Groundwater contamination inventory

A METHODOLOGICAL GUIDE

with a model legend for groundwater contamination inventory and risk maps

Edited by Alexander Zaporozec

IHP-VI, Series on Groundwater No. 2

Groundwater contamination inventory

A methodological guide

Prepared for the
International Hydrological Programme
within Project 3.1 (IHP-V)

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IHP-VI, Series on Groundwater No. 2

UNESCO, 2004

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Published in 2004
by the United Nations Educational,
Scientific and Cultural Organization
7, place de Fontenoy, 75352 Paris 07 SP

Layout and typesetting by Marina Rubio, Saint-Denis

ISBN 92-9220-004-6

Foreword

The need for hydrological research, basic as well as applied, is substantial to help rationally manage the world's water resources. To satisfy this need, and the interest of Member States, UNESCO, in 1975, launched a long-term intergovernmental programme, the International Hydrological Programme (IHP), to follow the first worldwide programme devoted to scientific study of the hydrological cycle, the International Hydrological Decade (1965–1974). Although the IHP is basically a scientific and educational programme, UNESCO endeavours to direct programme activities towards the practical solutions of the world's very real water resource problems, while maintaining the IHP scientific concept.

Among the most serious problems in water resources is the degradation of groundwater. Therefore, UNESCO selected for Theme 3 of the fifth phase of the IHP (IHP-V, 1996–2001) the topic 'Groundwater resources at risk'. Five projects were proposed under Theme 3:

- 3.1. Groundwater contamination inventory
- 3.2. Monitoring strategies for detecting groundwater quality problems
- 3.3. Role of unsaturated zone processes in groundwater supply quality
- 3.4. Groundwater contamination due to urban development
- 3.5. Agricultural threats to groundwater resources

Inasmuch as the project topics are not independent of one another, there were necessary overlaps and interactions during the implementation of the projects.

Objectives of the IHP-V Project 3.1 were to document the extent, spatial distribution, and types of contamination including point-source and non-point-source problems, as well as natural contamination due to saline water intrusion at regional scales and to develop a standardised methodological guideline. Data on the extent of contamination were gathered by IHP National Committees and Regional Offices of Science and Technology and presented at various conferences organized during the IHP-V. The methodological guideline on groundwater contamination inventory is presented in this publication.

A Working Group for Project 3.1 was established in November 1997, and met for the first time at the UNESCO headquarters in March 1998 to develop an outline of the guideline and to assign chapters to authors. The final draft was reviewed and approved at the Working Group meeting in Cape Town, South Africa, in November 2000. We would like to express our thanks to the International Association of Hydrogeologists for their support in implementing these project activities and to John C. Miller for a review of the report.

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Abbreviations and acronyms

Amer.	American
Assoc.	Association
BOD	Biological oxygen demand
Bull.	Bulletin
CD-ROM	Compact Disc - Read Only Memory
COD	Chemical oxygen demand
Conf.	Conference
DBMS	Data Base Management System – main software for row data organizing and management of GIS.
DDT	Dichloro-diphenyl-trichloroethane (insecticide, now banned)
Dept.	Department
DRASTIC	A standardised rating system, developed for the U.S. EPA, evaluating groundwater contamination potential of selected hydrogeological settings based on seven factors: Depth to Water, Net Recharge, Aquifer Media, Soil Media, Topography, Impact of Vadose Zone, and Hydraulic Conductivity of the Aquifer
ed(s).	Editor(s); also: edition
e.g.	For example (Latin *exempli gratia*)
Env.	Environmental
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute Inc. – the company that develops and sells Arc/Info, Arc/View, and other GIS products
et al.	and others (Latin *et alii*)
etc.	and so forth (Latin *et cetera*)
GIS	Geographical Information System – a computer system of geographically organized spatial data for interactive processing, storage, and real time mapping
GOD	An empirical system for rating aquifer vulnerability to contamination based on three factors: Groundwater Occurrence, Overlying Lithology, and Depth to Groundwater
GPS	Global Positioning System
GUI	Graphical User Interface – the total interaction between a computer system and the person using the system for applications involving the production or processing of graphic images
IAH	International Association of Hydrogeologists
ID	Identification number
i.e.	that is (Latin *id est*)
IHP	International Hydrological Programme
IHP-V	Fifth phase of the IHP
IKONOS	A space-imaging satellite that provides one-meter resolution imagery, ideal for mapping and planning (name derived from Greek word for image: *eikon*)
Inst.	Institute
Intl.	International
ISO	International Standards Organization
Jour.	Journal

LANDSAT	A United States satellite carrying a multispectral scanner that records image data of the Earth features
No., no(s).	Number (numbers)
Nat., Natl.	National
NRC	National Research Council (U.S.)
pp.	Pages
para.	Paragraph
PCB	Polychlorinated biphenyl (a component of plastics)
Proc.	Proceedings
Publ.	Publication
Rept.	Report
Soc.	Society
SPOT	Satellite Probatoire pour l'Observation de la Terre – a French satellite carrying two imaging systems allowing stereoscopic viewing of the Earth
Symp.	Symposium
TDS	Total dissolved solids
UK	United Kingdom
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
U.S.(A.)	United States (of America)
USGS	U.S. Geological Survey
UST	Underground storage tank
Vol., v.	Volume
VOC	Volatile organic compound
WHO	World Health Organization
WHPA	Wellhead protection area

1 Introduction

Alexander Zaporozec

The sources of groundwater contamination are many and varied because, in addition to natural processes, practically every type of facility or structure installed by man and each and every human physical activity may eventually cause groundwater quality problems (Fig. 1.1). The vulnerability of groundwater, especially of groundwater supplies, to existing or potential sources of contamination underscores the need for a systematic, detailed process by which these potential threats can be recorded and evaluated – an inventory of groundwater contamination sources.

Groundwater contamination inventory is an indispensable part of any comprehensive groundwater protection strategy. Before appropriate protection measures can be designed and implemented, groundwater contamination and its sources must be identified and assessed, and their impacts on groundwater quality determined. An inventory of the number, type, and intensity of potentially contaminating activities and of the extent of existing contamination of groundwater can serve a twofold purpose for groundwater protection:

1) It provides government officials, planners, and managers with an understanding of the potential for groundwater contamination needed for successful management programs.
2) It provides basic data that can be used for the design of the type and location of various controls and of the monitoring programs.

Results of a comprehensive, detailed inventory allow water managers to prioritise contamination sources according to intended purpose (e.g. to determine the level of risk to public drinking water supplies) and to develop differential management strategies to address these sources, thereby safeguarding public health and protecting groundwater in general.

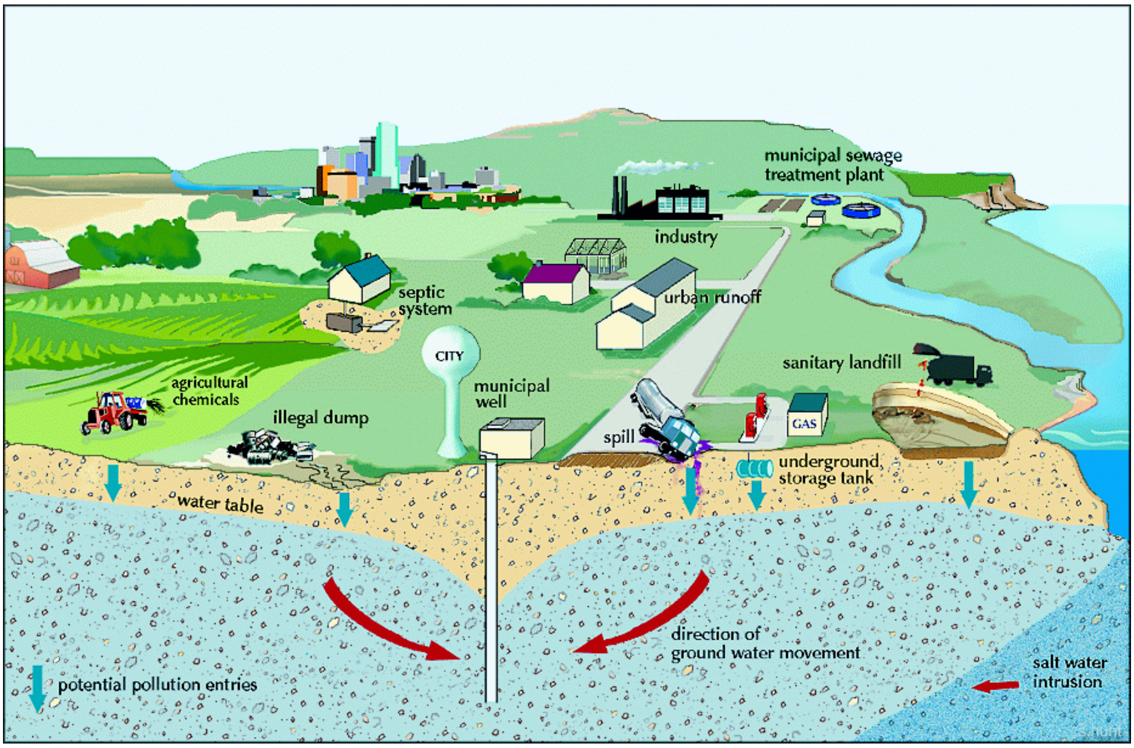
1.1 Objectives and scope of the document

The broad objective of this document is to present a methodology for the inventory of groundwater contamination and to provide a guideline for planning, conducting, evaluating, and presenting the inventory. The guideline is aimed at professionals – as a manual or reference material for hydrogeologists or other specialists responsible for organizing and conducting groundwater contamination inventories, particularly in developing countries. Understanding of basic principles of hydrogeology and groundwater chemistry fundamentals is expected.

