loosely cemented coral limestone which is characterized by high porosity and permeability with well developed solution cavities; examples are also known where the limestones are hard and impermeable. These limestone formations, locally known as coronas, typically contain a freshwater layer underlain by saline water. In some small coral islands and also in larger islands for example, Kiriwina Island, in the Trobriand Islands, the coral limestone is close to or a few metres above sea level with only a thin freshwater layer or lens.

Information is available on raised coral limestones in New Ireland, Bougainville, Misima Island and the coastal Madang area. During the construction of the wellfields at Kavieng, New Ireland, maximum bore yields of 19 l/s were reported with transmissivities in the range 1,000–9,000 m^2/day. At Bougainville and Buka Islands, village water supply boreholes had discharge rates in the range 0.5–2 l/s. At Misima Island, discharge rates in coral limestone were in the range 0.7–51.2 l/s with a mean of 10.2 l/s; specific capacities ranged from 0.2–1.3 l/s/m (mean 0.3 l/s/m); storativity was reported as 3.7×10^{-3}.

The Madang wellfield was constructed in the Wandokai Limestone formation consisting of coral limestone and some minor interbedded shelly clays, and also beds of shell and coral detritus. The aquifer is confined and overlain by argillaceous deposits. In tests, bore yields were in the range 30–58 l/s (mean 44 l/s); transmissivities ranged from 234–2,290 m^2/day (mean 822 m^2/day) and the mean storativity was 3.2×10^{-3}. However, when the boreholes went into production these bore yields were not sustainable.

Coastal sediments are problematic in that they occur in areas which can have large village populations giving rise to large demands on groundwater resources. Coastal sediments, particularly raised coral reefs, are not widely developed and commonly outcrop close to sea level and therefore have limited reserves of freshwater. As a result, they are susceptible to both saline intrusion and to pollution and have therefore only moderate aquifer potential.

There is limited information on the contamination of groundwater caused by human activity in PNG. An instance is known from Port Moresby where oil leaked from a storage tank and entered the groundwater. As a result, a nearby borehole had to be abandoned. Higher than normal nitrate levels (18 mg/l) have been recorded in some boreholes in the Markham Valley probably as a result of agricultural activities.

Deterioration of water quality has been caused by the intrusion of saline water as a result of over pumping. The old wellfield in Lae, was abandoned in the early 1960s partly as a result of this. Recently, the wellfield in Wesiria valley, Misima Island, which supplies water for mineral processing was overpumped causing saline intrusion and subsequent environmental damage in

the valley. The deterioration of water quality in the Rabaul wellfield was also the result of overpumping over many years, causing a number of boreholes to be abandoned.

There are a number of other problems associated with groundwater abstraction in certain wellfields. The Kimbe wellfield has been seriously affected by iron-reducing bacteria which are responsible for significant reduction in borehole yields and this has lead to a number of boreholes being abandoned. The Lae wellfield has been affected by carbonate encrustation causing partial blockage of the wellscreens.

The development of groundwater resources in Papua New Guinea has been primarily to supply domestic water in urban and rural areas. Groundwater has not been used to any great extent for agricultural or industrial purposes.

The PNG Water Board is currently responsible for water supply and sanitation in ten urban centres, excluding Port Moresby. Three of these centres use groundwater: Lae, Kimbe and Kavieng. In addition, the wellfield at Alotau in Milne Bay Province is used as a standby facility when the primary surface water source becomes inadequate during dry periods. A wellfield was developed for Madang in 1984 but shortly after it was commissioned, borehole yields were drastically reduced and the wellfield was abandoned. An alternative surface water source is currently under development.

Rabaul wellfield operated successfully until 1994 when volcanic eruptions caused the town to be abandoned. A new wellfield is currently being developed at Kokopo which is being expanded to replace Rabaul as a residential and industrial area.

At Vanimo in West Sepik Province a wellfield was constructed in 1982 but was never brought into production. The wellfield consisted of nine boreholes, all of which were successfully pump tested (Seidel, 1982). Surface installations deteriorated and as a result of encroachment by illegal settlements and vandalism the wellfield was eventually abandoned. The Water Board is planning an alternative surface water supply.

Production figures for wellfields controlled by the Water Board are given in Table 5.6.8.1.

Table 5.6.8.1 PNG urban water supply centers based on groundwater

Wellfield	*Province*	*Production (10^6 m^3/yr)*	*Comments*
Lae	Morobe	13.84	In production
Kimbe	West New Britain	0. 54	" "
Kavieng	New Ireland	0.59	" "
Alotau	Milne Bay	0	Standby facility
Rabaul	East New Britain	1.00 (1985)	Abandoned, 1994
Kokopo	" " "	1.26	Under development
Madang	Madang	1.20 (1985)	Abandoned, some boreholes still utilized
Vanimo	West Sepik	0.60	Abandoned before production stage

Many other small towns and institutions throughout Papua New Guinea are dependent on groundwater for their water supply.

Up to 1989 village water supply schemes used boreholes (deep groundwater), hand dug wells (shallow groundwater), surface water or rainwater catchments as their water source. In 1974,

Jacobson and Kidd estimated that 34–40% of water used in both urban and rural areas was from groundwater sources.

Since the 1980s financial support for rural water supply programs in PNG has been largely the responsibility of donor agencies, the Asian Development Bank and the European Union with projects implemented by Provincial Health Departments. Non-Government Organisations also assist in rural water supply projects. The emphasis has changed and more roof catchment and gravity reticulation schemes based on surface water or spring sources have been constructed. Hand dug wells continue to be important but fewer boreholes are being drilled.

There are a number of agriculturally based industries throughout PNG which depend on groundwater for their operations. These include: the sugar industry in Madang Province; and the oil palm industry with centres near Kimbe, and at Higaturu north of Popondetta. Both are dependent on groundwater for their domestic water supplies and factory processing facilities.

Since the mid-1970s there have been a number of major government projects to develop a rubber plantation industry. Several centres in Central Province were established, and at each site several hundred shallow boreholes were drilled and fitted with hand pumps to supply water for leaseholders. A rubber factory was set up at Moreguina for processing the raw rubber using groundwater.

There are a number of important mining centres located in remote parts of PNG, which depend on local water supplies for their operations. The large Porgera and Ok Tedi mines use surface water sources but Misima Mine on Misima Island, Milne Bay Province, uses groundwater to supplement surface water supplies. About 150 water bores have been drilled since the mid-1980s to provide water both for the mine residential area and also for mineral processing and general mining operations. At Lihir Island, off New Ireland, a wellfield comprising a number of shallow boreholes in river alluvium supplies water for the mine camp and the township.

In 1992–3 Port Moresby was seriously affected by drought, resulting in water shortages and power failures caused by low water levels in the Sirinumu Dam which supplies the capital with drinking water and electricity. To overcome these difficulties individuals and private businesses were responsible for drilling about 125 boreholes for water supply during this period. Some were used as standby facilities for factories but generally, poor water quality and low yields prevented the use of groundwater to provide complete back-up facilities.

Groundwater has not been used for any large scale irrigation schemes in PNG although there is the potential for this. A number of small-scale irrigation schemes have been reported in the Port Moresby area but have not been sufficiently developed to allow irrigation all the year round. There are plans to develop small-scale irrigation schemes in the Markham Valley to increase agricultural production. A pilot scheme has been undertaken to determine whether an infiltration gallery in the alluvials of the Bura River would be feasible for irrigating parts of the Ramu Sugar plantation.

Following the severe 1997–8 drought and famine, people in rural areas have realized the importance of sustaining food supplies in times of low rainfall, and there some initiatives to use groundwater for irrigation.

There are a number of geothermal occurrences in PNG (Fig. 5.6.8.3) which were classified by Heming (1969) into two types: those related to volcanism and those related to high regional heat-flows. The volcanic type includes occurrences at Lihir Island and Rabaul and the outer islands of the volcanic arc. The volcanic thermal waters tend to be acidic with temperatures up to 100 °C.

The other type is represented by occurrences in the Wau/Bulolo area where high regional heat-flows have been attributed to radiometric sources. The radiometric thermal waters are alkaline, have temperatures in the range 56–70 °C, and occur as small springs and seepages.

The geothermal occurrence at Lihir Island has been investigated in recent years in con-

nection with the development of the open pit gold mine. Lihir's thermal waters occur as natural hot springs emerging along the coastal zone with temperatures approaching 100 °C. Hundreds of boreholes have been drilled to a maximum depth of 730 m: in these exploratory boreholes, temperatures exceed 200 °C and water occurs as steam, The Lihir Island waters are unusual as, unlike other thermal volcanic waters, they have a neutral pH. There has been no development of any thermal waters in PNG for medical and recreational purposes or as alternate energy sources.

Groundwater resources in PNG are difficult to quantify because of limited exploratory drilling and borehole information. In general, the groundwater resources are under-developed. Exploitation of groundwater has been primarily for the supply of domestic water in urban and rural areas. There has been only limited development of groundwater for agricultural purposes or industrial use.

The most productive aquifers are in unconsolidated sediments which are present in much of the country. Aquifers in the unconsolidated sediments generally have low yields (1–5 l/s) but in the Lae area these aquifers are highly productive with borehole yields of up to 120 l/s.

Water quality is not a limiting factor in groundwater exploitation with certain exceptions; on the basis of our present knowledge increased salinity levels are normally the result of over-pumping of boreholes.

Over the past 10 years there has been a reduction in the use of groundwater (deep boreholes) for rural water supply programmes. The effects perhaps would not be significant in 'normal' wet years. However, during periods of severe drought when shallow hand dug wells and roof catchment schemes fail, then serious water shortages result. This was the case in the 1997 drought when there was widespread suffering as a result of crop failures allied with the failure or non-existence of rural water supplies.

6 General characteristics of groundwater resources of the Earth

6.1 Quantitative characteristics of the groundwater contribution to the water balance and total water resources

Groundwater runoff is an important component of the hydrological cycle. It is essential to the formation of the water balance of river basins and total water resources. That is why the quantification of the groundwater contribution to total water resources and water balances of individual regions is of importance both to objective quantification of the hydrological cycle and to the hydrogeological and hydrological substantiation of regional schemes of integrated use and protection of water resources.

The role of groundwater in the formation of the water balance and water resources of regions is quantitatively characterized by the groundwater runoff/precipitation ratio and the groundwater discharge to river/total river runoff ratio, expressed in per cent. The former ratio shows the portion of precipitation that constitutes groundwater recharge. High values of the latter ratio (over 100%) point to the existence of other sources of groundwater recharge apart from percolation of precipitation.

Groundwater runoff/precipitation ratios average 9% within Russia. Their magnitude is governed by complex natural factors among which the main ones are the precipitation/evaporation ratio and the composition and thickness of the vadose zone. For the plain areas of the USSR, a latitudinal zonality of distribution of average long-term values of the groundwater runoff/precipitation ratio is observed (groundwater runoff decreases from north-west to south-east, from 10–20% in the zone of excessive moistening to 1% and less in the steppe and semi-desert regions). In mountainous areas, groundwater runoff/precipitation ratios increase with an increase in precipitation with the altitude of the terrain. For instance, in the Carpathians, they increase from 5 to 10–15%, in the Urals from 10 to 20–40%, in the Altai area from 5–10 to 15–20% (Zektser, 1977; *Groundwater Flow of Areas of Central and Eastern Europe,* 1982).

Local hydrogeological conditions of river basins and the presence of permafrost strata exert a substantial effect on the distribution of groundwater runoff/precipitation ratios. In karst development areas (Silurian Plateau, Onega-Northern Dvina interfluve, Kuloi Plateau, and Timan), Groundwater runoff/precipitation ratios amount to 40–50% and more. In permafrost regions of Siberia and USSR North-East, these ratios are highly insignificant.

The effect of the composition of rocks of the vadose zone on the amount of infiltration of precipitation is seen from an example cited by Newport (1959) for an area in Nebraska. There, groundwater recharge varied from about 130 mm/yr in an area of sand dunes to less than 25 mm/yr for areas underlain by relatively impermeable rocks. Harder and Drescher (1954) report that in Langlade County, Wisconsin, in a sandy area the average annual recharge was over 18% of total annual precipitation.

Groundwater discharge to river/total river runoff ratios allows one to determine the proportion between groundwater and surface-water resources in many regions of the humid zone. Analysis of the ratio of groundwater discharge to total river runoff is of practical importance when solving problems of integrated use of water resources and when computing water-resources

balances in particular. For all the area of the USSR, the values of this ratio amount to 24%, ranging from 5–10% in regions with a relatively small thickness of the upper hydrodynamic zone, a poorly dissected topography and favorable conditions of surface-water runoff generation to 40–50% and larger in regions, composed of highly water-saturated rocks intensively drained by rivers.

For the United States of America the average groundwater discharge to river/total river runoff ratio amounts to 30%.

The contribution of groundwater runoff to the water balance and water resources of Central and Eastern Europe may be characterized by the results of the regional assessment and mapping of groundwater discharge and maps of the components of the water balance for this area (*Groundwater Flow of Areas of Central and Eastern Europe*, 1982).

Groundwater runoff/precipitation ratios range broadly for the vast area of Central and Eastern Europe, being under diverse climatic, orographical, geomorphological, geological, and hydrogeological conditions. The largest groundwater runoff precipitation ratios are typical of mountain-fold regions. Particularly great proportions are observed within the Crimea-Caucasus groundwater runoff province where they are over 50% in some regions, and in karst areas of the mountain Crimea they amount to 70%. The smallest ratios are generally common for insufficiently moist regions.

The distribution of groundwater discharge to river/total river runoff ratios shows distinctly the effect of the geographical and altitudinal zonality of the principal natural and climatic factors. This makes it possible to identify three latitudinal zones representing the most general distinctive features of the generation of groundwater discharge to rivers.

Groundwater discharge to river/total river runoff ratios range from 10 to 30% in the north (the Karelian-Kola region, Pechora River basin, basins of the Barents and White seas, northern portion of the USSR area adjacent to the Baltic Sea).

Highly beneficial conditions for generation of surface and overland flow exist here due to relatively rugged topography and shallow groundwater occurrence. A local contribution of groundwater discharge to river runoff of up to 35–40% is observed in karst areas (the Onega-Severnaya Dvina drainage divide and Kuloi Plateau).

Groundwater discharge to river/total river runoff ratios are as great as 40–50% in the middle portion of the Eastern Middle European groundwater runoff province (for the most part). Favourable conditions for feeding the rivers by groundwater in this region are explained by the presence of a thicker upper hydrodynamic zone and its more active drainage by rivers.

South of this area, the groundwater contribution to river runoff sharply diminishes down to 10–15% and less and even zero in arid zones where evaporation predominates among groundwater balance components (*Groundwater Flow of Areas of Central and Eastern Europe*, 1982).

Mountainous regions are characterized by higher groundwater discharge to river/total river runoff ratios as compared to adjacent plains. They are as great as 70–80% (sometimes 100%) within the mountain-fold areas of Central and Eastern Europe which is, above all, due to good drainage of water-bearing rocks, greater precipitation, and favorable infiltration conditions (higher rock fracturing, occurrence of detrital sediments and karst). As a whole, for the majority of mountain rivers the groundwater contribution commonly amounts to 40–60%, extreme values ranging widely (e.g. from 2–5 to 70–75% within the Greater Caucasus region).