The main objectives are to summarise and describe all kinds of contamination sources that planners and managers should be familiar with, and to help hydrogeologists in:

- designing and implementing an inventory of contamination sources,
- determining the extent and degree of existing contamination,
- explaining the impact of the existing and potential contamination sources on groundwater,
- presenting results of the inventory on maps, and
- using results of the inventory to suggest alternative strategies to protect groundwater.

FIGURE 1.1 Sources of groundwater contamination are numerous and are as diverse as human activities (*Source:* Zaporozec and Miller, 2000)



The guideline is divided into eight chapters. After the Introduction (Chapter 1), Chapter 2 briefly reviews concepts of groundwater vulnerability to contamination, the chemical composition of groundwater and its relation to rock types, and mechanisms of groundwater contamination. Chapter 3 describes the main sources of groundwater contamination and their impact on groundwater quality. Chapter 4 suggests the contamination source inventory process including the design of an inventory, source identification methods, a framework for field investigations, and basics of data management. Besides the contamination source inventory, an assessment of the existing groundwater contamination is also outlined. Chapter 5 deals with the rating of the identified contamination sources and proposes a rating system based on contaminant characteristics, mode of its disposition, contaminant concentration, and duration of contaminant load. Chapter 6 examines the approach to groundwater contamination inventory mapping and presents the preparation of contamination inventory maps and supporting maps. It also explains the role of geographical information systems in map production. Chapter 7 discusses the implications of the groundwater contamination inventory for groundwater protection and outlines the principal protection strategies. Examples of various types of contamination source inventories, conducted at different levels (nationwide, regional, and local) at various countries around the world are included in Chapter 8.

The guideline is accompanied by a list of abbreviations and acronyms, a glossary to explain technical terms used in the text (Appendix A), and an extensive list of references (Appendix B). References included in Chapter 8 are listed for each case study individually and not in the bibliography in Appendix B.

The guideline conceptualises the preparation of groundwater contamination inventory and of groundwater contamination risk maps and presents a model legend in a clear and comprehensive format (Appendix C). The legend is intended to facilitate the preparation of groundwater contamination maps in a standardised form, which conforms to the legend for groundwater vulnerability maps developed for the IHP-IV Project M-1.2a (Vrba and Zaporozec, 1994) and to the legend for hydrogeological maps developed for the IHP-IV Project M-1.3 (Struckmeier and Margat, 1995). The guideline also describes supporting maps, such as various groundwater resource maps, a map of the existing contamination of groundwater, a natural resource map, a land use map, or a groundwater vulnerability map, which can be used in combination with the groundwater contamination inventory map to derive a groundwater contamination risk map.

1.2 Definitions

In writing this guideline, authors made a conscious effort to use clear language, keeping technical jargon to a minimum. Terms used in the guideline are explained in a glossary (Appendix A) because different terms have a different meaning to different people. This is especially true in using the terms *groundwater contamination* and *groundwater pollution*, which are often used in the literature as synonyms. However, the authors would like to point out the difference in the meaning of these two terms, although for the sake of consistency and to avoid confusion, only one term, ***groundwater contamination,*** is used throughout the guideline and is defined according to WHO usage (UNESCO, 1992) as:

Introduction into water of any ***substance in undesirable concentration*** *not normally present in water, e.g. microorganisms, chemicals, waste or sewage, which renders the water unfit for its intended use*'. (Editorial note: Changes in the definition preferred by the Working Group are in the bold face.)

The term *groundwater pollution* was defined in the International glossary of hydrology (UNESCO, 1992) as: '*Addition of pollutant to water*'. (Pollutant was defined in the International glossary as: '*A substance which impairs the suitability of water for a considered purpose*'.)

The authors would also like to mention other confusing and inconsistently used terms related to contamination and contamination sources: groundwater vulnerability/groundwater susceptibility/contamination potential. Although these terms are interchangeably used as synonyms, practising hydrogeologists may want to differentiate them as follows (Vrba and Zaporozec, 1994):

- *Groundwater vulnerability:* An intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts.
- *Groundwater susceptibility:* Inability of groundwater to resist the impact of contaminants on the quality of groundwater.
- *Contamination potential:* Susceptibility of groundwater to contamination by a specific contaminant or from a specific contamination source.

For brevity purposes, the term ***groundwater contamination inventory*** used in this guideline generally includes both the inventory of existing and potential sources of groundwater contamination and the inventory of existing contamination, to eliminate multiple repetitions of these two meanings.

1.3 Relation of the document to International Hydrological Programme IHP-V

This document was prepared by members of the international Working Group as part of the IHP-V Project 3.1 *Groundwater contamination inventory* under Theme 3, 'Groundwater resources at risk'. The other projects within Theme 3 most relevant to this document are: Project 3.2 *Monitoring strategies for detecting groundwater quality problems*, Project 3.4 *Groundwater contamination due to urban development,* and Project 3.5 *Agricultural threats to groundwater resources.* These projects complement our project and, therefore, the reader is referred to reports on these projects for more details on certain topics.

For example, discussion on contaminant transport and behaviour in the subsurface was not included in our guideline because this topic will be presented in detail in the report 3.2 (Vrba, 2002). Also, monitoring is mentioned rather perfunctorily because it is the main topic of Project 3.2. In this guideline, sources of groundwater contamination are summarised, categorised, and reviewed only briefly. Two of the major categories of contamination sources, agricultural activities and urban development, and their impacts on groundwater are discussed in a great detail in reports on Project 3.5 (Candela and Aureli, 1998) and Project 3.4 (Lerner, 2001), respectively. Both of these publications, as well as the report on Project 3.2 (Vrba, 2002), are listed in the bibliography (Appendix B.2).

This guideline in its present form is simply a first attempt to reflect the combined thoughts of a number of international scientists drawn from their own experience and the experience of their colleagues. The authors hope that the methodological guideline presented in this document would be useful in everyday practise of hydrogeologists, environmental scientists, planners, and managers and would contribute to improved knowledge of the extent of groundwater contamination worldwide.

2 Groundwater quality and contamination

Erik Romijn

2.1 Vulnerability of groundwater systems to contamination

2.1.1 Threats to groundwater quality

The 'looming water crisis' is becoming a major issue on the world agenda for the twenty-first century. The World Water Council presented the 'World Water Vision' during the Second World Water Forum and Ministerial Conference at The Hague in March 2000 (Cosgrove and Rijsberman, 2000). The Vision reported that 1.2 billion people or one fifth of the world population do not have access to safe drinking water, while half of the world population lack adequate sanitation. The Vision document further states that 'rapidly growing cities, burgeoning industries, and rapidly rising use of chemicals in agriculture have undermined the quality of many rivers, lakes, and aquifers' and also emphasises that 'the impacts of agriculture on water quality are less visible over time but at least as dangerous (as industrial), because many of the fertilisers, pesticides, and herbicides used to improve agricultural productivity slowly accumulate in groundwater aquifers and natural ecosystems.'

The importance of groundwater is gaining recognition, because this resource:

- represents some 98 percent of the planet's freshwater resources (polar ice excluded),
- supplies more than 1.5 billion urban dwellers with water,
- is extensively used for low-cost rural water supply,
- is increasingly developed for both large- and small-scale irrigation,
- is generally reliable in periods of drought because of its large storage capacity,
- is cheap to develop because of its widespread occurrence and its generally good natural quality.

The term quality of groundwater refers to its physical, chemical, and biological characteristics as they relate to the intended use of water. Groundwater quality is threatened mainly by human activities, although harmful substances are sometimes introduced by natural processes. Sustainable groundwater management must be based not only on prevention of the overexploitation of groundwater resources but also on prevention of contamination, because unlike treatment at the point of use, prevention protects all of the resource.

Usually, economic activities are classified as primary activities, which produce commodities (mining, agriculture); secondary or industrial activities (energy production, manufacturing, building, etc.); and services (including transport). In addition, activities of private households play a role. As will become clear in Chapter 3, all of these activities create 'waste products', which may threaten the environment including groundwater.

In principle, waste sites can be isolated from the environment. This, however, is not possible with diffuse sources of contamination, which are either introduced into the air and subsequently rained out, or are used in agriculture and partly infiltrate into the subsurface. These sources, together with mine tailings and accidental spills of hazardous substances, represent major threats to groundwater quality and are described in Chapter 3.

2.1.2 Vulnerability assessment

The term 'vulnerability of groundwater to contamination' was introduced by Jean Margat in the late 1960s (Vrba and Zaporozec, 1994). The concept is based on the assumption that the soil-rock-groundwater system may provide a degree of protection against contamination of groundwater by 'self-purification' or 'natural attenuation'. Combining definitions given in Chapter 1 and in the Glossary (Appendix A), the (intrinsic) groundwater vulnerability could be described as the 'relative inability' of the soil-rock-groundwater system to protect its water against contamination.

In the ideal situation, the (intrinsic) vulnerability would allow us to calculate the contaminant concentration at a given place and time within the groundwater system as a function of the contaminant load. The contaminant load could be described in terms of contaminant characteristics (such as persistence and mobility), the mode of disposition (depth of introduction and hydraulic load), and the source strength (concentration, recharge area, and duration of load) of the contaminant (see para. 5.3.3).

Although considerable progress has been made in contaminant hydrogeology, modelling of the distribution and transport of contaminants is relatively complex and expensive. Therefore, as a first approach, various rating methods are used to evaluate the relative vulnerability of groundwater (Vrba and Zaporozec, 1994), some of which are described in Chapter 6. The philosophy behind these rating methods is based on the understanding of various processes, which are reviewed in paras. 2.2 and 2.3.

2.2 Natural composition of groundwater

2.2.1 Origin of the natural composition

The chemical composition of groundwater mainly depends on the composition of the initial pore water; the composition of infiltrating water and subsurface inflow that replaces the pore water; the composition and physical properties of the soil and rock; the chemical interaction between rock, pore water, and infiltrating water; and microbiological processes. From the moment rain falls on the ground and begins to infiltrate and pass through the soil and rock, the water dissolves the host materials, and minerals are added to the groundwater flowing through. In general, the amount of total dissolved solids (TDS) increases with the residence time of groundwater.

The dissolved constituents in groundwater take part in the geochemical cycle, which starts with the weathering of rocks. Weathering breaks up rock minerals and released elements react with water and enter into solution. In addition, the vegetative litter releases organic and mineral substances to the soil and groundwater as part of the biochemical cycle. The weathering is more intense in a warm and humid climate than in a dry and cool one. Rocks can be broken up either by mechanical forces, e.g. frost action (physical weathering) or transformed by chemical reactions, e.g. hydrolysis (chemical weathering). The disintegration of rocks by physical weathering increases the infiltration capacity and the surface area of the contact between rock and air and rock and water. Chemical weathering is most active above the water table, in the unsaturated zone.

Because the above mentioned processes vary from place to place or change in the course of time, groundwater greatly varies in composition. However, the number of major dissolved constituents in groundwater is quite limited and natural variations are not as great as might be expected from the complex mineral and organic material through which the water has passed and from the complexity of processes involved (Davis and DeWiest, 1966). Of the 22 elements that form 99.80 percent of the mass of the combined upper lithosphere, oceans, and atmosphere, only seven elements occur normally in groundwater in concentrations greater than 1 milligram per litre (mg/l) and form 95 percent of the chemical composition of groundwater. In addition, there are eight secondary constituents that regularly occur in groundwater, although in lower concentrations (0.01–10 mg/l) than the major ones (Table 2.1). Besides these more abundant elements, there are about 40 minor (<1 mg/l) and trace (<1 g/l) elements, the occurrence of which depends on the local situation with respect to the rock and pore water composition, pH, and redox potential. Eighteen of the more important ones are included in Table 2.1.

TABLE 2.1 Chemical constituents in groundwater (*Adapted from:* Davis and DeWiest, 1966)

Major constituents	*Secondary constituents*	*Selected minor and trace constituents*	
Calcium (Ca)	Potassium (K)	Aluminium (Al)	Molybdenum (Mo)
Magnesium (Mg)	Iron (Fe)	Arsenic (As)	Nickel (Ni)
Sodium (Na)	Manganese (Mn)	Barium (Ba)	Phosphate (PO_4)
Bicarbonate (HCO_3)	Strontium (Sr)	Cadmium (Cd)	Radium (Ra)
Chloride (Cl)	Boron (B)	Chromium (Cr)	Selenium (Se)
Sulfate (SO_4)	Fluoride (F)	Cobalt (Co)	Silver (Ag)
Silica (SiO_2)	Carbonate (CO_3)	Copper (Cu)	Uranium (U)
	Nitrate (NO_3)	Lead (Pb)	Zinc (Zn)
		Mercury (Hg)	Sulfide (H_2S, HS)

2.2.2 Chemical composition in relation to rock type

(i) Coarse- and medium-grained crystalline silicate rocks

This group includes igneous and metamorphic rocks like granite, gneiss, and amphibolite. Their primary porosity is negligible, but an interconnected system of fractures makes them porous and permeable. In warm humid climates the weathering of granite often creates a valuable aquifer, which consists of the disintegrated rock in its upper portion and the underlying fractured rock.

The chemical quality of natural water from igneous plutonic and metamorphic rocks is almost always excellent. Exceptions are found in arid regions where salts may be concentrated in recharge water by evaporation. The influence of evaporation has been clearly described by Larsson (1984). In humid climates, total dissolved solids (TDS) are reported to be less than 500 mg/l; in semi-arid conditions more than 3,000 mg/l is common. An example of water from granite is presented in Table 2.2.

(ii) Fine-grained schistose silicate rocks

This group includes metamorphic rocks like slates and phyllites. They have a low primary permeability, but during deformation, secondary porosity and permeability are easily developed. In general, slates and phyllites are mainly composed of aluminosilicates, mica, iron oxides, and quartz; therefore, weathering will bring only a few cations into solution. Of course, this is not the case when carbonate-rich layers are involved in metamorphism. They have larger amounts of calcium, which dissolves and participates in cation-exchange processes. Slates may contain pyrite, which brings ferrous iron and sulfate into solution during weathering. As a result, groundwater becomes acid and rich in iron.

(iii) Volcanic rocks

Volcanic rocks often exhibit a high primary porosity, which is caused by a vesicular or block structure. Cooling fractures may produce secondary porosity and permeability. Intrusive dikes often form water barriers but basic (dolerite) dikes can become water bearing by fracturing and weathering. Basic volcanic rocks often contain zeolites as alteration products. They influence the groundwater composition by their high exchange capacity for both cations and anions, which amounts to about 3 milliequivalent per gram (meq/g). As an example, the composition of a thermomineral spring in volcanic rocks of Iceland is presented in Table 2.2.

TABLE 2.2 Examples of various compositions of groundwater, in mg/l

Constituent	*Granite water, North Carolina, USA* [1]	*Thermal soda spring, Lýsuhóll, Iceland* [2]	*Karst spring, Areuse, Switzerland* [3]	*Quartz-sand water, Veluwe Heath, 1927* [4] *(1979), The Netherlands*
pH	6.5	6.7	7.2	8.5 (4.5)
Na	7	451.2	1.3	3.5 (4.3)
K	incl. in Na	34.2	0.8	incl. in Na (1.2)
Mg	2	20.7	3.5	1.4 (0.5)
Ca	5	86.8	82.8	8.2 (1.4)
Sr			0.3	
Fe	0.2		0.1	0.6 (–)
HCO_3 total [5]	34	1,500	257	17.0 (0.0)
H_4SiO_4	48	350	3.4	18.2 (–)
NO_3	0.9		2.7	2.4 (20.3)
SO_4	2	41.2	5.3	6.5 (28.8)
H_2S total		0.1		
F	0.1	5		
Cl	2	80	2.4	5.0 (8.2)

Notes

1. LeGrand, 1958
2. Hjartarson et al., 1980
3. Burger, 1983
4. Archives Amsterdam Waterworks, 1927; in parentheses: Appelo, 1982
5. HCO_3 total = $H_2CO_3 + HCO_3^- + CO_3^{2-}$

(iv) Carbonate rocks and evaporites

Carbonates and evaporites readily develop secondary permeability by dissolution of rock material along fractures. Subsequently, karstification may take place. Chalk is microporous, but joints and fissures cause a typical 'dual porosity' structure with a total porosity of 15 to 40 percent. Dolomite and gypsum often occur together in many places. Solution of gypsum layers results in an 'interstratal' karst structure. The composition of groundwater highly depends on the composition of the carbonates and evaporites in the rock. Groundwater that has circulated through soluble gypsum or halite deposits may contain elevated TDS levels (Pye et al., 1983). Anhydrite and gypsum layers bring calcium, magnesium, and sulfate ions into solution; rock salt forms brines. An example of the chemical composition of the Areuse karst spring in the Jura mountains is presented in Table 2.2.