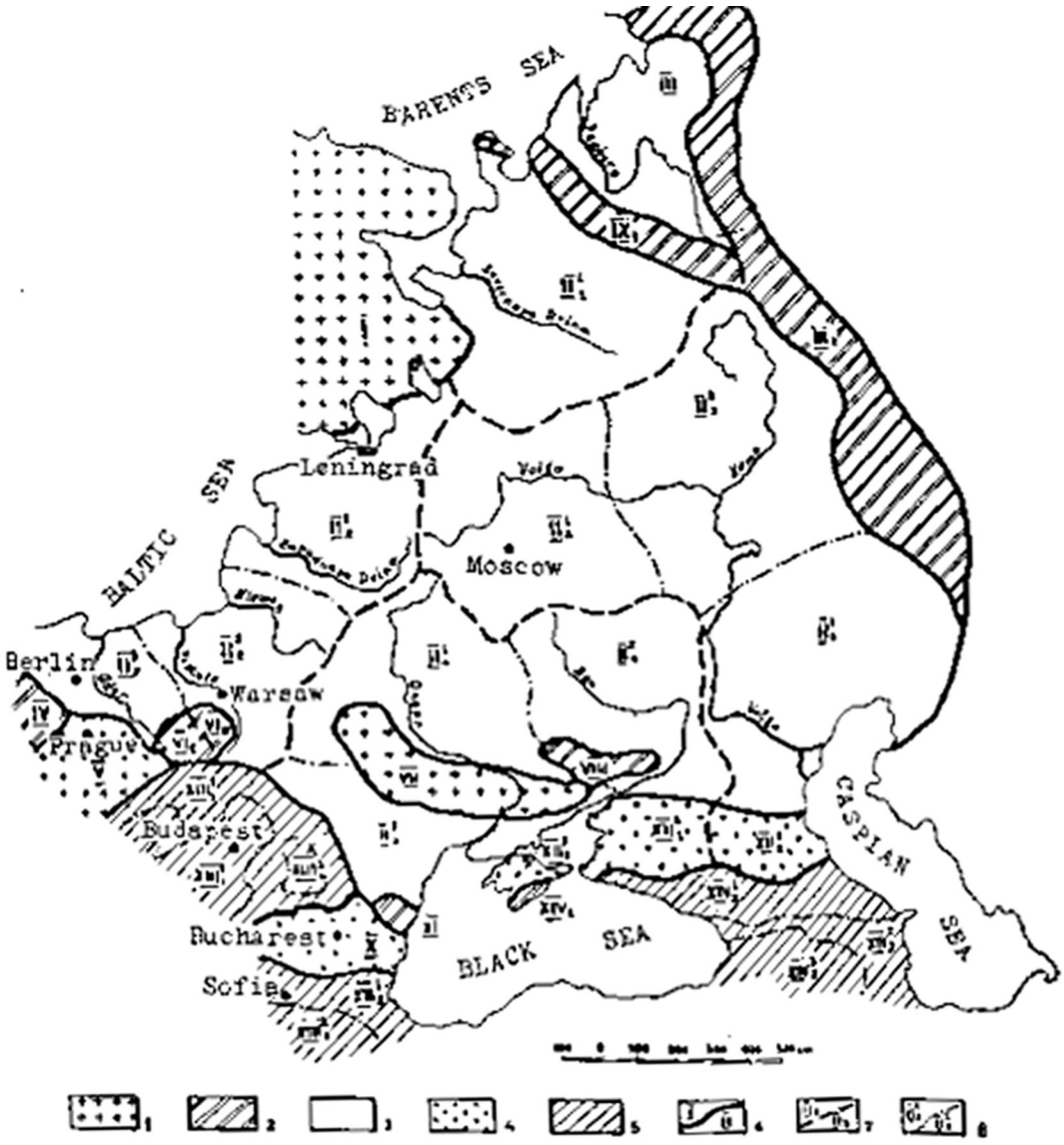
The main quantitative characteristics of the groundwater contribution to the total water balance and river runoff for Central and Eastern Europe are given in Table 6.1.1. The subdivision scheme for this territory according to groundwater generation conditions, is presented in Fig. 6.1.1.

Values of groundwater discharge, subsurface dissolved solids discharge, groundwater runoff/precipitation ratios and groundwater discharge to river/total river runoff ratios make it possible: to compare, on a quantitative basis, different groundwater runoff areas, reveal the main

Table 6.1.1 Average long-term water balances for some European countries

Country	Area (km^2)	Precipitation (mm)	Evaporation (mm)	Total river runoff (mm)	Groundwater discharge to rivers (mm)
Bulgaria	110.988	690	514	176	63
Hungary	93.030	689	630	59	29
Poland	312.677	715	550	165	91
Romania	237.500	738	590	148	42

Figure 6.1.1 Scheme of areal subdivision of Central and Eastern Europe according to groundwater runoff generation conditions



1) provinces of groundwater runoff of crystalliner shields and massifs; 2) provinces of groundwater runoff of old fold systems; 3) provinces of groundwater runoff of old plates; 4) provinces of groundwater runoff of young (Epi-Paleozoic) plates; 5) provinces of groundwater runoff of young (Alpine) fold systems; 6) boundaries and numbers of groundwater runoff provinces; 7) boundaries and numbers of groundwater runoff areas; 8) boundaries and numbers of groundwater runoff regions.

laws of generation and distribution of groundwater runoff under various natural conditions and to estimate the groundwater contribution to the water balance and total water resources.

For example, for France, it has been established that average annual groundwater runoff is equal to over half of the total river runoff (Bodelle and Margat, 1980). In regions with wide karst development, the groundwater discharge to river/total river runoff ratio amounts to 90% and for basins with semipermeable glacial deposits it diminishes down to 10–20%.

In the water balance of Ireland, groundwater runoff is over 30% (360 mm) of the average precipitation (1,130 mm). For the majority of river basins of Ireland, the groundwater runoff percentage of total river runoff amounts to over 50% (Aldwell and Burdon, 1979).

The publication *Water balance maps for Central and Eastern Europe* (1984) contains the information on the groundwater discharge to rivers and total river runoff for some European countries including: Bulgaria, Hungary, German Democratic Republic, Poland, Romania, and Czechoslovakia. The respective values of groundwater discharge to rivers and total river runoff, expressed in millimeters, for these countries are, 63 and 176, 29 and 59, 97 and 163, 91 and 165, 42 and 148, 89 and 216 respectively (Table 6.1.1).

The broad development of irrigated agriculture in India dictates the necessity of conducting regional and special hydrogeological studies in the country, including the study of the groundwater contribution to total water resources and the water balance. According to estimates of Indian specialists, the value of groundwater recharge in separate areas exceeds 50% of total precipitation in the monsoon period. Besides, groundwater receives additional recharge from irrigation canals and rivers, which results in increasing total groundwater resources. For the year 2000 the increase was up to 760 m^3/yr (Chaturvedi, 1981).

According to preliminary estimates, a high groundwater recharge rate is observed within oceanic islands, which are commonly composed of igneous rocks and products of weathering. For example, the groundwater runoff/precipitation ratio for the Philippines ranges from 5 to 30%, which with precipitation of over 2,000 mm/yr indicates considerable groundwater recharge and discharge to the ocean (*Groundwater in the Pacific Region,* 1983).

The specific features of water-balance characteristics of the USSR are also typical for North America. There, groundwater runoff/precipitation ratios gradually increase from north to south, from less than 5% to 30–40% and larger which are characteristic of middle and subtropic latitudes. These ratios average about 30% for the United States of America and Canada (*Groundwater in the Western Hemisphere,* 1976).

The above data point to the fact that the groundwater contribution to total water resources and the water balance of individual regions depends on the complex combination of various natural factors, which are now increasingly affected by human activities.

6.2 Groundwater contribution to the water and salt balance of seas and oceans

As was pointed out earlier, groundwater runoff is the hardest determinable component of the present and perspective water and salt balances of oceans, seas and large lakes, and specialists have to answer a number of complex questions: what is the quantity of groundwater runoff, does it greatly influence the water and salt balances of a water body, how will groundwater inflow change in the future, and to what extent the so-called subsurface (groundwater) component should be considered when studying the salt and heat balances of a water body?

Lack of validated quantitative data on direct groundwater discharge to seas and oceans has

restrained until recently the study of the total water balance and the hydrological cycle. The world water balance remained incomplete without data on submarine groundwater runoff.

Taking into account the groundwater component, the average long-term world water balance may be characterized by the following equations:

for the peripheral part of land giving runoff to the ocean

$$E_p = P_p - R_p - U_o \quad (6.2.1)$$

for closed (basin) areas

$$E_c = P_c \quad (6.2.2)$$

for oceans

$$Eo = Po + R_p + U_o \quad (6.2.3)$$

for the world

$$E = E_p + E_c + E_o = P_p + P_c + P_o = P \quad (6.2.4)$$

where E: evapotranspiration; P: precipitation; R: river runoff, including surface and subsurface components; U: groundwater runoff from land to the ocean bypassing rivers. The subscripts are: p is peripheral part of the land, c is a closed area, o is ocean.

It should be noted that another term characterizing seawater intrusion into coast zones could be introduced into the equations. However, this process under natural conditions of coasts is not considered as a component of the world water balance at the present stage because of its local character.

Studies of the groundwater contribution to the water and salt balances of seas and large lakes have been carried out in a number of regions. However, in most cases, groundwater discharge to seas was considered as a residual term of the long-term water balance, i.e. as was said above, all errors of determination of other components of the water balance were included into the groundwater discharge value. This led to basically incorrect conclusions, and values of groundwater discharge to the sea were completely dependent on adopted average values of precipitation, evapotranspiration, and river runoff. A vivid example in this respect are the earlier studies of the water balance of the Caspian Sea, where submarine groundwater discharge values, given by various investigators, differ 150 times.

In recent years practical demands, involved in the problem of inland seas' in Russia were a substantial impetus to formulation and development of studies on the subsurface water exchange between land and sea. The essence of this problem is that in many inland seas (above all in the Caspian and Aral seas) and large lakes the water level is greatly declining due to both natural factors and human activity in water-sheds. The problem of studying present and perspective water and salt balances of these water bodies now focuses on estimating the groundwater contribution to the formation of these balances. The effect of groundwater on the hydrochemical, thermal and hydrobiological regimes of a water body, in addition to the effect on the water and salt balances, should be also examined.

As indicated earlier Russian scientists have made approximate quantitative estimates of submarine groundwater discharge to oceans (Zektser and Dzhamalov, 1981). According to these estimates, the submarine groundwater discharge to oceans amounts to 2,400 cu km/yr, including 1,300 to the Pacific Ocean, 815 to the Atlantic Ocean, 220 to the Indian Ocean, and 50 to the Arctic Ocean. The direct groundwater discharge to seas and oceans from Europe is 108, Asia 328, America 729, Africa 236, Australia 25, and from major islands is 914 km^3/yr.

Oceans and inland seas are the main recipients of drainage of surface and groundwater runoff. In this connection, their salt balance is generated under the influence of salt transport by rivers and groundwater. Of these two main sources, dissolved solids transport has been studied

sufficiently. Estimation of the contribution of groundwater runoff to dissolved solids transport has been complicated until recently by a lack of data on the regional groundwater discharge directly to seas.

As results of studies carried out in separate regions show, direct groundwater discharge to the sea (bypassing the river network) compared to the total river runoff is usually expressed by a small value. At the same time, the contribution of subsurface dissolved solids discharge to the salt balance of inland seas is appreciable and accounts for tens of per cent of the surface dissolved solids transport by rivers. For example, the transport of salt by groundwater to the Caspian Sea accounts for 27% of the dissolved solids transport by rivers, while the groundwater discharge to the sea does not exceed 1% of river inflow.

In the distribution of the groundwater and subsurface dissolved solids discharge to seas, the general vertical hydrodynamic and hydrochemical zonality for groundwater is observed. This zonality governs the increase in the total transport of salts with depth, despite the general reduction in groundwater discharge. This is explained by the substantially larger salinity of the groundwater of deep aquifers as compared to the groundwater of upper aquifers. This general law is sometimes disrupted by the effect of local hydrogeological conditions (wide occurrence of karst, presence of salt-bearing rocks, and processes of continental salinization). For instance, the largest values of subsurface dissolved solids discharge to the Baltic Sea (48.5 t/yr.km^2) are characteristic for the coastal portion of the Silurian-Ordovician plateau, where submarine groundwater flow is mainly generated in aquifer systems composed of karstified limestones and dolomites.

It should be noted that the contribution of subsurface dissolved solids discharge to the generation of the salt regime of seas may appreciably increase with a decrease in total river runoff caused by natural factors and human impact. Salinization of the deep portion of seas would occur more intensively since at depth water-exchange periods are longer. The salinization of some deep canyons in inland seas (recently observed), may be caused, in addition to other factors, by the increased influence of subsurface dissolved solids discharge from deep aquifers. Apart from the effect of groundwater runoff on the total salt balance of seas, salty groundwater discharge is often the main cause of large geochemical anomalies in the bottom water layer and in sea sediments. In turn, as was indicated, anomalies in geochemical fields at sea bottom are indicators of submarine groundwater discharge.

The salt transport by groundwater to the Atlantic Ocean amounts to 470 mln. t/yr, to the Pacific Ocean 521 mln. t/yr, to the Indian Ocean 296 mln. t/yr, and to the Arctic Ocean (from estimated drainage areas) 7 mln. t/yr. The total supply of salts in groundwater to oceans amounts to 1,300 mln. t/yr. This is 52% of the salt supply by river runoff and amounts to 2,480 mln. t/yr (this last figure does not include the dissolved solids transport by rivers from major islands). The proportion between surface and subsurface dissolved solids discharge for the continents is presented in Table 6.2.1.

Subsurface dissolved solids discharge to seas is governed by the rate of submarine groundwater discharge, washing of water-bearing rocks, paleohydrogeological and current formation of groundwater dissolved solids and composition, presence of evaporites and development of continental salinization processes in arid regions.

The data of Table 6.2.1 shows that the average total dissolved solids content of groundwater discharging directly to oceans from Asia is equal to 0.9 g/l. However, in arid and semi-arid regions, a decrease in submarine groundwater discharge is attended by an increase in groundwater dissolved solids content which leads to an increase in total and specific values of subsurface dissolved solids discharge.

An anomaliosly high salt evacuation by groundwater is observed in areas with evaporite deposits where they contact water-bearing rocks (the Red Sea and the Persian Gulf). The Red Sea basin is noted for very peculiar groundwater runoff conditions. As to tectonics, the region is

Table 6.2.1 Estimated continental surface and subsurface dissolved solids discharge

Continent	*Surface dissolved solids discharge (mln t/yr)*	*Average salinity of river water (g/l)*	*Subsurface dissolved solids discharge (mln t/yr)*	*Average total groundwater dissolved solids content (g/l)*
Europe	240	0.077	60	0.4
Asia	850	0.065	296	0.9
Africa	310	0.072	288	1.0
North America	410	0.069	149	0.4
South America	550	0.053	113	0.3
Australia (including Tasmania, New Guinea, New Zealand)	120	0.060	199	0.5
World's total	2,480	0.063	1,045	0.6

Note: Data on surface dissolved solids discharge and average river water salinity are taken from Lvovich (1974). Table 6.2.1 does not include discharge from major islands.

located in a rift zone whose sides are a system of grabens of different age. The grabens are filled mainly with sedimentary rocks with large inclusion of evaporites. The principal structural elements continue to develop. In this connection, discharge sites of thermal water having a high dissolved solids content are observed largely in the depths of the Red Sea. The problems of the origin of thermal brines in the Red Sea rift are discussed in numerous publications. Many authors support the wide-spread hypothesis that this infiltration is the origin of the highly mineralized thermal water. This is evidenced, among other things, by the fact that the groundwater dissolved solids content increase from 4 to 50 g/l and from 4 to 380 g/l coastward and with depth, respectively (*Hydrogeology of Africa*, 1978). Unfavorable recharge conditions are responsible for very insignificant regional submarine groundwater discharge values commonly not exceeding 0.1 l/s.km^2. At the same time, the high dissolved solids content of groundwater is the cause of substantial salt evacuation to the sea (its total amount equals 22.2 mln. t/yr and the discharge rate is up to 150 t/yr/km^2).