(v) Terrigenous sediments and rocks

Clastic sedimentary rocks and unlithified sediments consist of detritus and alteration products of source rocks, such as rock fragments, minerals, clay particles, and organic remains. The grain size varies from boulders to clay particles. The primary porosity of sandstones is often reduced by cementation during the lithification process. Coarse unlithified sediments usually keep their high permeability. Clays have a high porosity but low permeability. The cation-exchange capacity (CEC) of clay minerals, expressed in milliequivalents of cations per unit weight of solid (meq/g) plays an important role in the chemistry of water. It amounts to about 0.2–0.4 meq/g for illite, and is somewhat lower for kaolinite.

Again, groundwater composition depends on the mineralogy of the rock. Marl will react like carbonate rock and arkose like granite. Composition of groundwater in inert quartz-rich sands reflects the composition of precipitation water. In Table 2.2, the composition of groundwater in quartz-rich sands, which are covered by heather, is given for 1927 and 1979. As a result of human influence, acidification of rainwater took place during that period. The acid rain leached the soil carbonates and produced a nitrate- and sulfate-rich groundwater, which now also contains toxic levels of aluminium (7 mg/l).

Marine shales and clay layers may act as large reservoirs of saline water, which was trapped during their sedimentation. Solutes may remain in the pore spaces, attached to clay particles, for very long periods, while the adjacent coarse sediments have been flushed and replenished by fresh water. Diffusion of salts or expulsion of saline water by compaction may subsequently influence the composition of the adjacent fresh water (Back and Hanshaw, 1965). The pyrite content of shales and clay layers may affect the groundwater as described under para. 2.2.2 *(ii)*.

2.3 Mechanisms of contamination

The contaminant introduced into the soil-rock-groundwater system will spread within the system only if a transport mechanism is available, for example, a flowing liquid. As soon as the contaminant reaches the subsurface water in the unsaturated or saturated zone, various processes* determine its fate (Jackson, 1980):

- physical processes: advection, dispersion, evaporation, filtration, and degassing;
- geochemical processes: acid-base reactions, adsorption-desorption, ion exchange, oxidation-reduction, precipitation-dissolution, retardation, and complexation; and
- biochemical processes: transpiration, bacterial respiration, decay, and cell synthesis (Fig. 2.1).

Many of these processes are related to each other or interact. Some of them may attenuate the contaminants, some have a reverse effect.

The soil zone is the most reactive part of the system due to the soil-water-air environment, the soil-plant behaviour, and the microbiological activity. Short-circuiting of this zone makes the soil-rock-groundwater system much more vulnerable.

Contaminants are carried by moving groundwater (advection) and travel at the same rate as the average linear velocity of groundwater. The process of dispersion acts to dilute the contaminant and lower its concentration. For example, because of hydrodynamic dispersion, the concentration of a waste plume will decrease with distance from the source. Dispersion increases with increasing groundwater velocity and aquifer heterogeneity. However, for removal of bacteria and viruses by filtration, a fine-grained and homogeneous material is needed. Volatile bacterial products, such as carbon dioxide, nitrogen, or methane, and volatile organic compounds may be removed by degassing.

Chemical reactions, such as adsorption-desorption and ion exchange, can retard the rate of contaminant movement. Adsorption and desorption are characterised by the distribution coefficient, which expresses the ratio of the amount of contaminant adsorbed per gram of soil material to the amount of contaminant remaining in groundwater per millilitre. The distribution coefficient can be used to compute the retardation of the movement of the contamination front (Fetter, 1994).

Bacteria use the reaction energy of oxidation-reduction (redox) reactions for their metabolism. After free oxygen is used up, anaerobic bacterial respiration may successfully reduce nitrate, sulfate, and even carbon dioxide and decompose organic compounds. Recent research has given strong evidence that many toxic organic chemicals can undergo microbial decay to more simple compounds.

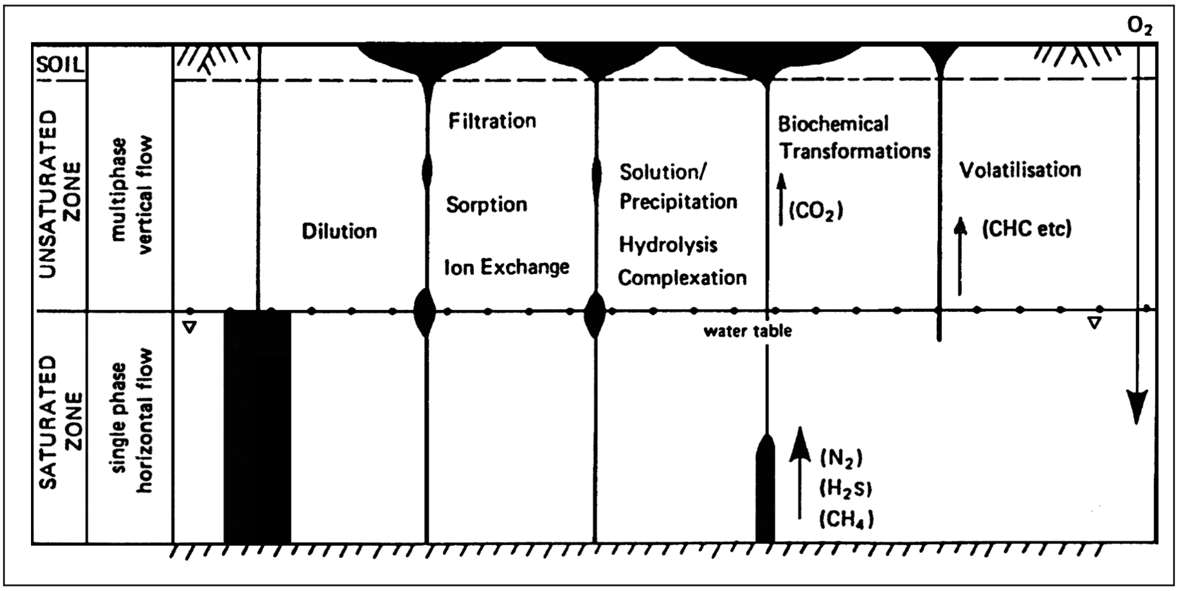
The mechanisms mentioned above are illustrated here with an example of nitrogen (nitrate and ammonium) contamination by fertilisers. Some of the nitrogen released from the fertilisers will be taken up by crops. However, about 30 to 70 percent of the consumable nitrogen output of a farm is leached into the subsoil (Frissel, 1977). Evaporation concentrates the leachate. Further, a part of the dissolved nitrogen will be removed, and another amount will be added to the soil water. Removal takes place by bacterial cell synthesis and further by nitrate respiration under anaerobic conditions, when bacteria break nitrate down to molecular nitrogen. Decay (mineralisation) of litter by bacteria will add nitrate and ammonium to the system. Ammonium ions will be adsorbed on clay particles (CEC, para. 2.2.2 *(v)*), but are under aerobic conditions

* Definitions are included in the Glossary (Appendix A).

subsequently oxidised to nitrate, which is very mobile. The nitrate moves with the infiltrating water to the saturated zone (advective transport) and is diluted by dispersion. The dispersive capacity of the porous medium is directly proportional to the pore-water velocity and the heterogeneity of the aquifer materials.

During residence in an anaerobic saturated zone, nitrate may be reduced by pyrite according to: $2FeS_2(s) + 6NO_3^- + 4H_2O = 2Fe(OH)_3(s) + 3N_2(g) + 4SO_4^{2-} + 2H^+$, where s = solid and g = gas. During oxidation, pyrite may release heavy metals, e.g. bivalent Cd, Ni, or Zn, which become mobile under acidic conditions or by complexation with organic substances and may contaminate the groundwater.

FIGURE 2.1 Processes affecting contaminant transport. The thickness of the corresponding line indicates typically the relative importance of the process in the soil and above, at, and below the water table. (*Source:* Foster, 1987; modified from Golwer, 1983)



3 Sources of groundwater contamination

J. C. Nonner

3.1 Classification of sources

The sources and causes of groundwater contamination are numerous, and are as diverse as human activities (Zaporozec and Miller, 2000). With the growing number of potential contamination sources, attempts to classify them have also been increasing. Agencies and scientists in the field of groundwater contamination have often followed their own categorisation. A large number of source classification methods have been developed and subclassifications have also been prepared. Table 3.1 shows the various ways of classifying contamination sources.

TABLE 3.1 Methods for classification of groundwater contamination sources

Classification	*Examples*
By way of release	Discharge sources; transport sources
By origin	Domestic sources; agricultural sources
By chemical type	Heavy metals; hydrocarbons; pesticides
By location	Above ground surface; below surface
By character	Point, diffuse, and line sources

An early categorisation of groundwater contamination sources was developed by the U.S. Environmental Protection Agency (1977). The sources were divided into four categories considering the *way in which the contaminants were released*. For example, Category I included systems, facilities, and activities designed to discharge substances. In 1984, the U.S. Office of Technology Assessment revised this classification (OTA,1984) and expanded it into six categories (Table 3.2). An especially significant improvement was the addition of naturally-occurring sources.

The source classification by *origin* has been used most often throughout the last decades. Already at the start of the 1970s, Jean Fried (1975) suggested a simple classification consisting of industrial sources, domestic contamination, agricultural sources, and environmental contamination. Nowadays, the classifications by origin are more extensive and subclassifications, by origin and/or by type of chemical compound, are common. For instance, municipal waste may form a major category of groundwater contamination sources. Subcategories such as solid (municipal) waste and liquid (municipal) waste may be defined, and further differentiated by chemical character of the waste into inorganic solid waste and organic waste.

TABLE 3.2 Potential sources of groundwater contamination listed by the character of discharge (*Adapted from:* U.S. EPA, 1989)

CATEGORY I. Sources designed to discharge substances

- Subsurface percolation (e.g. septic tanks and cesspools)
- Injection wells
  - Hazardous waste
  - Non-hazardous waste (e.g. brine disposal and drainage)
  - Non-waste (e.g. enhanced recovery, artificial recharge, solution mining, and in-situ mining)
- Land application
  - Wastewater (e.g. spray irrigation)
  - Wastewater by-products (e.g. sludge)
  - Hazardous waste
  - Non-hazardous waste (e.g. whey)

CATEGORY II. Sources designed to store, treat, and/or dispose of substances; discharge through unplanned release

- Landfills
  - Industrial hazardous waste
  - Industrial non-hazardous waste
  - Municipal waste (sanitary landfill)
- Open dumps, including illegal dumping (waste)
- Residential (or local) disposal (waste)
- Surface impoundments
  - Hazardous waste
  - Non-hazardous waste
- Waste tailings
- Waste piles
  - Hazardous waste
  - Non-hazardous waste
- Materials stockpiles (non-waste)
- Graveyards
- Animal burial
- Aboveground storage tanks
  - Hazardous waste
  - Non-hazardous waste
  - Non-waste
- Underground storage tanks
  - Hazardous waste
  - Non-hazardous waste
  - Non-waste
- Containers
  - Hazardous waste
  - Non-hazardous waste
  - Non-waste
- Open burning sites
- Detonation sites
- Radioactive disposal sites

CATEGORY III. Sources designed to retain substances during transport or transmission; discharge by accident or negligence

- Pipelines
  - Hazardous waste
  - Non-hazardous waste
  - Non-waste
- Materials transport and transfer operations
  - Hazardous waste
  - Non-hazardous waste
  - Non-waste

CATEGORY IV. Sources discharging substances as a consequence of other planned activities

- Irrigation practices (e.g. return flow)
- Fertiliser applications
- Pesticide applications
- Animal feeding operations
- De-icing salt applications
- Urban runoff
- Percolation of atmospheric contaminants
- Mining and mine drainage
  - Surface-related mine
  - Underground-related mine

CATEGORY V. Sources providing conduit or inducing discharge through altered flow patterns

- Abandoned domestic wells
- Production wells
  - Oil (and gas) wells
  - Geothermal and heat recovery wells
  - Water supply wells
- Other wells (non-waste)
  - Monitoring wells
  - Exploration wells
- Construction excavations

CATEGORY VI. Naturally-occurring sources; discharge is created and/or exacerbated by human activity

- Groundwater – surface water interactions
- Natural leaching
- Salt-water intrusion/brackish water upconing (or intrusion of other poor-quality natural water)

A principal classification in terms of *chemical type or location* has been considered by some scientists. Chemical and biological type classifications may include broad categories such as inorganic and organic compounds, bacteriological species, etc. Inorganic substances may be further subdivided into heavy metals, halogens, radioactive compounds, etc. A classification by location refers to the original location of the sources, e.g. above ground surface, in the unsaturated zone, or in the saturated zone (Zaporozec, 1981). Classifications by chemical or biological type and by location, are usually reserved to set up subclassifications for groundwater contamination sources.

In addition, the behaviour of the contaminant in the saturated zone may also be a key element for subcategorisation. Some contaminants dissolve in the water and travel along with the groundwater flow in the form of a *plume*. Others are known to 'float' on groundwater (e.g. petrol), and a third category 'sinks' rather directly to the bottom of a groundwater system (dense non-aqueous phase liquids, such as chlorinated hydrocarbons).

Finally, a classification based on *character* usually refers to a distinction between point, line, and diffuse (non-point) sources. At point sources, the contaminants are confined to a restricted area of well-defined dimensions. Examples are sites for solid waste, leaking petrol station tanks, or injection wells. Line and diffuse sources spread contaminants over larger distances or areas. These sources may include contaminants in a river, a road, a leaking pipeline, and agricultural contamination whereby large areas may be affected by fertilisers or pesticides. To some extent, this classification became popular in countries with rapidly growing agricultural and industrial outputs. The increased application of agriculture-based contaminants and air contamination by industry emphasised the threats from diffuse sources, which subsequently led to the formulation of a character-based classification of contaminants.

In this guideline, the contamination source classification based on origin will be adhered to. The widely accepted use, the ease of physical recognition, and flexibility have been the major reasons for its selection (Table 3.3). Moreover, the origin-based classification is thought to fit well into the concepts of the users of this guideline, including hydrogeologists, engineers, and officials working at national, regional, and provincial levels. Contamination sources were divided into six categories, and their normal character and location described. The major contamination sources of the six categories listed in Table 3.3 are discussed in para. 3.2 through 3.7.

3.2 Natural sources

Sources of groundwater contamination are usually associated with human activities (Fig. 1.1). Through these activities, materials or waste may come into contact with groundwater, which may become contaminated. It is true that the majority of sources of groundwater contamination are of human origin; however, contamination may also have a natural origin. Groundwater with its large variations in chemical composition contains elements that can be considered as nutrients or substances essential to human and animal life and plants, but in places it may also contain natural substances that can be harmful to human health and the ecosystem.

Contaminating natural substances usually enter the groundwater cycle through a combination of processes (Chapter 2). On one hand, there is the dissolution of minerals containing toxic elements. Dissolution usually does not act alone, but is assisted by oxidation and reduction processes. Ion exchange, acid-base reactions, precipitation, and complexation are other chemical processes that may influence the quantities of those dissolved constituents that may contribute to, or reduce, contamination. On the other hand, there is also the interaction of infiltrating groundwater with plant remains, peat, and humus in the unsaturated zone. Processes like cell synthesis, organic decomposition, and microbiological growth may also lead to toxicity of groundwater.

The risk of groundwater contamination from harmful natural sources may be described by a further subclassification by type. The natural contamination sources are discussed below according to their chemical and bacteriological type. Throughout the discussion it should be kept in mind that, more so than for anthropogenic contamination sources, the contaminant concentration determines whether a natural source can be considered as threatening groundwater

TABLE 3.3 Summary of groundwater contamination sources by origin

Category	*Source type*	*Usual character*	*Normal location*
Natural sources	Inorganic substances	Not applicable	Not applicable
	Trace metals		
	Radionuclides		
	Organic compounds		
	Microorganisms		
Agriculture and forestry	Fertilisers	Diffuse	Surface
	Pesticides	Diffuse	Surface
	Animal waste	Diffuse/point	Surface/unsaturated zone
	Animal feedlots	Point	Surface
	Irrigation return flow	Diffuse	Surface
	Stockpiles	Point	Surface
Urbanisation	Solid waste sites	Point	Surface/unsaturated zone
	On-site sanitation	Point	Surface/unsaturated zone
	Wastewater, effluent	Point and line	Surface/unsaturated zone
	Salvage and junk yards	Point	Surface/unsaturated zone
	Leaking underground storage tanks	Point	Unsaturated zone
	Runoff, leaks, spills	Line and point	Surface
Mining/Industry	Mine tailings	Point	Surface/unsaturated zone
	Mine water	Point and line	Various
	Solid waste	Point	Surface/unsaturated zone
	Wastewater, effluent	Point and line	Surface/unsaturated zone
	Injection wells	Point	Below water table
	Spills, leaks	Point	Surface
Water mismanagement	Well-field design	Point	Below water table
	Upconing	Point	Below water table
	Seawater intrusion	Line	Below water table
	Faulty well construction	Point	Below water table
	Abandoned wells	Point	Below water table
	Irrigation practices	Diffuse	Surface
Miscellaneous	Airborne sources	Diffuse	Surface
	Surface water	Line	Below water table
	Transport sector	Point and line	Surface/unsaturated zone
	Natural disasters	Point and line	Surface/unsaturated zone
	Cemeteries	Point	Unsaturated zone

safety. Most natural, potentially hazardous, sources produce contaminant concentrations that are well below the maximum permissible levels listed in Table 3.4. And some naturally-occurring contaminants are quite innocuous, causing only aesthetic, taste, or odour problems (e.g. iron and manganese).