The values of specific submarine groundwater discharge to the Mediterranean Sea from of the Near East and Asia Minor are usually no more than 3 l/s.km^2. The artesian basins of this region are generally composed of karstified limestones, dolomites, conglomerates, and sandstones ranging in thickness from several hundred to 3,000 m. The groundwater dissolved solids content is diverse and commonly increases southward (up to 12 g/l) where gypseous limestones and terrigenous deposits occur among other rocks. The higher salinity of groundwater is responsible for the fairly appreciable subsurface dissolved solids discharge to the Mediterranean Sea from the Asian continent. The specific discharge rates gradually rise from north to south from 46 to 140 t/yr.km^2.

Submarine springs are known from ancient times in the off-shore area of the British Isles and Ireland. They emerge from karstified Mesozoic limestones which are distinguished by their high water yield and generate a substantial submarine discharge, amounting up to 6 l/s.km^2. In the off-shore area of Southeastern Kent alone, from Dover to Folkestone, the submarine groundwater discharge is as large as 23,000 m^3/d and accounts for 40% of the natural recharge of groundwater in this area. The total groundwater dissolved solids content commonly is not over 0.7 g/l, but where salt-bearing rocks occur and with depth it is as great as 14 g/l and larger. The total dissolved solids discharge from both islands amounts to about 30 mln. t/yr. The specific discharge values ranging from 100 to 140 t/s.km^2.

The broad development of karstified carbonate rocks and fissured sandstones on the Florida Peninsula results in an azonally high submarine groundwater discharge whose specific rates sometimes exceed 6 l/s.km^2. A tongue of fresh and brackish groundwater formed inland in Paleogene and Cretaceous limestones is traced under the floor of the Atlantic Ocean 120 km off shore down to a depth of over 600 m (Manheim, 1967; Manheim and Paull, 1981). The distribution of groundwater salinity points to the fact that groundwater flow originating from infiltration progressively forces out water of sedimentation origin from the aquifers. As the infiltration flow effect gradually weakens, the submarine groundwater salinity can rise up to 35 g/l and larger seaward and with depth. In some sections of the strata underlying the sea floor, salt-bearing rocks are encountered whose interaction with submarine water leads to the formation of brines having a salinity from 50 to 200 g/l. These brines occur not only in parent rocks, but also in adjacent horizons where they penetrate is a result of convective and diffusive processes. Consequently, submarine groundwater is commonly freshened in the influence zone of coastal artesian basins. At the same time, the existence of submarine water with a salinity of over 35 g/l is indicative of the occurrence of salt-bearing rocks at some depths in the majority of cases.

On the whole, the wide distribution of fresh groundwater over the Atlantic Coast of the United States of America is responsible for insignificant subsurface dissolved solids discharge. Its specific discharge rates gradually increase from 10 to 40 t/yr.km^2 in the direction of the Florida Peninsula.

The Eucla basin is a typical example of artesian basins in arid desert regions of Australia. In this artesian basin, potentially water-bearing, permeable, Paleocene cavernous limestones are not practically recharged because the annual precipitation here does not exceed 180 mm. In this connection, the groundwater discharge to the ocean in the vicinity of the Eucla basin is as small as 0.1 l/s.km^2, while the subsurface dissolved solids discharge amounts to 75 t/yr.km^2 due to the high salinity of the groundwater.

The distribution of submarine dissolved solids discharge values, depends on the latitude of the site. Fresh and weakly mineralized groundwater flows to oceans largely from the upper hydrodynamic zone. The dissolved solids content of groundwater increases largely due to the presence of salt-bearing rocks, processes of continental salinization, and the slow flushing of aquifers. These conditions effecting the composition of groundwater are often encountered within African and Australian coasts and lead to atypically high values of submarine dissolved solids discharge areas. The complicated character of dissolved solids discharge distribution shows that this natural process is greatly governed by paleo- and recent geological and hydrogeological conditions of groundwater generation. In other words, the regional effect of the latitude of the principal runoff-forming factors is simplified or complicated in separate coastal areas by local conditions, which generate the groundwater chemical composition.

Thus, submarine groundwater discharge may exert a considerable influence on the salt and hydrogeological regimes of seas and oceans, on processes of biogenic sedimentation and on the formation of mineral deposits on the sea floor. The significant role for salt transport by groundwater discharge to seas and oceans (52% of surface dissolved solids transport) should drastically modify existing concepts in which the primary biological products of the oceans and the scale of biogenic sedimentation are considered to be limited only by the amount of salt transported by rivers to the seas and oceans (Zektser et al., 1984).

6.3 Predictive evaluation of possible changes in groundwater flow under the effect of climate changes and the human impact

Considering future human impacts on the hydrologic cycle, great uncertainties center around the implications of possible greenhouse warming of the Earth. Although general circulation models (GCM) predict a long-term 1–5°C increase of global mean surface temperature as a result of doubling CO_2 concentrations over the current mean level (which is about 345 ppm), there is substantial uncertainty in predictions concerning disturbances on the hydrosphere as a result of greenhouse warming. This uncertainty stems from GCM's limitations in representing the complex climate of the earth (Mitchell, 1989; Giorgi and Mearns, 1991). Chief among the processes that complicate predictions of climatic effects of global warming are the feedback that water vapor, clouds, ice-albedo, and ocean-atmosphere interactions have on greenhouse warming (Ramanathan, 1988; Ramanathan et al., 1989). Some of the limitations of numerical climate simulations in predicting modifications of regional and global hydrologic regimes as a result of global warming have been studied by Dooge (1989), Gleick (1987, 1989) and Mitchell (1989).

Given the larger atmospheric concentrations of water vapor that would result from warmer temperatures, a potential impact scenario for global warming could be an increase in precipitation rates for a warmer earth. (Some GCM results indicate increments in global precipitation ranging from 5 to 15% of world-wide precipitation – which is about 100 cm/yr – according to Washington and Meehl (1984), Hansen et al. (1984), Wetherald and Manabe (1986), Schlesinger and Zhao (1987) and Wilson and Mitchell (1987)). Larger global precipitation would imply more runoff, water percolation, and groundwater flow. The major fluxes of the hydrologic cycle would be intensified. In coastal areas, potentially higher sea-levels, of a purportedly warmer Earth, would increase the landward encroachment of ocean water, partly upsetting the potential gain in direct groundwater flow that would otherwise result from larger groundwater recharge rates.

The analysis of hydrologic cycle disturbances (due to climatic change) based on global changes in precipitation is overly simplistic, however, because it does not yield specific information on the regional and seasonal climatic disturbances that can be expected throughout the planet as a result of global warming. That is, at the watershed or river basin scales, the resolution of GCM does not permit predictions of water-balance modifications. The most the GCM simulations can tell us at this point is that there seems to be general agreement that there would be increased precipitation over the high latitudes of the planet as a result of enhanced moisture transport from low to high latitudes on a warmer planet. With regard to available moisture at the Earth's surface, it would be enhanced over most of the northern extratropical continents in winter due to increased precipitation there. During the summer, however, there is no general agreement as to the status of surface moisture in these northern (important grain-producing) lands (Mitchell, 1989). Some authors, however, consider it probable that summer soil moisture would decrease in these midlatitude continental interiors due to shorter winter precipitation periods and earlier snowmelt (Dickinson, 1990).

In view of the limitations of GCM in predicting the regional climatic impact of potential greenhouse warming, climate models have adapted to the so-called limited-area-meteorological (LAM) models. These fine-mesh models are imbedded in a coarse-resolution GCM over an area of interest. The GCM provides initial and boundary conditions for the LAM, which, in turn, provides high-resolution hydroclimatic predictions. Hydrologists have used a similar nesting approach , whereby GCM outputs, such as average temperature and precipitation over the area of interest drive a numerical model of the regional hydrologic cycle (Gleick, 1986, 1987*a*; Lettenmaier and

Sheer, 1991; Mimikou et al., 1991). Typically, precipitation is assigned a range of values, say, from 25 to 25% increments over current levels in the area of interest, and the associated impact on runoff, soil moisture, and evapotranspiration is calculated by simulation of a regional hydrologic model. Invariably, the baseflow and the direct groundwater flow are not isolated in these simulations. Therefore, there is virtually no information on the possible effects of greenhouse warming on regional groundwater systems. This is due to the uncertainties in modeling groundwater systems under such transient climatic conditions and to the relatively long residence times of water in the earth's crust (compared with over-land and atmospheric water residence times), which hinder their incorporation in short-term hydrologic simulations.

In spite of the difficulties of predicting disturbances of groundwater in a potentially warmer planet resulting from CO_2 doubling, earlier results on global water balances are useful in assessing the expected relative impacts on global groundwater fluxes under specified scenarios. Suppose, for the sake of argument, that global precipitation increases 10% over current levels. It was previously calculated that the baseflow is about 9% of global precipitation (total global precipitation is approximately 100 cm/yr). Therefore, assuming that the baseflow/precipitation ratio remains constant, the increase in baseflow corresponding to a 10% rise in global precipitation would be 0.9% of current precipitation levels, or about 9 mm/yr distributed over the Earth's land surface. Considering that the land area of the world – excluding ice caps and glaciers – is 128×10^6 km^2, this 9 mm/yr flux is equivalent to, approximately, an additional 1,200 km^3/yr of the baseflow contribution to runoff. This represents a gain of baseflow approximately equal to 3% of current river runoff (current river runoff is approximately 38,000 km^3/yr).

With respect to direct groundwater flow (that bypasses the river network) the data in Table 6.3.1 provide a global estimate of direct groundwater flow of approximately 2,400 km^3/yr. This is equivalent to 19 mm/yr over the Earth's land surface. Based on an average global precipitation of 100 cm/yr, the direct groundwater flow is then approximately 2% of precipitation. Therefore, the increase in direct groundwater contribution to oceans and seas associated with a 10% increment of precipitation would amount to approximately 0.2% of global precipitation, or 2 mm/yr. This is equivalent to an additional flux of direct groundwater to oceans and seas of approximately 260 km^3/yr, which represents about 0.6% of the annual total water input to oceans and seas (i.e. including river runoff and direct groundwater flow of 40,000 km^3/yr). Although this additional flux of direct runoff is unequivocally small, the salt load in direct groundwater is approximately 540,000 km^3/yr (i.e. 2,400 km^3/yr of groundwater carry 1,300,000,000 t of salts annually, which is equivalent to a dissolved solids concentration of 540 mg/l). Therefore, an additional 260 km^3/yr of direct groundwater would mean about 140,000,000 t/yr of additional salts being added to the oceans and seas. Whether this additional salt load would increase the salinity of the oceans and seas is unclear. In an intensified hydrologic cycle there would be a larger water input to the oceans and higher rates of evaporation. If the water fluxes to and from the oceans eventually became equalized and the salt load increased at the rates previously calculated, then the salinity of the receiving water bodies would increase only if their total water volumes increased at a rate insufficient to dilute the salt content to at least present levels. At this point in time, it is not clear how much, or if at all, the volume of the oceans will increase as a result of thermal expansion and ice melting on a warmer planet (Chao, 1991).

The above are estimates of global groundwater disturbances arising from the hypothetical scenario for greenhouse warming (i.e. 10% increase of global precipitation), and assuming that the hydrologic cycle has reached a steady state. Whereas the baseflow contribution to river runoff might take from tens to hundreds of years to reach its new equilibrium, direct groundwater flow might stabilize over time scales one or two orders of magnitude longer.

Table 6.3.1 Groundwater runoff and its proportion to precipitation and total river runoff in the area of Central and Eastern Europe

Groundwater runoff provinces	*Groundwater runoff areas*	*Groundwater runoff regions*	*Area (ths. km²)*	*Water volume (km³/yr)*			*Groundwater runoff precipitation ratio (%)*	*Groundwater discharge to river/total river runoff ratio (%)*
				Water volume (km³/yr)	*Discharge (1/s per km²)*	*Water column (mm/yr)*		
1	2	3	4	5	6	7	8	9
I Karelian-Kola	–	–	334	22.4	2.1	66	9	15
II Eastern	II_1 Barents and White Sea	II_1^1 Severnaya Dvina	613	360	1.8	57	11	20
	II_2 Baltic	II_2^1 Ladoga and Chudskoye	329	24.0	2.3	72	10	30
		II_2^2 Neman and Vistula	300	26.6	28	88	10	30
		II_2^3 Oder	157	13.3	2.7	85	9	35
	II_3 Volga and Caspian	II_3^1 Upper Volga	415	23.9	1.8	57	10	27
		II_3^2 Volga and Kama	750	39.4	1.7	54	8	25
		II_3^3 Caspian	556	5.4	0.3	9	–	–
	II_4 Azov and Black seas	II_4^1 Dnieper	291	9.9	1.1	35	6	32
		II_4^2 Don	324	6.1	0.6	19	3	25
		II_4^3 Black Sea	220	5.2	0.8	25	3	15
III Pechora	–	–	275	10.4	1.3	41	8	15
IV Thflringen	–	–	23	1.7	2.2	92	19	40
V Czech Massif	–	–	87	66	2.4	76	10	45
VI Silesian and Sventojan	–	–	35	3.5	3	94	15	35
VII Ukrainian	–	–	151	2.3	0.5	16	3	26
VIII Donets	–	–	42	10	0.8	25	4	35

Table 6.3.1 (Continued)

Groundwater runoff provinces	Groundwater runoff areas	Groundwater runoff regions	Area (ths. km²)	Water volume (km³/yr)			Groundwater runoff precipitation ratio (%)	Groundwater discharge to river/total river runoff ratio (%)
				Water volume (km³/yr)	Discharge (1/s per km²)	Water column (mm/yr)		
1	2	3	4	5	6	7	8	9
IX Timan and Ural	IX_1 Timan	–	88	8.2	2.9	101	17	30
	IX_2 Ural	–	513	21	1.3	41	11	32
X Mizian	–	–	126	26.3	1.7	54	3	9
XI Dobrugian	–	–	6	0.09	0.5	15	3	10
XII Scythian	XII_1 Black and Azov seas	XII_1^1 North Crimean	19	0.4	0.8	25	2	5
		XII_1^2 Azov and Kuban	89	2.7	1	32	2	6
	XII_2 Caspian	XII_2^1 Terek and Kuma	75	14	0.6	19	6	5
XIII Carpathian and Balkan	$XIII_1$ Carpathian	$XIII_1^1$ Mountain-fold Carpathian	165	266	5	158	20	35
		$XIII_1^2$ Pannonian	129.5	5.4	1.3	41	10	20
		$XIII_1^3$ Transylvanian	21	0.8	1.2	38	18	32
	$XIII_2$ Balkan	$XIII_2^1$ Upper Thracian	48	2.4	1.6	50	20	35
		$XIII_1^3$ Rodopian	21.5	1.3	1.9	60	26	40
XIV Crimean and Caucasian	XIV_1 Mountain Crimea	–	105	261	7.9	249	25	35
	XIV_2 Caucasian	$XIII_2^1$ Greater Caucasus	105	26.1	7.9	149	25	35
		$XIII_2^2$ Transcaucasian	70	3.8	1.7	54		–
		$XIII_2^3$ Minor Caucasus	63	10.3	5.2	164	20	40