3.2.1 Inorganic substances

The major inorganic ions in groundwater include sodium, potassium, calcium, magnesium, silica, bicarbonate, sulfate, and chloride (Table 2.1). The distribution of these constituents largely depends on the type of geological formations in contact with the groundwater flowing through.

Most of them are rarely harmful to health but some may cause physical inconveniences if digested in large concentrations (e.g. sulfate). High concentrations of calcium and magnesium compounds cause hardness of water. For people suffering from diseases of the heart or kidneys, it is recommended to avoid drinking water with high concentrations of sodium.

The major ions form the majority of chemical compounds found in groundwater. The summed ion concentration of minerals dissolved in water is referred to as total dissolved solids (TDS). There is no evidence of adverse health effects at TDS levels over 1,000 mg/l, although at about 1,200 mg/l taste problems are likely to arise, and at levels over 1,500 mg/l, gastrointestinal irritation may occur.

Certain minor inorganic constituents may be present in groundwater and may render it unfit for human consumption. Perhaps the two best known examples of such constituents are arsenic and fluoride. Arsenic may be released into groundwater through the reduction of arsenic-containing iron hydroxide coatings on sand grains, which are present in some fluviatile and deltaic river sediments. A case at hand is the release of arsenic in the sedimentary basin of Bangladesh and neighbouring India (see Chapter 8, case study 8.1). The consumption of groundwater with excessive arsenic levels is toxic and may eventually lead to the loss of limbs, cancer, or death. Fluoride may be present in groundwater by the disintegration and dissolution of igneous and metamorphic rocks containing minerals such as amphiboles and micas (Hem, 1970). The drinking of groundwater with high concentrations of fluoride may cause mottled teeth and disturb the growth of bones in children. Extremely high concentrations of fluoride are toxic and could lead to death. The recommended limits for arsenic and fluoride are listed in Table 3.4.

Table 3.4 Maximum permissible concentrations of potentially harmful or objectionable substances in drinking water, in mg/l (*Source:* WHO Guidelines, 1993)

Constituent	*Concentration*	*Constituent*	*Concentration*
Total dissolved solids	1,500	Iron	0.3
Arsenic	0.01	Lead	0.01
Cadmium	0.003	Manganese	0.05
Chloride	250	Nitrate	50
Chromium	0.05	Selenium	0.01
Copper	2	Sulfate	250
Fluoride	1.5	Zinc	3

3.2.2 Trace metals

Concentrations of trace metals, including aluminium, cadmium, chromium, cobalt, copper, lead, nickel, silver, zinc, etc., are usually extremely small in groundwater. Trace metals are normally associated with igneous and metamorphic rocks, and in particular, with ore bodies. Weathering of these rocks, including oxidation and leaching, may give rise to elevated trace metal levels in groundwater. However, trace metals may also be brought into the groundwater system by human activities. Naturally-occurring elevated concentrations of trace metals in groundwater (maximum limits are listed in Table 3.4) may locally make this resource unfit for human consumption or affect the natural ecosystem.

3.2.3 Radioactive elements

Groundwater contaminated by radioactive elements is usually associated with human activities such as nuclear power generation and the disposal of nuclear waste. Nevertheless, naturally-occurring radioactive substances are by no means exceptional. Radon, radium, and uranium are found as trace elements in most soils and rocks. They are formed principally by radioactive decay of uranium and thorium isotopes. Sedimentary deposits like shales and clays are known to contain radioactive potassium, and, in places, relatively young intrusive granites, pegmatites, and syenites have elevated levels of radon. Also, various ore bodies contain radioactive minerals. For example, the Morro do Ferro ore body in Brasil contains the radioactive uranium isotopes ^{234}U and ^{238}U, resulting in the presence of the thorium isotope ^{232}Th and the radon isotope ^{228}Ra (Bonotto, 1991). Disintegration and dissolution of the isotope-containing minerals in the Morro do Ferro ore body has led to groundwater containing excessive levels of radioactive isotopes, in particular radon. Although excessive levels of carcinogenous radioactive isotopes may be present in groundwater, the normal isotope concentrations in groundwater percolating through sediments and ore bodies are low and cannot be considered as toxic.

3.2.4 Organic compounds

In addition to resulting from human activities, organic compounds may be released in groundwater as a result of natural processes. These processes usually take place near the surface in the humus-containing soil, but may also be present in deeper layers where peat, lignite, coal, or even shallow oil deposits are present and in contact with groundwater. Through metabolism, decay, dissolution, advection, and other processes, organic compounds are formed and become part of the groundwater system. Humic acids, pectins, and hydrocarbons, are amongst the natural organic substances occurring in groundwater (Rail, 1989). In most places, the concentrations of naturally-occurring organic compounds are low and cannot be considered as contaminating groundwater.

3.2.5 Microorganisms

Naturally-occurring microorganisms in groundwater rapidly decrease with depth. There is usually a correlation with the concentrations of organic compounds in groundwater, which also tend to decrease with depth. The few microorganisms found in groundwater pumped from deep wells are usually the so-called chemolithotropic bacteria. Nevertheless, groundwater may contain bacteria that play vital roles in oxidation-reduction processes. Well-known examples are: 1) the bacteria-assisted reduction of carbon dioxide and organic acids into methane, 2) the bacteria-aided reduction of sulfate into hydrogen sulfide, and 3) the bacteria-based oxidation of dissolved iron and manganese into iron and manganese oxides and hydroxides. Especially, the last two reactions are known to produce bacterial slimes, which make groundwater less suitable as drinking water, and which also clog well screens and pumping mechanisms.

3.3 Agriculture and forestry

Agriculture is perhaps one of the most widespread human activities that can affect groundwater, although forestry may also have some adverse effects on this resource. The practices include the cultivation of crops, cattle and poultry farming, fish farming, logging, etc. The use of fertilisers and pesticides, the storage and disposal of manure, stockpiling of materials, and a large number of other activities carry the risk that groundwater resources may be affected. Although the activities are carried out at the land surface, infiltrating rain and irrigation water may take the associated contaminants down to the groundwater. In particular, the diffuse character of the application of fertilisers, pesticides, and manure may contribute to serious contamination of large parts of a groundwater system. As opposed to the control of point source contamination, the measures to be taken to manage the hazards from diffuse agricultural sources and forestry practices are usually far more complicated. Although a large number of agricultural practices threatening groundwater resources could be mentioned, only the more important ones have been included in this guideline. More details and case studies documenting agricultural threats to groundwater can be found in Candela and Aureli (1998) and Vrba and Romijn (1986).

3.3.1 Application and storage of fertilisers

Fertilisers can be either inorganic or organic. The inorganic fertilisers will be discussed in this section; the animal-related organic fertilisers are included in para. 3.3.3. Inorganic fertilisers used to stimulate crop growth usually contain potash, nitrogen, and phosphorous compounds. The application of these compounds enriches the soil with potassium, calcium, chloride, nitrate, and phosphate. Other inorganic substances may be added to the soil as well: for example, magnesium, sulfate, and metals like cobalt, molybdenum, and copper. Most potash and nitrogen compounds are highly soluble and may reach the water table if applied in excessive amounts. Phosphorous compounds are usually insoluble and remain fixed in the soil structure or are washed away by surface water. Metals are soluble in an acid environment, but it is uncertain whether these elements will reach the saturated zone as they may be fixed in the unsaturated zone by complexation. When applied in excessive amounts on the field or improperly stored in stockpiles, inorganic fertilisers may lead to unacceptable or even toxic concentrations of chemical constituents in local, regional, and even national groundwater systems.