The relationship of flux to runoff and precipitation, has been presented above. The analysis of these data leads to the following conclusions:

1. The world-wide ratios of baseflow/precipitation and baseflow/river runoff are approximately 10% and 30%, respectively. These ratios show a high geographical variability, which is controlled by the prevailing regional climatic and hydrogeologic factors. The baseflow/precipitation ratio can vary from 0% in areas with impermeable ground (e.g. permafrost) to, theoretically, over 100%. In practice, the largest observed ratios are on the order of 70% (they have been documented to occur in karstic terrain of the Crimean region in Eastern Europe). The range of observed values of the baseflow/river runoff is from 0%, in permafrost areas, up to 100%. The latter high values are known to occur in mountain-fold karst areas with favorable recharge conditions, such as those that prevail in central and Eastern Europe.
2. Recent studies indicate that, on a world-wide basis, the direct groundwater flow (this is the direct exchange of water between oceans/seas and the adjacent coastal aquifers, bypassing the river network) is approximately 2,400 km^3/yr. This is equivalent to about 6% of the total annual water input to oceans and seas. In spite of its relatively low volume, direct groundwater recharge accounts for some 13 million t/yr of salts discharged to oceans and seas on a world-wide basis. This volume of salt is equal to 52% of the total dissolved solids annual output to oceans and seas by rivers.
3. Baseflow has increased over approximately the last 300 years, as a result of infiltration from large-scale irrigation and seepage from man-made reservoirs. This gain in baseflow is approximately equal to 6% of the current river runoff (which equals 38,000 km^3/yr). Surface runoff (excluding baseflow), on the other hand, has decreased over the same period as a consequence of reservoir evaporation and infiltration losses (the loss amounts to about 12% of current total runoff). The combined effect of the gain in baseflow and the drop in surface runoff is a net decrease in global river runoff over the last 300 years of about 2,500 km^3.
4. Assuming a possible 10% increase of global precipitation as a result of potential greenhouse warming, the associated change in baseflow would be 9 mm/yr, which is equivalent to 1,200 km^3/yr. The change in direct groundwater discharge to oceans and seas would be approximately 2 mm/yr, or, 260 km^3/yr. Establishment of baseflow and direct groundwater flow will take place over different time scales, with the latter flow taking a much longer time to reach equilibrium. The impact of the larger direct flow on the global water balance would be minimal from a volumetric point of view. The increment in salt discharge, however, is appreciable. The salinity of oceans and seas would increase if the increased salt load were maintained over long periods of time and the gain in the volume of receiving water bodies was not sufficient to offset the gain in salt content.
5. Information gaps remain on groundwater fluxes for some parts of the world, some of which include large aquifers in regions with intense hydrologic cycles (e.g. equatorial areas in developing countries). The importance of groundwater as a water source in the world points to the need for a greater understanding of the rates of groundwater and salt transport throughout the land masses of the Earth.

The existing map (*World Map*, 1999) of groundwater flow for different areas in the world, characterizes groundwater runoff under conditions similar to natural conditions. In order to predict the regional effect of the various kinds of human impacts on specific groundwater discharge values and total groundwater resources it is necessary to have information about the spatial and temporal extent of this effect, its intensity and direction. Such information is contained in design plans and specifications. The following conceptual model of the character of the human impact on the groundwater regime and balance make it possible to predict regional changes in specific groundwater discharge values, within certain regions. The deviations of the groundwater moduli

and coefficients from their average long-term values presented on the maps, obtained from these computations, should be checked and defined more exactly using data on the known drainage basins with a similar impact under the same or similar set of natural conditions. In other words, to avoid gross errors, regional predictions should be checked and corrected by comparison with sites where more accurate computations have been made.

Directed changes in the groundwater regime and balance may occur under the effect of various anthropogenic factors. Regional and global transformations in the conditions that generate groundwater and its resources occur primarily as a result of climatic changes, considered above, large-scale hydraulic construction of regional amelioration systems, land development, development of mineral deposits, creation of large urban areas, and construction of industrial enterprises. Each human activity affects in a specific way the groundwater regime and balance. In the following material, the possibility of using the map (*World Map*, 1999) data for predictive assessments, without considering each of these processes in detail, will be discussed.

Large hydraulic structures (reservoirs, main, canals, etc.) also have a regional effect on the groundwater regime and balance, though the spatial scale of this effect is incompatible with the hydrological after-effects of climate changes. The generation of the so-called additional groundwater resources due to the leakage from reservoirs, canals, and flooding is of particular interest. This effect commonly covers a belt several kilometers wide along the both banks of a river, and in some cases may extended for tens of kilometers from the hydraulic structure (e.g., the Karakum Canal). Changes in the seepage characteristics of groundwater flow caused by losses from a reservoir may result in the reduction in groundwater moduli in the hydraulic structure influence zone. However, the total value of ground flow to a reservoir as compared to a non-regulated river may increase due to the considerable increase in the reservoir perimeter. In other words, groundwater moduli in the shore area of a reservoir may decrease by tens of percent as compared to natural groundwater runoff. On the other hand, the coefficient of the subsurface alimentation of rivers in this zone do not change greatly since they characterize the groundwater runoff of the drainage area and may decrease only in the case of a sharp increase in evapotranspiration with a substantial backing of the groundwater level over large areas.

Particular attention should be given to discussion of the effect of the regional reclamation on groundwater characteristics and resources. The effect of drainage and irrigation on the groundwater regime and balance are different. The scale of the reclamation effect on groundwater depends on the proportion of the reclaimed area and the total area of the river basin, as well as on the water-transmitting parameters of the vadose zone and the upper aquifer, the degree of the hydraulic connection between the aquifer and natural and artificial drains, and the rate of natural groundwater recharge. Drainage commonly lowers the groundwater level and natural recharge, and that ultimately results in a decrease in specific groundwater discharge and in some reduction of the total water resources.

Irrigation of large land areas, in contrast with watersheds of small and mid-size rivers is accompanied by reverse processes. Water-use and irrigation flooding in spring and autumn periods generally lead to a sharp increase in groundwater recharge as compared to natural recharge. In some irrigated areas, groundwater recharge increases several times or even by an order of magnitude. However, such an increase in groundwater recharge does not lead to a similar increase in the specific groundwater discharge values. This is due to the fact that a substantial portion of an additional rise is intercepted by the artificial drainage or is lost as a result of evapotranspiration. At the expense of these processes the specific groundwater discharge values within a drainage basin usually increase by tens of percent, and in some cases 2–3 times.

Land development including field management and forest reclamation affects the environment and for this reason, the regime and balance of groundwater. Particular attention should be given to processes caused by tree removal in large forest areas accompanied by transformation of

the hydrological regime of these territories. During such processes there is sometimes substantial decline in groundwater levels, small rivers become dry, bogs and natural water bodies may disappear. Groundwater levels lowered by several meters, along with the rapid spring flood runoff, result in a reduction of the recharge to the upper aquifer and, consequently, a reduction in specific groundwater discharge values by tens of percent. Deforestation is similar in many respects to drainage reclamation in regard to its effect on the hydrological and hydrogeological regimes of these areas.

The effect of large urban and industrial areas on groundwater runoff has not been studied sufficiently. It is known that leakage from water-supply lines and sewerage nets, as well as reduction in evaporation from areas covered with asphalt result in a sharp groundwater level rise and flooding of urban and industrial areas. According to existing assessments, groundwater recharge in urban areas has increased several times or even by an order of magnitude compared to recharge under natural pre-development conditions. However, groundwater runoff is not subjected to appreciable changes as seen in groundwater recharge. Besides, groundwater discharge is augmented in urbanized areas by numerous foundation pits and service lines. In this regard, the effect of urban and industrial zones on specific groundwater discharge values requires special studies and predictive estimates depending on the problem posed and the scale of the phenomenon, i.e. on the site-specific scale.

The effects of mineral deposit development on regional hydrogeological conditions have been investigated to a great extent. Groundwater runoff and resources in mining areas are mainly affected by mine drainage and the decline in groundwater levels. Cones of depression, in these cases, may extend over hundreds of kilometers, and their depth may amount to tens and hundreds of meters. This leads to a disappearance of small rivers, complete de-watering of the upper water-bearing strata, and a decrease in recharge from mid-size and large rivers. Therefore, specific groundwater discharge values and groundwater resources decrease in these regions by several times the values necessary to account when estimating present and future water balances.

The human impact on drainage basins leads not only to a transformation in groundwater balance characteristics, but also to a substantial transformation of groundwater quality that will result in regional pollution of aquifers. Regional changes in groundwater composition and properties are commonly caused by non-point and point pollution sources. When predicting potential and existing groundwater pollution on a regional scale, particular attention should be given to non-point pollution sources, which are difficult to control. For example, acid precipitation, fertilizers, and agricultural chemicals have an effect on natural waters practically everywhere. At the present time, the pH values of the water of upper aquifers in the Northern and eastern Europe, and in some regions of the United States of America and Canada, declined to a pH of 4 or 5 and less, while the concentration of nitrates in the groundwater of agricultural areas amounts to tens and even hundreds of milligrams per liter. Such large-scale effects on the hydrochemical regime of groundwater is necessary to consider, and to predict future trends. The information about groundwater recharge presented on the map allows us to estimate as a first approximation the probable scale of regional pollution of groundwater with known or accepted pollutant concentration values as input to the buffer or neutralizing properties of the vadose zone and the saturated medium of aquifers.

In this regard, particular attention above has, been given to the regional assessment of groundwater vulnerability to various pollution sources. The vulnerability of the upper aquifer primarily depends on the conditions and value of its natural recharge, composition and thickness of the vadose zone, and water-transmitting characteristics of the aquifer itself. Currently, some approaches have been developed to evaluate groundwater vulnerability. Some methodologies exist which obligatorily take into consideration natural groundwater recharge. Therefore, ground-

water runoff maps, including the map presented here showing values and conditions of groundwater recharge may be used to approximate the regional assessment of groundwater vulnerability.

Finally, the *Map of Hydrogeological Conditions and Groundwater Flow* quantitatively characterizes conditions of groundwater generation and groundwater resources in various natural zones. The map may facilitate, in conjunction with the basic information on the kind, the extent, and the nature of the human impact on the drainage areas under investigation, basic assessment of the nature and extent of the resultant changes in groundwater conditions, and a regional predictive assessment of deviations of specific groundwater discharge values, and of changes in the quality and quantity of groundwater resources within a given region. The map also may be used as the basis for regional evaluation of groundwater vulnerability to contamination.

6.4 Human activities impact on groundwater resources and their use

Intensive human activities can lead to changes in groundwater resources quantity as well as their quality.

The main aspects of human-induced activities essentially influencing groundwater resources are as follows:

- groundwater exploitation by well fields for domestic-potable and industrial water supply;
- irrigation, and pasture watering;
- mineral deposits mining, development of oil and gas fields;
- industrial and civil construction, engineering operation;
- rural development, including irrigation and drainage, and also forestry actions;
- hydraulic construction and construction with exploitation of other power stations (nuclear power stations).

All of the above anthropogenic factors lead to changes in generation conditions of natural dynamic resources and groundwater storage as well as its safe yield.

These changes occur in two essential guidelines:

- changes in groundwater recharge and discharge affecting changes in inflow and outflow components of the water balance;
- change in groundwater quality due to contamination from anthropogenic sources or influx of natural water (ground or surface water) characterized by other qualitative indices in the direction of water-supply well fields.

Consider in more detail the peculiarities in groundwater resources changes under various human-induced factors.

6.4.1 Groundwater withdrawal by well fields

Groundwater withdrawal by group and individual well fields may contribute to generation of large cones of depression, change in groundwater flow movement, transit of discharge areas into recharge ones. In specific conditions the withdrawal leads to groundwater depletion below its safe yield.

Intensive groundwater withdrawal contribute to substantial changes in groundwater quality and, as result, in many cases to its degradation due to inflowing non standard natural ground and surface water to well fields and also contaminated water from anthropogenic sources of contamination. The deterioration of water quality can be caused by physical-chemical processes in system 'water-rock'.

The impact of groundwater abstraction on its resources in various hydrogeological conditions manifests itself in different ways. In one case, groundwater withdrawal leads to the increase of its 'resulting recharge'[1] that is connected with the decrease or cessation of evaporation from the water table (its discharge to aeration zone), when decreasing the water level. In upper aquifers a small level reduction can cause a considerable reduction of water discharge to the unsaturated zone, particularly in arid areas. Nevertheless, even under humid conditions, this process can play an important role. When operating well fields, the rise of resulting recharge contributes to increasing groundwater storage.

In other cases, if resulting recharge does not increase, and the withdrawal can not be compensated with groundwater recharge, the reduction of groundwater storage occurs, as a result of operation, i.e. groundwater exhaustion is observed, and sometimes, its safe yield (Section 3.4). The safe yield depletion is consequently due to excessive groundwater withdrawal over fixed amounts of the safe yield. For instance, one can refer to the area of plain Crimea where in 1950–70s generally for irrigation purposes the multiannual intensive groundwater withdrawal substantially exceeding the safe yield led not only to the generation of deep cones of depression and to regional drop of groundwater level over admissible standards, but also caused the change in groundwater quality (salinization).

In the 1980s the undertaken measures related to decreasing groundwater abstraction and artificial recharge of its storage, improved the hydrogeological situation.

When operating groundwater withdrawal, the changes in conditions of safe yield generation (for instance, conditions of surface and groundwater interaction, during the operation of well fields in the coastal area) can contribute to the depletion of the groundwater safe yield. This is due to colmatage processes in channel deposits that causes decreasing induced resources from streamflows and leads to productive rate reduction of well fields.

As was said above, the depletion of the groundwater safe yield is due to its quality degradation. It is connected with the fact that the intensive withdrawal over the determined amount of the safe yield contributes to non-standard water inflowing from other aquifers or affects the seawater intrusion. The change in groundwater quality of operating aquifer is often observed in multilayer composition of water-enclosing media when aquifers adjacent to operating ones contain saline water. The change in head ratio increases or leads to generation of non-standard water runoff.

In specific conditions large-scale groundwater withdrawal can promote the improvement of its quality. So, referring to Kulakov (1990), in the area of Zayatchi within Ostrovni groundwater reservoir in the valley of the Amur River a water lens without iron was formed. Its origin is connected with surface water entrapment from the Amur. The iron content in groundwater off this area amounts to tens mg/dm^3.

6.4.2 Mineral deposits mining

Use and exploitation of mineral deposits in most cases is accompanied by drainage and water-level declining measures connected with high-rate groundwater withdrawal and leading to the same consequences as groundwater abstraction by well fields (change in conditions of groundwater recharge and discharge, generation of large cones of depression, irrigation of aquifers, change in chemical composition of groundwater, etc.). However, when mining mineral deposits, these processes are characterized by specific features. In contradistinction to operating

1. Resulting recharge is understood to be the difference between groundwater infiltration into the aquifer and evaporation from this water table.

well fields, in these cases the water withdrawing is being made from all aquifers forming the hydrogeological system. At the present time, the depth of operating aquifers attains 500–600 m and up, that appreciably leads to more considerable level drops amounting to hundred meters than during well fields exploitation. In cases, when mineral deposits mining is exerted by roof caving, the increase of seepage properties in overlying deposits and generation of the conducting-fissured zone are observed. This fact often contributes to increasing groundwater infiltration recharge.