3.3.2 Application and storage of pesticides

The term pesticides generally includes herbicides, insecticides, fungicides, and other chemical compounds, which are applied to combat pests and diseases in agricultural areas where crops are being cultivated. They are mainly organic compounds and can be subdivided into ionic pesticides and non-ionic pesticides (Vrba and Romijn, 1986). Due to their inclination to take on positive or negative charges in an aqueous environment, the ionic pesticides are usually far more soluble than the non-ionic pesticides. Nevertheless, pesticides in solution may be fixed in the soil or unsaturated zone by soil organisms and by adsorption to organic matter (peat) or clays. In addition, pesticides may be broken down by chemical degradation or by biodegradation under the influence of microorganisms. As a result of their tendency for fixation, and the possibility of biodegradation, the impression may be created that pesticides do not form a threat to groundwater. However, an example of pesticide application in an agricultural area around the town of Emmen in the Netherlands shows that this impression is not always correct (Zhang et al., 1998). The application of the soluble, hardly biodegradable pesticide (dichloropropane) to combat potato diseases in this sandy area devoid of major clay or peat layers has contaminated local groundwater resources. Recent reports from many countries including Denmark, Sweden, and the United States also confirm groundwater contamination by pesticides. Full knowledge of the physico-chemical and biological characteristics of the compounds involved and the local hydrogeology is essential to assess the risk of groundwater contamination by pesticides.

3.3.3 Animal waste

Animal waste products are deposited on agricultural land to serve as fertiliser or to be stored and disintegrated in a natural environment. Waste products comprise solid manure, liquid manure, slurry, dung water, straw, and compost (Vrba and Romijn, 1986). These waste products contain potassium, nitrogen, and phosphorous compounds in varying concentrations, whereas trace elements and organic matter are also common. Table 3.5 shows that the application of nitrogen and phosphorus contained in these animal waste products (and other fertilisers) is excessive in western European countries (Boers, 1996). On the other hand, in less developed countries like Angola or Tanzania, there is a lack of nitrogen and phosphorus (Table 3.5). The release of excessive amounts of animal waste does not serve the purpose of crop fertilisation because the crop cannot fully utilise the suddenly available nitrogen. However, the release of large quantities of nitrogen compounds and trace elements endangers groundwater resources at a large scale.

TABLE 3.5 Surplus nitrogen (N) and phosphorus (P) in selected countries (*Source:* Boers, 1996)

Country	*Nsurplus (kg N per ha)*	*P surplus (kg P per ha)*
Belgium	208	37
Denmark	160	20
Great Britain	129	12
Netherlands	340	39
Norway	87	10
Angola	–2	–1
Tanzania	–9	–2

Animal feedlots are rather confined areas where a large number of cattle or other animals are kept. Animal herds produce waste in large quantities, which, if not properly disposed of, may be washed away with surface water into ponds or streams or infiltrate groundwater. Because of the great concentration of animals in a relatively small area, animal feedlots may be considered as significant point sources of groundwater contamination (Conrad et al., 1999).

3.3.4 Irrigation return flow

Irrigation return flows are responsible for the deterioration of groundwater quality in a large number of countries, in particular in semi-arid and arid regions. When a crop is irrigated, approximately one half to two thirds of the applied irrigation water is absorbed by the soil and by the plants or lost by evaporation. The salts dissolved in water, however, remain behind and tend to accumulate in the soil. Good irrigation practice has to take into account these salts by using extra water for leaching so that it can carry the salts away. The excess water percolates down to groundwater and this return flow carries with it an increased concentration of salts. Gradually, by repeating this process, the dissolved solids content of the groundwater will increase. Besides the salts, the return flow also washes down fertilisers, pesticides, and animal wastes. Cases concerning the degradation of groundwater quality and contamination accelerated by irrigation return flows have been reported from many countries including the United States, India, and China.

3.3.5 Stockpiles and crop residues

Stockpiles of a variety of agricultural products and crop residues may also become potential point sources of groundwater contamination. For example, a number of cases of silage making have been reported to cause the formation of contaminated liquids with high BOD demands and the release of sulfates and phenols (Cole, 1974). Crop residues left in the field may constitute diffuse sources of groundwater contamination. Up to now, no extensive research has been carried out in connection with the contaminating effects of crop residues.

3.3.6 Forestation and deforestation

Forestry practices may include both the planting and the removal of trees and natural vegetation. Both activities may significantly alter recharge into the groundwater system, thereby upsetting its delicate water balance. A modified water balance will lead to changes in the hydrochemical composition of groundwater that may affect groundwater quality. In addition, the use of fertilisers and pesticides, in particular in nurseries, and the replacement of forest area by agricultural land can increase the threat of groundwater contamination.

In Western Australia, for example, the large-scale clearing of forests have resulted in unparallel hydrological changes and extensive salinisation (George et al., 1997). The clearing resulted in reduced transpiration and increased recharge to groundwater, enabling groundwater levels to rise by more than 30 m in places. As a result, salts accumulated in soils overlying the aquifers were leached out. About 1.8 million hectares of cleared, formerly productive farmland is affected by salinity and this area is expected to double in 25 years if no action is taken. Production from this land has been either lost or reduced. Estimated financial investments required to reduce the salinisation of land to 1980 levels range from $(Australian) 3.6 to 13.5 billions.

3.4 Urbanisation

During the last few decades, urbanisation has taken on an alarming expansion, especially in the developing world. Capitals and small country towns have increased in size tremendously and facilities for the disposal of waste, wastewater, stockpiling, etc. have not always been implemented in a satisfactory manner. Therefore, there are numerous known cases of waste, stockpiles, leaking tanks and pipelines, and accidents damaging the urban environment. Not only the urban area itself is threatened, but also the subsurface framework, including the groundwater resources (Chilton et al., 1997). The most common sources of groundwater contamination in urban areas are included below. The impact of urbanisation on groundwater quality is described in detail in Lerner et al. (2001).

3.4.1 Domestic and municipal solid waste disposal

Solid waste generated by private homes, businesses, industries, and public buildings can be disposed of in the direct vicinity of these places or be collected and deposited at solid waste disposal sites. In many cases, these disposal sites may just be pieces of open land that have been fenced off, excavations and old mining areas, or isolated ravines and valleys (Fig. 3.1). In the case that no proper sanitary measures have been taken at the site, leachate may form and infiltrate into the subsoil. Leachate is the contaminant-loaded liquid that is formed at the base of the disposal site when infiltrating and percolating rainwater is available in sufficient quantity. In the case that concentrated leachate, which may be enriched with toxic metals and organic compounds, intrudes the subsoil and reaches the water table, the risk of groundwater contamination is imminent. The leachate usually contains inorganic components including chlorides, sulfates, carbonates, nitrogen

FIGURE 3.1 Burning waste at a landfill in Gaza

compounds, and metals, and a wide range of organic compounds. The U.S. Environmental Protection Agency analysed 20 leachate samples from municipal waste disposal sites in the U.S.A. (Table 3.6). The table shows the main analyses done on the leachates and the large variations in concentrations of the individual dissolved components.

TABLE 3.6 Selected leachate components in municipal waste disposal sites (*Source:* U.S. EPA, 1977)

Component	*Range (mg/l)*	*Component*	*Range (mg/l)*
Alkalinity ($CaCO_3$)	0 – 20,850	Magnesium	17 – 15,600
BOD (5 days)	81 – 33,360	Nitrogen (NH_4)	0 – 1,106
COD	40 – 89,520	Sodium	0 – 7,700
Calcium	60 – 7,200	Sulfate	1 – 1,558
Copper	0 – 9.9	TDS	584 – 44,900
Chloride	4.7 – 2,500	Zinc	0 – 370
Iron, total	0 – 2,820	pHi	3.7 – 8.5
Total dissolved solids	1,500	Iron	0.3
Arsenic	0.01	Lead	0.01
Cadmium	0.003	Manganese	0.05
Chloride	250	Nitrate	50
Chromium	0.05	Selenium	0.01
Copper	2	Sulfate	250
Fluoride	1.5	Zinc	3

3.4.2 Disposal of domestic wastewater

In many urban areas, the disposal of liquid waste by septic tanks, cesspits, and latrines is still practised. The discharge of human waste more or less directly from latrines into pits is still common in many parts of the world. In case no sanitary precautions are taken, the waste may infiltrate directly into the soil. Poorly-functioning septic tanks buried in the ground may overflow and discharge nitrogen-rich liquids into the unsaturated zone. Well-functioning septic tanks and their associated drain fields, when present in highly drained soils with a deep water table, and when densely distributed, tend to release heavy loads of nitrate to the water table. A rather worrisome development in the developing world is the installation of cesspits. Cesspits usually are 1.5 by 1.5 m shafts dug down several meters into the ground. To prevent nuisance at the land surface, liquid waste like urine and human excrements, washing water, etc. is discharged into these shafts and, in the case where liquid levels are high, it may reach the water table and contaminate nearby water wells. Especially in populated urban areas where their density is high, septic tanks, cesspits and latrines, may contaminate local groundwater resources beyond easy repair.