The construction of tailing dumps, hydrodumps represents an important factor relating to changes in groundwater resources when developing mineral deposits. On the one hand, these engineering constructions may induce water inflows to mines and quarries, and on the other, they lead to groundwater contamination.

In most cases, when mining mineral deposits, the groundwater generated with specific chemical composition by groundwater mixing of various aquifers and its interconnection with water-enclosing rocks, and also groundwater contamination directly in mine workings occurs.

In some countries the withdrawal of mine water amounts to considerable values (up to 20% of the total groundwater withdrawal). The large part of withdrawn water falls on surface without its use despite the fact that in many cases the pumping water is distinguished by a high quality. Thus, mineral deposits mining contributes to the depletion of groundwater safe yield which manifests itself not only in the fall down of withdrawn water without its use, but also in putting out of operating well fields, level recession on vast areas, including promising well fields for their installation.

The features of groundwater contamination in mineral deposits are determined by the accepted procedure of their protection from waterlogging. As a rule, the groundwater chemical composition and its salinity within mine workings are appreciably different. This is due to groundwater oxidation in mine workings, activization of rocks leaching processes, change in gas and bacteriological composition, and also directly spreading of hydrocarbons, oils, suspended substances in groundwater.

In coal deposits acid water is often formed, in coal and ore deposits a high content of microcomponents (cadmium, zink, chrome, strontium, nickel, and others) is observed.

High concentrations of sulfates, chlorides in groundwater and also water hardness are often noted. As pointed out above, when developing mineral deposits, groundwater protection from contamination and depletion is of particular value. In this aspect, when selecting a system of mineral deposit protection from groundwater, it should be given preference to outside water-declining systems with simultaneously pumping water use for water supply.

As distinct from mineral deposits, the impact of oil and gas fields development on resources and groundwater quality is mainly connected with water injection into productive layer for keeping aquifer pressure. On the one hand, the above process can lead to contamination of fresh and brackish water in upper aquifers in course of seepage of oil and high mineralized groundwater through fracturing zones (Oborin et al., 1994). On the other hand, the injection of surface potable water in large volume may affect the impoverishment of valuable mineral water.

6.4.3 Civil and industrial construction, engineering facilities operation

Industrial and civil construction has a variable influence on groundwater resources and quality. In one case, the above human-induced activities lead to increasing groundwater recharge at the expense of losses in undergroundwater-bearing utility systems, waste seepage from accumulators, waste water, infiltration of irrigated water, moisture condensation under building structures and asphalt, construction of ponds and water reservoirs, etc. In other cases, the anthropogenic factors affect the groundwater discharge increasing (pumping out from construction pits, underground

railways, water abstraction by various drainage facilities) or its recharge decreasing (asphalting of the territory, snow removal, etc.). Increasing recharge, in particular, at the expense of industrial waste leakage may induce substantial negative changes in groundwater quality.

Groundwater withdrawal by well fields and water-declined constructions were considered in detail in preceding chapters. Therefore, the consequences of increasing groundwater recharge will be discussed in this chapter. In many cases, this process is accompanied by rising groundwater level, that contributes, on the one hand, to generation of new anthropogenic aquifers, and on the other, causes waterlogging.

6.4.4 Rural development

Rural development including irrigation and drainage actions leads to significant changes in groundwater resources and its quality. These changes are connected with following factors:

- change in conditions of groundwater recharge caused by percolation loss through main-line and irrigation channels, infiltration of irrigated water. In some cases, percolation losses through channels form the conditions for generation of fresh water lenses in saline water areas;
- large amount of salt inflow to subsurface water, especially when dissolving salts in unsaturated zone;
- increasing groundwater yield for evapotranspiration when rising water level;
- groundwater withdrawal by vertical and horizontal drainage facilities;
- vast use of organic and inorganic fertilizers, pesticides and, as result, transfert of contaminants into aquifer;
- inflow of contaminants in aquifers from irrigation fields by waste water and from accumulating storage of cattle-breeding farms, poultry plants, etc.

The above factors contribute, on the one hand, to increasing groundwater recharge, and on the other – to groundwater contamination, which as compared to industrial one spreads all over vast areas. The main contaminated components are nitrogen and iron compounds, fecal coliform, and also pesticides.

6.4.5 Hydraulic structure and other power facilities

Hydraulic structure (construction of dams, water reservoirs, etc.) affects a variable impact on groundwater resources. Construction of water reservoirs contributes to groundwater blockage that leads to formation of anthropogenic water storage in the coastal zone during the flooding of dry soils in the vadose zone. In regions under hydraulic construction the changes in groundwater exploitation occur. In the majority of cases these changes have a positive effect. So, if in natural conditions in coastal areas groundwater were distributed in floodplain deposits composed of fine-grained sands of small thickness with a low coefficient of permeability, when constructing water reservoirs and flooding tidal areas in the coastal zone of these water reservoirs, terraces become water-bearing ones characterized by important thickness and high properties of permeability. It is possible to construct coastal infiltration water intakes structures in areas where before setting up water reservoirs the conditions for construction of such water intakes were unfavorable.

Hydraulic construction in a number of cases may affect the depletion of groundwater safe yield due to change in conditions of its generation. So, in most regions for water supply, groundwater is widely used in river valleys where operating aquifer in bedrock is separated from river by another aquifer located in alluvial deposits. In this case, if riverbed deposits are subjected to colmatage, in the course of low water period is observed the draining of alluvial aquifer with subsequent recharge of reduced water storage during high water and flood times. The value of

recharge depends on duration and intensity of the latter. More recharge occurs when flooding occurs in a coastal plain. The construction of water reservoirs upgradient well fields can substantially reduce the duration, number and intensity of high water that leads to reduction of the productive capacity of well fields and the deterioration of groundwater quality. The safe-yield depletion may also be caused by flooding of productive alluvial aquifers with water reservoir that it makes impossible to operate.

An important impact on groundwater quality can affect the exploitation of nuclear power stations in regions which are characteristic of heat and radioactive contamination.

6.4.6 Forecasting of changes in groundwater resources under human induced factors

As briefly pointed out above, the effects of different types of human-induced activities on groundwater resources and quality have a multicriteria nature. In one case, the anthropogenic factors lead to increasing groundwater recharge, generation of artificial storage, rising the safe yield and improving the conditions of operation. In others, the drainage of water-enclosing rocks (decrease of groundwater storage) and depletion of the safe yield occur. With respect to groundwater use for public water supply the groundwater quality under anthropogenic factors is deteriorating. However, in some cases groundwater quality is increasing.

When evaluating possible changes in groundwater resources under anthropogenic factors, first of all, it should be noticed, that processes of groundwater exhaustion, and more over, its safe yield depletion are mainly of a local nature although in individual regions, especially in the course of intensive development of hard mineral deposits, vast areas are subjected to safe yield exhaustion. Anthropogenic contamination processes of main confined aquifers operating for public drinking water supply are also of a local nature. The most areas under anthropogenic groundwater contamination are noted in upper aquifers, in particular, in developed urban and rural areas as well as in river valleys with active interaction of surface and groundwater.

Nevertheless, while the fact that processes of groundwater contamination and depletion are of a local nature, groundwater protection remains one of the important problems of comprehensive use. When solving this problem, possible predicting change in groundwater resources and their quality is a serious task in the very distant future. In regional aspects, methodological basis and theoretical principles of long-term and superlong-term forecasting of possible change in groundwater resources are not practically elaborated. Thus, the efforts of such forecasting mainly to reveal general tendencies are implemented with expert estimates.

In the 1980s in the paper (Zektser et al., 1992) for the territory of the former USSR an effort of a such forecasting has been made. On the basis of analysis obtained related to changes in groundwater drinking resources, including those of their contamination, the authors of the above-mentioned paper concluded that with scientifically based management use, governing artificial recharge of groundwater resources, and also providing protective measures from contamination, the total value of the groundwater safe yield for the territory, as a whole, is being maintained at the actual level in the coming 50–70 years. At the same time, in individual regions an important decrease of the safe yield may occur.

Apart from the factors considered in this chapter, technical progress in the field of groundwater technology such as elaboration of new pumping equipment for water withdrawal at the depth of 400–500 m, modern well construction of recent design with a high productive capacity, cheap techniques for freshening of brackish and saline water, etc. will contribute to increasing groundwater safe yield. An important contribution is also an improvement of hydogeological studies.

In the following pages it will be presented the main types of human activities that have or are going to have a more serious impact on future groundwater use. This human activities are classified in three groups: 1) socio-economical or ethical actions; 2) ecological or sthetical); and 3) technological. The third group will include the more or less conventional human activities. Most of them have been already described in certain detail elsewhere in this monograph. In this section we are going to emphasize more the ethical and sthetical actions because they usually are less taken into consideration although in fact they may be the real driving force in the water policy of many countries.

As it is shown in Chapter 5 of this monograph, the absolute and relative use of groundwater varies much from country to country. Climatic and geological factors use to play the leading role to explain the relevance of groundwater use. Generally the arid and semiarid countries endowed with extensive and thick pervious geological formations are those in which groundwater is more used. Nevertheless, the exceptions to this rule are frequent. There are many countries, like Spain, in which the predominance of surface water use in relation to groundwater use has been caused by cultural and administrative motives. The frequent attitude of those water planners who separate surface and groundwater projects, in general forgetting the latter, was described as 'hydroschizophrerua' by the American hydrologist Nace in the seventies. An analysis of the Spanish 'hydroschizophrerua' was done by Llamas (1985, 1997) and Llamas et al. (1996).

Unfortunately, in many cases this usually more advantageous solution (based on groundwater development) will not be adopted. The principal motives that may induce such a wrong decision may be the following: 1) lack of hydrogeological training among the water planners; 2) the love of politicians for 'grandiose hydraulic works' that will give them a good image in the media, mainly in the corresponding inauguration festival; 3) the pressure of the lobbies of large construction companies; 4) the 'subsidy culture' because usually the 'grandiose hydraulic works' are paid with public money and not by their direct beneficiaries; and last but not least 5) the large budgets of such grandiose projects are an easy pray for completed decision makers.

The Commission of the European Union has prepared a proposal of 'Environmental Water Framework Directive' (*Official Journal of the European Communities*, 17 June 1997) that includes a new and important provisions in relation to water economy. The article No. 17 says 'The total cost of the works made to develop water resources have to be paid by the beneficiaries of those resources. The indirect subsidies should be avoided because they disrupt the free market rules'.

This provision may encounter strong political opposition in various countries, mainly driven by farmers and constructors lobbies. Nevertheless, in the next decades the idea of transferring the hydraulic work costs to the beneficiaries will probably be socially accepted not only in the European Union but all over the world (Young et al., 1994). In the United States of America this principle has been almost established (National Research Council, 1996).

Some water conflicts have had an economic background, mainly in water scarce countries, e.g. Egypt *vs.* Sudan and Ethiopia; Israel *vs.* Syria, Palestine and Jordan; and many other cases (Llamas, 1997). Nevertheless, even in these cases, the emotional issues related to water use to play a role more significant than the pure economic issues.

The emotional issues are more evident in those water conflicts related to real or pretended ecological impacts. These conflicts are widespread all over the world mainly in relation to the construction of new reservoirs. This is what has been denominated 'the dam dilemma'. This frequent opposition to new dams does not always mean that the conservation groups are usually in favor of groundwater development.

It is well known that in many cases aquatic ecosystems, mainly wetlands, are located on groundwater discharge zones. The pumping of groundwater in such aquifers may have a significant impact in the discharge flow and consequently in the low flow of rivers and in the

wetlands functioning. A few years ago, some hydrogeologis1s considered that the EPA proposed regulation on wetlands would become a real threat for groundwater development in the United States of America. In the United Kingdom the influence of pumping in the low flow of about 40 rivers is being studied. In some cases, e.g. Pang river basin, the pumpage has been reduced in order to keep the amenity value of the river that required a minimum flow (cf. to be quoted later). In Spain, several relevant wetlands have been destroyed or threatened because of the water table depletion caused by intensive pump age for irrigation (Llamas, 1994).

The ecological issues will probably constitute a relevant constraint for groundwater development in many countries. This is not probably a simple fashion that will fade away within a few years. The 'success' of the water ecological issues in the communication media – although sometimes might be exaggerated – is not merely the love of the media for sensationalism. It corresponds to the increasing awareness about the ecological role of water, which is the 'blood or sap' of nature. It also is related to the relevance of water in the shaping of the different landscapes.

In conclusion we would like to stress that the human impacts would influence in positive and negative ways the use of groundwater in the near future.

Groundwater abstraction will probably increase because of:

- the general augmentation of water demand for urban and rural use;
- the use of aquifers as an effective means to mitigate surface water scarcity during droughts;
- the progressive implementation of the principle 'user pays' that will prohibit the construction of grandiose surface water projects financed with public money but that are economically unfeasible.

Groundwater abstraction will probably diminish because of:

- environmental impacts related the water table depletion caused by excessive pumping;
- pollution of important aquifers caused by current agricultural practices and by extended urbanized areas.

7 Mineral and thermal-power water

7.1 Mineral water

Mineral groundwater, due to its ion-, salt- and gas composition (carbon dioxide, hydrogen sulphide, etc.), increased content of biologically active components (sulphides, organics, arsenic, boron, iodine, bromine) and to its specific properties (radioactivity, temperature, redox potential) (Table 7.1.1), presents a natural curative remedy which has a healing effect on the human organism.

Mineral waters are widely used at health resorts, sanatoria, in numerous urban and rural prophylactic clinics, balneological centers, and by bottling factories.

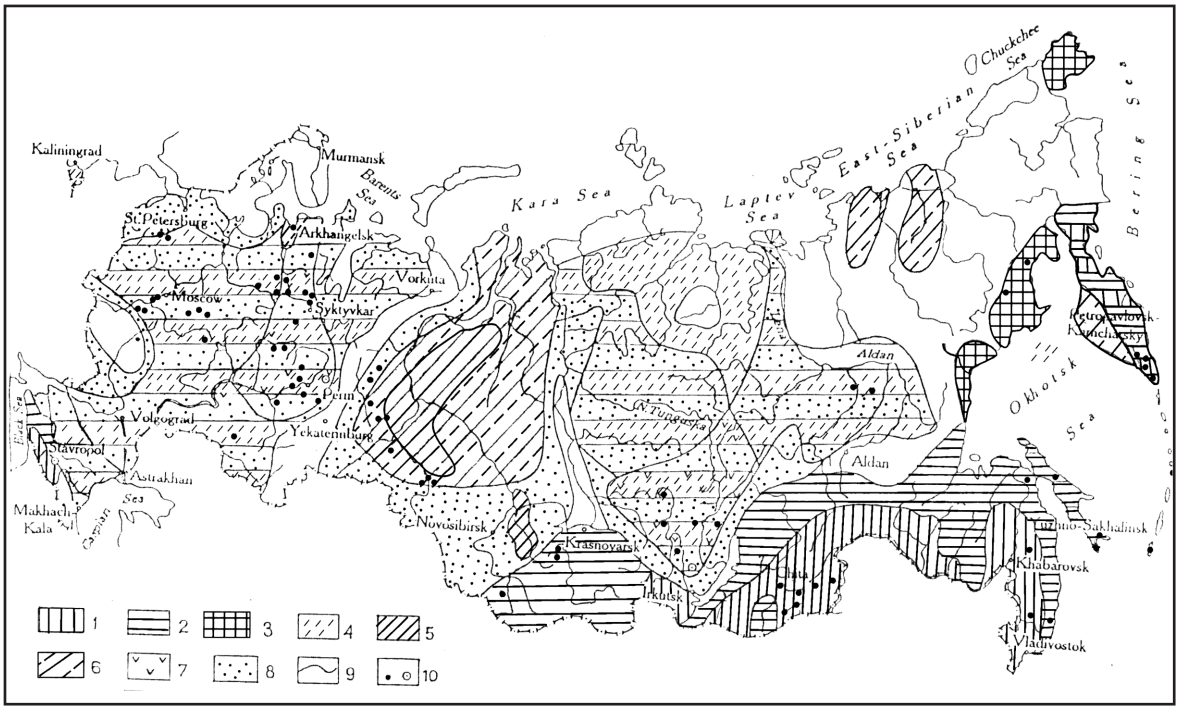
Basic features of occurrence

The formation and spreading of mineral waters depend on a complicated combination of geologic, structural, tectonic, geochemical, geothermal and hydrodynamic conditions. The most important among them are geologic, structural and tectonic factors, which, to a considerable degree, determine the mechanism, conditions of formation and resource basis of different-type mineral waters. Just these factors are used as the basis for zoning of mineral waters into provinces. Among such provinces, the most typical are the provinces of carbon dioxide water, nitrogen thermal water, and the waters of nitrogen-methane and methane types (Fig. 7.1.1). Figure 7.1.1 demonstrates an example of zoning different mineral waters on the territory of Russia.

Table 7.1.1 The allowed concentrations of biologically active components in mineral waters

Type of mineral water	*Components*	*Mass concentration (mg/dm^3)*
Drinking water		
Carbon dioxide	Free carbon dioxide (dissolved)	500.0
Ferriferous	Iron	10.0
Arsenious	Arsenic	0.7
Boric	Orthoboric acid	35.0
Siliceous	Metasilicic acid	50.0
Bromide	Bromine	25.0
Iodic	Iodine	5.0
Organics-containing	Organic substances (as calculated for carbon)	5.0
Balneological water (for external use)		
Carbon dioxide	Free carbon dioxide (dissolved)	1.4
Hydrogen-sulphide	Hydrogen-sulphide, General	10.0
Radon	Radon	5 nKi/dm^3
Thermal	Temperature	350° C

Figure 7.1.1 Distribution of different types of mineral water over the territory of Russia



The province of carbon dioxide mineral water

The province of carbon dioxide mineral water covers the Alpine folded regions or those rejuvenated in the Alpine tectono-magmatic cycle that are subjected to abyssal processes of regional thermometamorphism. These include, first of all, the mountain-folded structures and the adjacent territories. The province is confined to the Alpine folded zone and Mesozoic and Paleozoic folded structures rejuvenated in Cenozoic period. These regions are characterized by the existence of fissure waters in crystalline strata, fissure-vein water and fissure-stratum or pore-stratum waters in the overposed or intermountain areas. The common condition for the formation of carbon dioxide water lies in that CO_2, which primarily originated thermometamorphically, penetrates from depth to the upper layers of the Earth's crust and saturates the circulating groundwater. Most often the penetration of abyssal CO_2 occurs in rupture zones.

The enrichment of atmospheric water which infiltrate the earth circulating in washed sedimentary or crystalline rocks, through carbonic acid, forms low-mineralized CO_2-containing waters of hydrocarbonate magnesium-calcium, calcium-magnesium or sodium types that are typical, mainly, of hydrogeological strata. In artesian basins of intermountain and overposed depressions where groundwater has a higher mineralization (of a marine or mixed genesis, or associated with saline rocks), the penetration of CO_2 causes the formation of carbon dioxide waters of chloride-hydrocarbonate, hydrocarbonate-chloride sodium or other compound composition.

The province of predominantly nitrogen-methane and methane mineral waters

This province involves the platform-type areas and piedmont troughs of folded zones. The waters within the province, which are associated with the sedimentary cover (sedimentary complexes) of platforms, piedmont troughs and large intermountain depressions in folded areas, are exclusively of a stratum occurrence. The water mineralization varies from fresh water in the upper layers to

super-strong brines in the lower ones. The temperature varies from super-low to super-high. The majority of waters are of chloride-sodium, chloride-calcium-sodium and chloride-calcium types. High concentrations of iodine and bromine (in some cases they are developed on a commercial scale) give these waters a curative value. The saline (to a different degree) water in the top of the sedimentary cover has various ionic compositions. Methane prevails in the gas composition of groundwater in deep layers, and nitrogen is found in the top of the sedimentary cover; in local zones carbon dioxide or hydrogen sulfide is available.

The province of nitrogen-type thermal mineral water

The province of nitrogen-type thermal mineral water covers the areas of the most recent activization of the earth's crust affected by neotectonic motions with intensive displacements of blocks in some particular parts of rock formations. It borders on the province of carbon dioxide waters and includes areas where thermal water lies close to the surface, through intensive outside discharge areas. The province involves the mountain zones in alpine or rejuvenated areas of Cenozoic jointing. Nitrogen sources are formed in the zones of young tectonic faults due to the heating of infiltrated water or in artesian basins discharging from the basement. The specific feature of the province is the wide manifestation of young deep-set, steep faults, the manifestation of hydrotherms along which are known in literature as 'thermal lines'.

The most wide spread areas are the fissure- and fissure-vein water deposits in crystalline rocks. However, rather often they are associated with stratum systems of intermountain and overposed depressions, associated with a hydro-injection origin.

Nitrogen sources are chiefly low-mineralized and of sodium anion-variable composition, having most often an increased content of silica acid. Methane plays a considerable role in the gas composition of thick sedimentary strata. With respect to chemicals, the thermal waters are of chloride-sodium and calcium-sodium type, mean- to high-mineralized and brines, which are typical of some intermountain and piedmont artesian basins.

In thermal waters of zones with young faults, the carbonic gas is becoming of higher significance. Sometimes, nitrogen therms are characterized by a high content of helium, in some places by hydrogen sulfide; in granites they have an increased radioactivity.

7.2 Thermal-power water

Thermal water which has heat-power value creates groundwater that can be used as a source of heat energy or for producing electrical power. The main factors that determine the possible and efficient usage of thermal waters are temperature and the level of heat technology and heat-power engineering equipment.

The worldwide-accepted classification of thermal water is made on the basis of differences in its temperature and includes three basic classes: low-potential, mean- and high-potential waters.

Low-potential waters – with a temperature of 20 to 100 °C

Such waters also include a sub-class with an ultra-low potential (temperature to 40 °C) which can be used for heat-technological purposes, chiefly, with application for heat pumps. Low-potential waters are used to supply heat for industrial, agricultural and municipal projects. The efficiency of their use can be much higher when heat-consuming objects are equipped with special heating and ventilation systems optimized for the conditions of low-potential heat-carriers, including the combination of these systems with heat pumps.

Mean- potential waters – with a temperature of 100 to 150 °C

They are used for heat supply and, in some cases, for electrical power production with application of intermediate working media with a low boiling temperature.

High-potential waters – with a temperature of over 150 °C

They are used mainly for electricity production via a direct cycle. Taking into consideration the phasic state of these waters and the related specific technology of the electric power production, they are subdivided into overheated (with a temperature of 150–250 °C), highly-overheated (250–350°C) and maximum overheated (over 350 °C) waters.

Mean- and high-potential thermal waters are vapor-water mixtures and have become known in the literature as 'vapor-hydro-therms'.

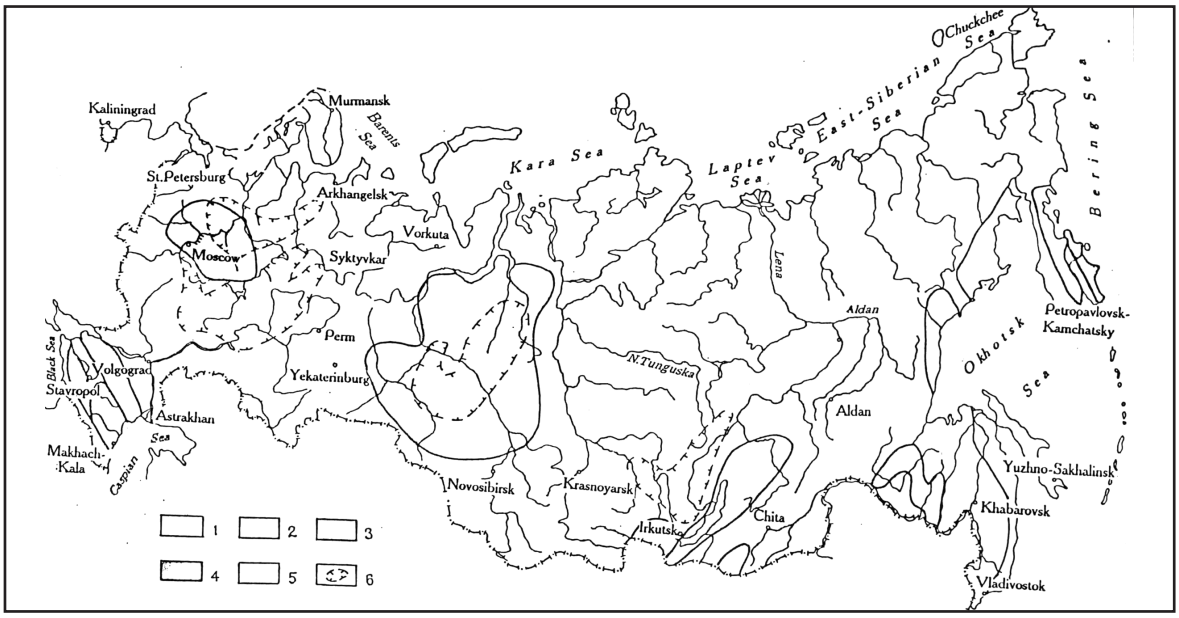
Due to the complicity of the practical use of natural heat-carriers (i.e. corrosion of mining and technological equipment, possible salt sedimentation, requirements of environmentally safe disposal of waste water), the assessment of these carriers as a heat-power resource takes into account the following factors: temperature, the total mineralization of waters, their gas saturation, hardness, pH value, contents of particular components and compounds (e.g. heavy metals, arsenic, phenols, hydrocarbons, etc.).

Basic regular features of occurrence

Thermal-energy water features are rather irregular. The determination whether one or another territory has potential for thermal-energy water development depends on a favorable combination of three basic interrelated natural factors – *geologo-structural, geothermal and hydrogeological*. In conjunction, these factors determine the resource availability of thermal groundwater, hydraulic capacity of rocks, conditions of recharge, water- and heat-exchange in hydrothermal systems, and, as a final result, determine the quantity and quality of natural heat-carriers (Fig 7.2.1).

It is generally accepted to distinguish two types of hydrothermal confined systems with basically different conditions of forming safe yield (exploitable reserves) of thermal-energy waters – *stratum and fissure-veined systems*.

Figure 7.2.1 Distribution of thermal and industrial waters over the territory of Russia



Stratum hydrothermal systems are associated with artesian basins of Epipaleozoic and Precambrian platform-type areas, as well as with intermountain and piedmont artesian basins of mountain-folded areas.

Fissure-veined hydrothermal systems (areas) are located in folded zones of different ages, characterized by a rather irregularly developed system of tectonic jointing in intrusive, metamorphic and volcanogenic-sedimentary formations and, as a rule, by availability of a sufficiently local source of heat. The fissure-veined systems cover in Russia, the areas of Cenozoic jointing of modern and young volcanism, the areas of Cenozoic (alpine) jointing, as well as the areas of Precenozoic jointing (Mesozoic, Hercinian, Calendonic and Baicalian epochs), which have undergone an intensive impact of neotectonic motions.

Potential resources of mineral waters

'Potential resources of mineral groundwater' is a conventional term since in a real situation evenly placed water intake structures are actually impossible. The following evaluation of potential resources of mineral waters in Russia makes the above point.

Water intake stuctures are located depending on climatic, geographic, technico-economic and environmental factors, which, in general, determine the conditions for the construction of health recovery and medical institutions, and, bottling factories. To solve the problem of prospecting and exploring for mineral waters and for planning of sanatoria locations and constructing health resorts in the USSR in 1980–6, a regional evaluation of predicted resources and safe yield of mineral water was conducted. On the basis of the estimates obtained, a map on a scale of 1:5 000 000 has been compiled. The evaluation has shown that the mineral waters occur almost entirely over Russia in amounts enough to provide the operation of sanatoria, prophylactic and balneological clinics and bottling factories. A number of regions have considerable resources with two or three types of mineral waters, that can satisfy the demands of large sanatoria-resorts complexes.

The highest potential resources are typical of the mineral waters which have areal spreading, i.e. which are developed in the platform-type artesian basins in the European, West-Siberia and East-Siberian Areas, and in the large piedmont and intermountain basins of the Caucasian hydrogeological folded area. They include differently-composed low-, mean- and high-mineralized waters and brines 'without specific components', iodine, iodine-bromine and bromine brines. The modules of potential resources vary from 1 to 50 $m^3/day.km^2$.

Such hydrogeological areas, covering the major part of Russian, are able to satisfy the mineral-water demands of any medical and prophylactic clinics and bottling factories, since the water well yields range from 500–600 m^3/day. The real demands of most sanatoria and prophylactic institutions for mineral waters are not more than 100–200 m^3/day, and the demand from bottling factories is 100 m^3/day. Potential resources of mineral waters in platform-type areas are usually many times higher than those explored or already exploited and much more than the needs of future mineral water consumers.

The artesian basins of platform-type areas and large piedmont and intermountain basins of folded regions contain considerable resources of curative hydrogen dioxide waters having a more local areal distribution but have a sufficiently wide occurrence.

The highest amounts of hydrogen dioxide waters are located in areas of Perm, Kuibyshev, Saratov, Irkutsk Cities, the Krasnodar Area, and in the Republics of Chuvashia, Tatarstan, Bashkorstan. The large potential resources (the prevailing modules are 20 to 50 $m^3/day.km^2$) are typical also of nitrogen-containing thermal waters in the southern part of Russia, associated with the Azov-Kuban and East-Forecaucasian basins of the Caucasian folded area (Krasnodar and Stavropol Territories, the Republics of North Caucasus). The water resources available there allow

the possibility of using water as a remedy, as a heat carrier, and for balneological purposes. Besides the above-listed types of mineral waters, the platform-type areas contain locally spread mineral waters (containing iron, radon, boron), that are small in size, and have not been evaluated.

The hydrocarbon mineral waters and nitrogen-containing therms in the mountain-folded areas of Russia have a more local occurrence due to their strict association only with certain geologo-tectonic structures. Because of this, their resources are not high (Table 7.2.1).

Table 7.2.1 Potential resources of mineral waters in mountain-folded areas (ths. m^3/day)

	Carbon dioxide waters		*Nitrogen-containing therms*	
Hydrogeological mountain-folded areas	*Number of perspective structures*	*Total potential resources*	*Number of perspective structures*	*Total potential resources*
Caucasian	23	50.0	2	29.6
Sayano-Altaiskaya	3	7.5	8	18.6
East-Siberian	34	20.8	8	72.0
Zee-Bureinskaya	1	0.4	4	20.9
Sikhote-Alinskaya	13	26.6	5	2.7
Sakhalinskaya	5	16.3	2	9.0
Koryaksko-Kamchatsko-Kuril	–	27.0	46	517.0
TOTAL	79	148.6	75	669.8

Potential resources of thermal power waters

According to regional evaluations, the total potential resources (ths. m^3/day) and thermal power (ths. Hcal/yr) of thermal waters are equal if exracted using traditional technology: in stratum confined aquifer-systems – using a spouting method of exploitation: 573 and 10,491 respectively; with pumping method: 19,018 and 229,783; in fissured confined water systems: 591 and 12,850.

Potential resources of high-potential heat-carriers (vapor-dominated hydrotherms) with a temperature of 150 to 250 °C in the Kuril-Kamchatka zone are estimated at about 1,000 MW of electrical capacity (Kuril; Kamchatka – over 900).

7.3 The utilization of thermal water

Utilization of natural heat carriers (thermal energy waters, vapor and hydrotherms) play a significant role in solving fuel and power production problems in a number of countries. About, 22 countries have electrical power, produced on the basis of vapor and hydrotherms, with a total capacity of geothermal electrical power plants equal to 5,832 Mwe in 1990, 6,833 Mwe in 1994, 7,947 Mwe in 1999, and an expected increase in the year 2005 to 11,414 Mwe (Hutter, 1995, 2000).

The scales of 'direct' thermal energy utilization of heat carriers are characterized by the following basic indices as estimated for the end of 1999 (the figures in the brackets are the analogous characteristics of 1994 and 1990).

Table 7.3.1 shows how the above-mentioned and some other characteristics are distributed between 55 countries which are using geothermal energy (1994: 27 countries).

Table 7.3.1 Summary of direct-use data from individual countries (Freeston, 1995; Lund and Freeston, 2000)

	Flow (kg/s)		*Capacity (Mwt)*		*Annual (TJ/yr)*		*Utilization (CWh/yr)*
Country	*1994*	*1999*	*1994*	*1999*	*1994*	*1999*	*1999*
Algeria	550	516	100	100.0	1657	1586	441
Argentina	0	2,515	0	25.7	0	449	125
Australia	–	90	–	10.4	–	294	82
Austria	173	210	19.5	255.3	184	1609	447
Belgium	57.9	58	3.9	3.9	101.6	107	30
Bulgaria	–	1,690	–	107.2	–	1637	455
Canada	–	–	–	377.6	–	1023	284
Caribbean Islands	–	–	–	0.1	–	1	0
Chile	–	–	–	0.4	–	7	2
China	86,281	2,677	19,152	814.0	16,981	31,103	8,724
Columbia	–	222	–	13.3	–	266	74
Croatia	–	927	–	113.9	–	555	154
Czech Republic	–	–	–	12.5	–	128	36
Denmark	44.3	44	3.5	7.4	45	75	21
Finland	–	–	–	80.5	–	484	134
France	2,971	2,793	337	326.0	3,190	4,895	1,360
Georgia	1,363	894	245	250.0	7,689	6,307	1,752
Germany	–	371	–	397.0	–	1,568	436
Greece	242	258	23.2	57.1	133	385	107
Guatemala	12	–	2.64	3.4	83	107	30
Honduras	–	12	–	0.7	–	17	5
Hungary	1,714	67.7	340	328.3	5,861	2,825	785
Iceland	5,784	7,619	1,443	1,469	21,158	20,170	5,603
India	–	316	–	80.0	–	2,517	699
Indonesia	–	–	–	7.3	–	43	12
Israel	1,217	1,672	44.2	63.3	1,196	1,713	476
Italy	1,612	1,656	307	325.8	3,629	3,774	1,048
Japan	1,670	1,670	318	257.5	6,978	5,836	1,621
Jordan	–	574	–	153.3	–	1,540	428
Kenya	–	–	–	1.3	–	10	3
Korea	–	1,054	–	51.0	–	1,077	299
Lithuania	–	13	–	21.0	–	599	166
Macedonia	761	761	69.5	81.2	5,096	5,100	142
Mexico	–	4367	–	164.2	–	3,919	1,089
Nepal	–	25	–	1.1	–	22	6
Netherlands	–	–	–	10.8	–	57	16
New Zealand	353	132	264	307.9	6,614	7,081	1,967
Norway	–	–	–	6.0	–	32	9
Peru	–	–	–	2.4	–	49	14
Philippines	–	–	–	1.0	–	25	7
Poland	298	242	63	68.5	740	275	76
Portugal	–	49	–	5.5	–	35	10
Romania	300	890	130	152.4	1,230	2,871	797
Russia	1,240	1,466	210	307.0	2,422	6,132	1,703
Serbia	892	827	80	80.0	2,375	2,375	660
Slovak Republic	353	623	99.7	132.3	1,808	2,118	588

Table 7.3.1 (continued)

Country	Flow (kg/s) 1994	Flow (kg/s) 1999	Capacity (Mwt) 1994	Capacity (Mwt) 1999	Annual (TJ/yr) 1994	Annual (TJ/yr) 1999	Utilization (CWh/yr) 1999
Slovenia	573	656	39.1	42.0	780	705	196
Sweden	455	455	47	377.0	960	4,128	1,147
Switzerland	–	120	–	547.3	–	2,386	663
Thailand	–	–	–	0.7	–	15	44
Tunisia	–	–	–	19.7	–	174	48
Turkey	700	700	140	820.0	1,987	15,756	4,377
United Kingdom	–	25	–	2.9	–	21	6
United States	3,905	4,550	1,874	5366	13,890	20,302	5,640
Venezuela	–	–	–	0.7	–	14	4
TOTAL	35,998	54,416	8,228	16,210.7	105,671	162,009	45,006

Note: '–' indicate no value reported.

The types of geothermal resources utilization are shown in Table 7.3.2 (Lund and Freeston, 2000).

Table 7.3.2 Categories of geothermal energy utilization worldwide

Category	Utilization 1999 TJ/yr	Utilization 1999 %	Utilization 1994 TJ/yr	Utilization 1994 %
Geothermal heat pumps:	23,214	14.3	14,617	13.0
Space heating	59,696	36.8	38,230	34.0
Greenhouse heating	19,035	11.8	15,742	14.0
Aquaculture pond heating	10,757	6.6	13,493	12.0
Agricultural drying	954	0.6	1,124	1.0
Industrial uses	10,536	6.5	10,120	9.0
Bathing and swimming	35,892	22.2	15,742	14.0
Cooling and snow melting	968	0.6	1,124	1.0
Others	957	0.6	2,249	2.0
TOTAL	162,009	100	112,441	100

Consider the status of the practical use of geothermal resources in Russia where these resources are high and the results of their utilization are promising. Unfortunately, the disintegration of the Soviet Union fully destroyed the system of prospecting, exploration and production of thermal waters. The organizations, that were dealing with them earlier, were partially reorganized. Their activity today has sharply dropped. The interest of local authorities and private firms to the use of the earth's heat is reduced due a dramatic rise in cost for 1 m^3 of thermal water which, formerly under state regulation of prices, was artificially understated.

Electrical power generation

Electrical power produced today by geothermal electrical power plants in Russia is negligible: the installed capacity of the single (for the time being) Pauzhetskaya geothermal power plant in Kamchatka is equal only to 11 MWe (1995) and 23 MWe (2000) (Table 7.3.3). The increase of 12 MWe in 2000 was achieved by exploitation of the Verkhne-Mutnovskaya geothermal station in Kamchatka. At the same time the total reserves of vapor-hydrotherms of Kamchatka and the Kuril Islands can provide for the next 100 years the electrical power production of at least 1,000 MWe (Shpak et al., 1989).

Table 7.3.3 The present-day and planned production of electrical power in Russia (Kononov et al., 1995, 2000)

	Geothermal		*Fossil fuels*		*Fuel*		*Nuclear*		*TOTAL*	
	Capacity (MWe)	*Gross production (GWh/yr)*	*Capacity (MWe)*	*Gross production (GWh/yr)*	*Capacity (MWe)*	*Gross production (GWh/yr)*	*Capacity (MWe)*	*Gross production (GWh/yr)*	*Capacity (MWe)*	*Gross production (GWh/yr)*
In operation in January:										
1995	11	28.3	140,000	622,000	39,000	165,000	21,000	125,000	200,000	912,000
2000	23	85	151,000	558,000	43,600	155,000	21,200	108,000	216,000	822,000
Under construction in January:										
1995	110	750	9,000	–	1,000	–	1,000		11,000	
2000	93	400	1,200	2,800	530	460			1,770	3,420
Funds committed, but not yet under construction in January:										
1995	250	2,300								
Total projected use by the year of:										
2000	110	750	150,000	707,000	42,000	173,000	22,000	135,000	214,000	1,015,000
2005	171	700	155,000	580,000	45,000	162,500	24,200	124,000	224,300	867,000

In 2001 with the first phase of the Mutnovsky geothermal power plant the first power-producing block of 25 MWe capacity has been developed and the second block of the same capacity is nearing completion. A binary-circulated heat scheme of a geothermal power plant with a capacity of 6.5 MWe is planned for the Verkhne-Mutnovsky geothermal power plant. The second circulating contour will have a binary installation with a nominal capacity of 4 MWe as a prototype of serial binary energy-producing blocks (for the second phase of the Mutnovsky geothermal power plant and other areas) (Povarov, Tomarov, 2001).

The thermal power supply

Direct use of the Earth's heat is most widely spread in the following regions of the Russian Federation: Caucasus and the Fore-Caucasian area, West Siberia, Baikal and Kuril-Kamchatka areas.

Hydrogeothermal resources are used for space heating and regional heat supply, for

different industrial purposes, in agriculture, livestock farming, fish-breeding and balneology (Tables 7.3.4 and 7.3.5).

By 1994 the total amount of geothermal wells drilled for the above-listed purposes reached 446, among which 293 wells are productive and 77 are observation wells. Within the period from January 1995 to 31 December 1999, 78 wells were drilled in deposits of vapor-hydrotherms (including 40 wells for research purposes, 26 productive (exploited), 12 wells for reinjection of worked-out heat-carrier wells, and 306 wells in deposits of thermal waters for direct heat-technical and technological applications (including 90 wells for research purposes, 200 productive (exploited) and 16 for reinjection) (Kononov et al., 2000).

Table 7.3.4 The utilization of geothermal energy for direct heat supply in Russia in December 1994 and 1999 (Kononov et al., 1995,2000)

			Maximum utilization		*Annual utilization*	
Locality	*Year*	*Type*	*Inlet*	*Outlet*	*Average flow rate (kg/s)*	*Energy use (TJ/yr)*
Kamchatka	1994	H, B, G	80	30	455	3,000
	1999	H, B, G	85	30	372	2,701
Magadanskaya territory	1994	H	60	30	17	67
Fore-Caucasus:						
Krasnodar area	1994	H, G, F	75	30	262	1,555
	1999	I, F, H, B, G	80	30	222	1,465
Stavropol area	1994	G, H	90	30	25	198
	1999	H, G	100	30	36	162
Adygei Republic	1999	G, H	80	30	25	162
North Caucasus:						
Kabardino-Balkar Republic	1994	G	70	30	11	58
	1999	G	70	30	6	33
Chechen Republic	1994	G, H	80	30	220	1,450
Dagestan Republic	1994	H, G, I	80	30	225	1,682
	1999	H, B, G	80	30	203	1,340
Karachaevo-Cherkess Republic	1999	O	65	30	13	58
Northern Osetiya Republic	1999	O	60	30	10	41
TOTAL	1994				1,245	8,010
	1999				888	6,135

I = Industrial process heat;
H = Space heating;
B = Bathing and swimming;
G = Greenhouses;
F = Fish and other animals farming;
O = Hot water supply.
Energy use (TJ/yr) = annual average water flow rate (kg/s) x [Inlet temp. (°C) – outlet temp. (°C)] x 0.1319

Table 7.3.5 The summary table of geothermal direct heat uses as of 31 December 1994 and 1999 (Kononov et al, 1995, 2000)

	Installed thermal power, MWt		*Energy use, TJ/yr*	
	1994	*1999*	*1994*	*1999*
Space heating	200	110	3,154	2,185
Swimming and bathing	15	4	237	63
Greenhouses	230	160	3,627	3,279
Fish and other animals farming	13	4	205	63
Industrial process heat	50	25	788	473
Agricultural drying*	–	4	–	69
TOTAL	508	307	8,010	6,132

Inst. thermal power (MWt) = max. water flow rate (kg/s) x inlet temp.(°C) x 0.004184

Energy use (TJ/yr) = annual average water flow rate (kg/s) x [Inlet temp.(°C) – outlet temp. (°C)] x 0.1319

* Includes drying or dehydration of grains, fruits and vegetables.

At the present time the following main tendencies are considered when we increase the extraction of geothermal resources from the interiors of the earth and the efficiency of the resource utilization:

- introduction of geocirculation technologies (reinjection of a worked-out heat carrier) that would provide a sharp growth of heat carrier production (due to keeping stratum pressure in a reservoir, replenishment of groundwater resources) and an effective solution to the problem of environmentally safe exploitation of geothermal deposits and electrical energy generation systems and heat supplies;
- use of heat pumps that would provide more complete extraction of thermal natural heat carriers, including those with low potential;
- development and practical use of technologies for extraction of unlimited heat from dry hot rocks;
- extension of scientific investigations aimed at the development of heat from magmatic sources and hydraulic energy from the underground artesian water systems.

8 Groundwater management

8.1 Main factors aiding and constraining groundwater management

Groundwater management sets out to reconcile conservation goals with the objectives behind the resource's use and development, according to selected priorities. Hydrogeological conditions and the aquifer system's characteristics have a direct bearing on the ways and means of groundwater management.

Tapping groundwater is subject to fewer site-specific limitations than surface water. Catchworks can be spread over a larger area. This facilitates the decentralized action necessary to produce an overall effect (intensive exploitation, extensive drawdown or recharge).

Tapping groundwater does not, as a rule, demand artificial regulation. Installing underground dams or drainage gates and valves, etc. can, however, remain an option if considered useful locally.

An aquifer system functions as both an accumulator and a conductor. This means it needs separate management of storage and flow – though a wide variety of possibilities exists for interlinking the two.

Generally speaking, an aquifer system offers a renewable resource with flow management more or less regulated by change in storage. The ability to magnify that change gives a degree of freedom of action over the aquifer: allowing pumping regimes to be adjusted and made more or less regular than natural inflow – of which they are relatively independent – in order to keep up with changing demand, even over a period of years. In some cases, the aquifer storage can offer a non-renewable resource and be subject to groundwater mining.

The need to preserve the discharge and/or regime of surface water – not to mention the level of natural water bodies (to be kept for specific users or protected) – can call for restrictions to be placed on the freedom to exploit groundwater

Equally, groundwater – quantity or quality – conservation may require any of a wide range of restrictions to be placed on the tapping and development of surface watercourses, or on land use.

Groundwater management can be more or less interdependent with the management of the river basin into which it discharges; though in some cases (e.g. confined deep aquifers), they will be independent of each other.

Management conditions vary as widely as hydrogeological conditions. They can, however, be boiled down to a few key types (cf. Table 8.1). Building such a 'typology' appears to hinge on two main criteria: storage-flow ratios and the interrelationship between aquifers and surface watercourses. Both of these are in turn highly variable: average storage-average flow ratio – i.e. the capacity of the reservoir of an irregularly recharged aquifer to regulate overall flow (expressed in overall turnover time): can vary from under a year to somewhere in the region of 10^4 to 10^5 years in the case of deep aquifers (often described as 'fossils'); interrelationships between aquifers and surface rivers can range from very strong, steady and continuous linkage (narrowly spread alluvial groundwater bodies linked to unclogged watercourses) to full independence (confined deep aquifers or some coastal aquifers).

The natural qualities of groundwater are among the resource's leading attributes, making

Table 8.1 Types of aquifer systems and related management conditions

Type of aquifer system	*Linkages to surface water*	*Sensitivity*	*Suitable pumping regime*	*Constraints*
Alluvial (in most cases unconfined) aquifer. Limited expanse and storage capacity. Low regulating capacity.	Strong. Two-way aquifer/river exchange possible.	Sensitive to watercourse development and land use. Vulnerable to pollution from surface and boundary watercourses.	Regime 1. Short-term equilibrium. 'Overbalance' permitted by induced inflow from rivers. Management: mainly flow.	External: clogging of banks, low-flow discharge conservation. External: spring and low-flow watercourse discharge conservation.
Shallow, lowland/ plateau or Karst aquifer. Large reservoir (storage often > 10 times average annual flow). Good regulating capacity. High hydro-dynamic inertia.	Broad, one-way linkage: drainage via rivers (which may disappear in Karst zone). Density differs with hydrographic structure.	Sensitive to variable inflows during periods of drought, etc. Sensitive to land use.Vulnerable to pollution, above all diffuse.	Regime 1 or Regime 2. Long-term equilibrium. Management: flow and regulating storage.	External (upper-layer unconfined aquifers): spring and low-flow watercourse discharge conservation.
Multi-layered system of interconnected shallow and semi-confined aquifers. Large reservoirs (storage > 100 to 1,000 times average annual flow). Partial regulating capacity. Variable inertia.	Variable: restricted to upper-layer unconfined aquifers.	Sensitive to land use (upper-layer unconfined aquifers). Vulnerable to pollution. Risk of aquifers holding different quality water becoming interconnected by boreholes.	Regime 2. Equilibrium may be restored after a long period of disequilibrium. Management: flow and storage at start, then just flow.	Internal constraints (confined aquifers): drawdown only possible within max. acceptable limits.

quality conservation a key strand of groundwater management; one which, given the proliferating threat of deterioration, is now attracting more widespread attention than the goals of quantity management, especially in countries relatively less affected by dwindling supplies. That said, qualitative and quantitative management are not mutually exclusive issues as far as resource conservation and allocation are concerned.

The first step in the management of groundwater qualities is to take stock of their existing state and assess how they measure up to the users' expectations. This is followed by an appraisal of the groundwater body's vulnerability to various types of pollution (cf. Sections 4.3 and 4.4).

Unlike quantitative management – which mainly revolves around the exploiters – quality management depends far more on the behaviour of the vast numbers of agents not involved in groundwater exploitation, yet whose use of the land above the aquifer could lead directly or indirectly to its pollution. With a view to preventing such an outcome, groundwater quality management – in combination with resource protection policies – will therefore strive to modify

their behaviour by implementing measures of varying degrees of strength: according to quality-objective zoning (top priority if drinking-water sources are at risk), how hazardous are the local activities, how vulnerable to pollution or resilient the groundwater. Groundwater quality management thus forms an integral part of resource-conservation-sensitive urban and regional development or land use planning policies. Its field of action will also extend to regulating any exploiters indulging in quality-threatening activities (e.g. those that cause saltwater infiltration into coastal aquifers).

Quality management may include:

- special development work to protect against – and minimize the risks of – pollution from potentially hazardous sites (passive underground barriers or dynamic processes such as drainage or pumping);
- direct clean-up operations (e.g. pumping or in situ biochemical treatment) aimed at stemming the spread of pollutants and neutralizing the impacts of local accidents;
- quality improvement by means of artificial recharge (pumping freshwater into aquifers containing brackish water or subject to diffuse pollution).

Finally, quality-monitoring data can be used to assist resource allocation policy agencies determining how suitable a particular body of groundwater is for a particular end use (the better quality and/or naturally best protected largely being reserved for drinking water).

8.2 Socio-economic conditions: management objectives and agents

The agents

Groundwater management – in the hands of a management authority – concentrates on all the economic agents exploiting or influencing the resource's state and qualities in the course of their activities (see Section 3.6).

These various agents can be broken down into various categories: users or non-users; exploiters or developers or both (cf. Table 8.2.1).

Levels of management

With the physical aquifer unit on one side counterbalanced by a multiplicity of different agents with at times widely diverging interests on the other, aquifer management has to regulate those agents' behaviour by means of incentives or deterrents. It thus requires some measure of indirect action (unlike the management of a dam reservoir, for instance, where manager and operator are one and the same) and involves managing:

- the direct and intentional impacts or external effects on groundwater resulting from the activities of an ensemble of agents specific to each aquifer system;
- the behaviour of those agents.

This two-tiered approach applies to water management as a whole. What makes it particular to groundwater – and so difficult to implement – is the fact that:

- level (a) agents are not naturally inclined to develop genuine 'resource management' goals of their own; they are the only ones actually tapping the groundwater, but do not look beyond their own individual fields of action to see how they interact with others and impact on the aquifer system as a whole;

Table 8.2.1 Agents involved in groundwater development, exploitation and management

	Users, beneficiaries	*Intermediaries, non-users*
Developers (non-exploiting)	Resource industry, underground worksites, surface projects (hydraulics, land-use planning, etc.) liable to impact on the state and qualities of groundwater	Government and government agency sponsors
Developers (exploiting)	Companies or irrigated farming unions, self-supplied industry Resource industry, underground worksites, dewatering operators (with conversion: underground dams, artificial recharge)	Producers-distributors of drinking water, industrial water, irrigation water
	Users, beneficiaries	Intermediaries, non-users
Exploiters (non-developing)	User-exploiters of water (without conversion): households, self-supplied industry, farmers (for irrigation). Exploiter-users of geothermal energy	Producer-distributors of drinking water, industrial water, irrigation water (without conversion). Exploiters-distributors of geothermal energy (heat distribution network)

- level (b) agents – the management authorities (those that exist) – are fully able to draw up sets of relevant, collective management guidelines, but tend to lack the means for direct intervention on the ground: they remain confined to the use of indirect 'management tools' on the exploiting or 'developing' agents (cf. Chapter 7).

Management objectives

Management objectives and decision-making criteria are different at each of the above two levels.

At individual agent level

Level (a): microeconomic goals hold centre stage: the groundwater is at best regarded as a consumer commodity, a factor of production – a 'raw material' – and just naturally impact-prone. Those actually pumping it – for immediate use or distribution – manage their own catchworks according to their own criteria: they do not manage the resource itself; until, that is, they themselves feel the backlash of their influence on the environment. Their conception of 'resource management' narrows down to just a single (implicit) goal: continuous productivity.

At management authority level

Level (b): territorial jurisdiction, and, hence, the scope of decisions made, can correspond to the aquifer system (or 'management unit'), and genuinely macroeconomic management objectives (not all of them necessarily compatible) can be drawn up and prioritized: to anticipate and mediate disputes between individual agents co-exploiting (or influencing) the same aquifer by enforcing external restrictions: i.e. to prevent conflict between the community of groundwater users and the wider community of agents using water or space, above or below ground – in short, the standard basic objectives of the water policing authorities; to maintain groundwater yield rates and 'accessibility' at initial levels, thus effectively benefiting the first exploiters up and running; to protect the resource's storage

capacity and qualities in the interests of the community of exploiters (present or future); to prevent the potentially damaging effects of excessive pumpage on the water's renewability or qualities: i.e. to guard against 'overexploitation' and pollution; to ensure that resource allocation satisfies the key demands of the day (e.g. drinking water supply) by means, among others, of designated 'set-asides': a form of planning or interventionist action developed for the good of long-term common interests, or stemming from water rights-related market mechanisms; to promote more intensive pumping in response to a particular demand – and in preference to other sources of water supply – when the resource is judged 'underexploited': the objective being the beneficial use of what would otherwise remain an 'idle' factor of socio-economic development.

Groundwater resources by and large form an integral part of water resources as a whole, so the above management goals are subordinate to general water management objectives. They may also need to be reconciled with those of the management of underground works (mining, tunnelling, etc.) and even land use. But in the final analysis, they are dominated by the overriding socio-economic objectives of the corresponding community.

These objectives may clash: conservation-oriented management, for instance, is not compatible with a development-driven approach geared to transformation and redistribution. The first step in the management process is to prioritize the objectives.

8.3 Decision making criteria and constraints

Groundwater management is subject to constraints stemming from an assessment of the internal and external effects of exploitation, according to a variety of criteria. The internal effects – ways in which exploitation inevitably affects the resource's exploitability – generate internal constraints stemming from cost-benefit analysis carried out according to the exploiters' criteria. The externalities – or impacts – can generate external constraints stemming from efforts to strike a balance between the interests and objectives of the water users and those of other agents.

Internal constraints

These tie in with the global or sector-specific exploitation limits set in line with such criteria as: discharge, localization, accessibility and pumping conditions, water qualities, cost. Because they are not defined at the same level, the criteria of exploiting agents and management authorities are liable to differ: exploiting agents are primarily focused on microeconomic concerns: local productivity, necessary pumping practices, the quality of water produced (measured against the strictest end-use standards), production security, minimized direct production costs; management authorities, on the other hand, are more interested in macroeconomic concerns: resource conservation (quantity and quality), reasonably equal access and withdrawal opportunities, optimized overall exploitation costs.

External constraints

These relate to the will or need to prevent or abate externalities detrimental to other agents – users of dependent surface water, land, etc. – or, at a broader level, the environment (to protect spring-dependent, aquatic or humid-zone ecosystems). They may be necessary for the purposes of maintaining a 'reserved discharge' above ground. They can lead to the introduction of

internalizing financial mechanisms. More often than not, they also take the shape of maximum acceptable levels of groundwater depth.

One particular external constraint of a geopolitical nature arises in the case of transboundary aquifers serving two separate countries: when exploitation in one influences the resource's condition – and threatens productivity – in the other. It calls for an international convention negotiated with a view to balancing up the countries' mutual influences with equal access to the resource. This is a more complex matter than the relatively simple (and more commonplace) share-out of transboundary or frontier-zone river flows – both natural and regulated. Indeed, since the influences evolve over time with tapping project and catchwork development, it requires a legally endorsed harmonization of exploitation plans and growth rates plus common conservation policies.

External restrictions

For the purposes of resource conservation and/or protection, groundwater management can equally involve imposing external restrictions on other agents: surface-water developers and/or users liable to influence the groundwater regime and/or qualities in ways detrimental to its users; various land-use or underground development activities: in order to prevent declining water levels – due to dewatering – or pollution, particularly when the sanitary protection of potable water sources is at stake.

Descision-making support tool

A range of methods and tools (not to be confused with those outlined in Chapter 7) are available to support management authority decision-making – be it strategic (selecting overall exploitation plans and pumping regimes, internal and external quality conservation constraints) or tactical (choosing the right production management, machinery and techniques).

Just for the record, here is a brief reminder of those methods and tools.

- Modelling and forward-looking management;
- Hydrodynamic simulation models help to forecast the effects of intended action – especially pumpage – on the aquifer system and, hence, to enable managers to plan ahead: the results provide data for weighing up the exploitation project's feasibility and constitution within given parameters;
- Kinematics groundwater transport models help to estimate the possible impact of pollution and effectiveness of recommended measures of protection;
- Unit production cost forecasting;
- Unit production costs and their likely evolution – measured against a constant monetary unit per cubic metre of water – are essential data for comparative exploitation-project feasibility studies, acting as a basis for cost-benefit projections in particular.

External cost forecasting

Project feasibility studies and cost-benefit analyses must also estimate the costs likely to arise owing to the externalities or detrimental impacts of groundwater exploitation – whether or not the results will serve as a basis for internalising and passing them on to the direct costs borne by the exploiters. While wholly reliable figures may be hard to establish in monetary unit terms here, they can be deduced by estimating potential damage, cost of repairs or compensation based on physical impact projections: deteriorating water quality, subsidence, dewatering, productivity loss at previous catchworks, etc.

Optimisation methods

Simulation and forecasting are useful for weighing up various exploitation options or scenarios – their expected expenses and results – yet leave the matter of determining the optimal solution unresolved. Beyond objective-function or single-criterion optimisation techniques such as linear or dynamic programming, multicriterion methods for the analysis of management options have paved the way to an effective new approach.

Management monitoring

Management authorities need to be able to monitor aquifer exploitation – and accompanying externalities – so as to ensure that progress remains in keeping with forecasts and programme guidelines. They must therefore have access to regularly updated data concerning both the current state of the aquifer itself and withdrawal rates and impacts. This means having to keep track of two key sets of variables: aquifer state (piezometric water level, salinity and water quality, natural spring discharge where necessary) and decision-making (withdrawal rates, drilling installations).

Periodically gathered and ratified data is now filed in a computerized geodata bank which can be linked up to a 'Geographic Information System'. This gives users the opportunity to produce up-to-date maps, tables and graphs showing a variety of variables -groundwater levels, qualities and withdrawal – which can serve as aquifer exploitation management indicators.

Analyses of current situations and future trends can be expressed using global indicators, including:

- exploitation indices (annual net withdrawal/average inflow ratios);
- average drawdown compared to start-up water levels;
- average yield per catchwork;
- proportion of volumes pumped with salt content in excess of recommended levels.

Each of these indicators can include a specific threshold value, which, if overstepped, would signal a risk of unsustainable development.

9 Conclusion

It should be once again noted that the problem of groundwater use is a composite part of a common problem of rational natural use and environmental protection. Only a joint consideration of all the aspects of interaction between the groundwater and other environmental components can make it possible to elaborate on a long-term program for rational groundwater use and protection.

Natural protection restrictions for groundwater withdrawal must be considered and possible changes in groundwater resources under the impact of engineering and economic activities must be investigated. It is particularly important to work out predictions of increased groundwater pumping for centralized water supply of a population and for industry and agriculture. It should again be stressed that the task of specialists at present is not only to calculate the water volume that can be pumped out of an aquifer in specific hydrogeological conditions during a certain time period, but also to assess the possible changes in different environmental components that may be caused by the withdrawal of groundwater. As a result, specialists must prove and recommend, if necessary, special measures to minimize possible negative consequences of groundwater withdrawal, particularly when exploiting large well fields.

Determining the function of groundwater in a total water resource program and in calculating the water balance of separate regions – river basins, lakes, and seas – is a separate, but no less important, problem.

Solving the problems mentioned will absolutely provide for increased effectiveness and rationality of groundwater use and will make it possible for decision makers to prove modern and prospective projects for the water supply of separate regions.

Thus, in conclusion, it is reasonable to briefly formulate the main tasks of further scientific and practical investigations on the problem considered.

These tasks are the following:

- to improve the available and to develop new methods for assessing groundwater resources accounting for natural measures;
- to develop and put into practice nature-protecting criteria determining the acceptable impact of groundwater withdrawal on other components of the environment, and also the acceptable effect of anthropogenic activities on ground-water resources and quality;
- to perfect the available and to develop new methods for predicting changes in groundwater resources and quality under intensive anthropogenic activities and possible climate changes:
- to substantiate the principles of conducting groundwater monitoring in different natural-climatic and anthropogenic conditions as a component of the general monitoring of water resources and the environment;
- to improve methods of assessing groundwater vulnerability to pollution in the main aquifers used for water supply;
- to perfect methods of artificial groundwater recharge and to use them more widely in active well fields;

- to develop mathematical models of interaction between ground- and marine water in different geologic-hydrogeologic conditions of the coastal zones and also methods for predicting marine-water intrusion into the aquifers under intensified groundwater withdrawal by coastal well fields;
- to develop and to put into practice legislative norms emphasizing preferred use of fresh groundwater of high quality primarily for drinking and domestic water supply.

Solving these problems will considerably increase the effective use of groundwater.

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