3.4.3 Disposal of collected wastewater and effluents

In most large urban centres, liquid waste is partially or completely collected and transported by sewerage pipes. At the outlet of the system, the wastewater may be discharged untreated, partially treated, or fully treated. The discharge of partially treated wastewater has been reported from a number of cities where the capacity of treatment plants was not adjusted in accordance with the rapid population growth. Untreated or partially treated wastewater contains a wide variety of inorganic, organic, and biological contaminants. Even treated wastewater, commonly referred to as effluent, may contain elevated concentrations of various chemicals including chloride, nitrate, hydrocarbons, and metals.

Untreated and partially treated wastewater may be stored in ponds and lagoons or be discharged on the land or into an open water system. Treated wastewater may be used as irrigation water for agricultural purposes or as artificial recharge to augment groundwater supplies. Leaking treatment facilities, the storage of wastewater in ponds and lagoons, and the discharge of untreated or partially treated wastewater on the land or into an open water course carries the risk that infiltration of contaminants will take place and groundwater will be contaminated.

3.4.4 Salvage and junk yards

Although higher in density in urban areas, salvage and junk yards can be found all across the country. At salvage and junk yards, worn-down consumer goods like cars, home appliances, etc. are stored. However, as a result of the recycling of materials, many of these yards are not increasing in size anymore. Nevertheless, they may contain various hazardous materials such as grease, oil, solvents, and lead-bearing battery acids, and may affect groundwater, especially in areas where they are located in coarse textured sediments or in fractured rock.

3.4.5 Other urban sources

A large number of other potential urban sources of groundwater contamination can be mentioned. These could be leaky sewers, urban runoff, garden and lawn pesticides, leaking fuel tanks at homes and at petrol stations, oil spillage at garages, etc. Sewerage systems may not be well-maintained and wastewater losses in the order of 20 to 50 percent into the subsoil are by no means an exception. Almost all sewerage pipes leak and release nitrogen compounds and micro-organisms to the water table. The rate of leakage is high. Urban runoff, which washes solid and liquid waste from gardens, roads, and parks down to low-lying areas and water courses, may also have an effect on the soil zone, and consequently, on the groundwater. Leaking fuel tanks, in particular, and oil spillage expose the subsurface to hydrocarbons and are a big threat to groundwater.

3.5 Mining and industrial activities

Mining and industry are a potential risk for groundwater contamination. The improper handling and disposal of solid and liquid waste from mines and factories, accidents, and leaks may form sources for contamination. These sources could be located at the land surface, in the unsaturated zone, or even below the water table itself. Mainly, but not exclusively, they are point sources that may result in well-defined contaminant plumes in the groundwater system. Especially during recent years, many efforts have been spent in both the developed and developing countries to identify these contamination sources. Actions for monitoring programs and cleanup have been initiated. Nevertheless, a lot of work remains to be done to complete the identification and inventory of these sources and to analyse the results of the measures taken. The major potential sources of groundwater contamination within the mining and industrial sector are described below.

3.5.1 Mine tailings

The disposal of solid waste (tailings) is inevitable during mining operations for metals, radioactive minerals, salt, coal, phosphate, etc. At many mines, these tailings are deposited on the land surface or in shallow excavations without proper protection or landscaping. The forming of leachate at these open dumps by infiltrating rainwater or water from other sources is common. The composition of the leachate is extremely diverse and depends on the minerals that are mined, source rock composition, and mining and processing techniques. Leachate percolating through the subsoil may threaten groundwater resources underlying the tailings and surrounding area, or endanger nearby open water courses.

3.5.2 Mine dewatering, mine drainage, and mine wastewater

Mine dewatering implies that the water table is lowered, which brings about the oxidation of rocks and minerals at deeper levels. The chemical composition of the groundwater to be dewatered changes and may contain more metals, phosphates, sulfates, fluorides, trace elements, etc. The groundwater pumped from the mine may be spread on the land surface or discharged towards a stream. Infiltration from the land surface or the stream into the subsurface has spoilt local groundwater at many mining sites. Mine dewatering may have other adverse affects on groundwater quality. It changes the groundwater flow pattern, which may result in water of a high salinity or otherwise poor quality from deeper parts of the groundwater system moving toward water wells. In addition, termination of mine dewatering and a following rise of groundwater levels may further dissolve disintegrated, oxidised, and leached minerals, which may lead to groundwater contamination downstream of the direct mining area.

Another source contributing to groundwater contamination is acid mine-water drainage (Zaporozec, 1981). This problem is most commonly associated with coal mining. The acid forms when precipitation brings water in contact with pyrite (FeS_2). Before mining starts, the rocks above the coal seam usually are completely saturated with groundwater. As the mining progresses, the overlying rocks crack and the groundwater drains through fractures into the coal seam. When the pyrite is exposed to air, it begins to oxidise. The oxidised material dissolves in water, and mine water becomes acid. The mine-water drainage does not have a typical composition, but generally it contains relatively high concentrations of sulfate, iron, and other metals; low pH; and high acidity (U.S. EPA, 1977).

The use of water for mining operations may produce wastewater of an undesired quality. Water used for reducing mine dust, for the cooling of equipment, for washing and processing purposes, etc. may pick up undesirable substances. Storage of the wastewater or other liquids from mining activities in ponds or slurry lagoons may form a potential risk to the environment. For example, in a mine close to the town of Mosul in Iraq, bituminous sulphur deposits are mined by passing hot water through the mineral rich layers (Al-Dabbagh and Al-Dabbagh, 1991). During purification and filtration processes, the sulphur is produced, but the remaining wastewater is acid, and contains very high levels of sulfates and organic substances. The wastewater is temporarily stored in a pond and subsequently discharged into the Tigris River. Leakage of wastewater from the pond caused local groundwater contamination, and the deteriorated water quality of the Tigris River threatens the groundwater resources adjoining the river.

3.5.3 Industrial solid and liquid waste

Industrial activities produce waste that may come in the solid or liquid form. Such waste may be dumped on the land surface or in excavations at or near the site of a plant. Waste may also be transported to special dump sites or incinerators. Leachate accumulating in industrial waste dumps may form point sources for groundwater contamination. For example, waste from a secondary aluminium smelter near the town of Ronda in Brasil is dumped at a site in gneissic-granitic terrane (Bernardes et al., 1991). Since fluoride salts are also produced in the smelter, leachate at the dump site contains high levels of fluoride, chloride, and sodium. The leachate has infiltrated into permeable sands and lesser permeable sandy clays that have formed on top of the gneissic-granitic rock. This has led to the formation of a contaminant plume of more than 300 m long. The development of contaminant plumes below industrial solid waste dump sites seriously harms the environment and may endanger domestic or agricultural water supplies.

Industries may also produce liquid waste and wastewater, which may be discharged on the land surface or into open water courses, stored in lined and unlined basins, or treated. Waste in the form of industrial by-products, process water, cleaning water, and wastewater effluent may infiltrate from the land surface or open streams and leak from basins. There are quite a number of cases whereby basins are not lined or the lining has been improperly installed. An interesting example is the former disposal of liquid waste in an unlined ditch-like basin near the town of Zwolle in the Netherlands (Wang et al., 1998). Liquid acenaftene, benzene, bromacil, trichloroethane, and other organic compounds originating from a gas factory and petrochemical activities infiltrated from the ditch into the open fluviatile, sandy groundwater system and affected drinking water wells. Cleanup of the contaminated groundwater in the affected area of about 1 to 2 km^2 has been a major effort. Fortunately, the disposal of liquid industrial waste is nowadays practised under the constraints of strict regulations, but it still needs attention as a result of the continuing discovery of accidents from past and illegal dumping.

3.5.4 Disposal and injection wells

The use of disposal and injection wells forms a special case of industrial activities that may affect groundwater resources. At disposal wells, industrial effluent, cooling water, and processing water enters the groundwater system through the well bottom or a well screen assembly. These, mainly industrial wastes, are point sources of chemicals and microorganisms that may directly contaminate the aquifer. Injection wells are usually associated with the disposal of hazardous waste into deep-seated geological formations that supposedly have no contact with fresh groundwater resources. Waste that may be disposed of through injection wells includes brines, radioactive materials, chlorinated hydrocarbons, steel pickling liquors, etc. Although precautions would have been taken, the waste may enter the fresh groundwater system as a result of well failure, well annulus leakage, and upward leakage through inadequately confining or fractured beds. Deep-well disposal should be considered only after a careful evaluation of geological and hydrological factors, the chemical character of waste, and potential impacts on human health (LaMoreaux and Vrba, 1990).

3.5.5 Spills and leaks

Accidental spills and leaks in tanks and pipelines at industrial compounds may also affect the groundwater. Leaks in tanks and pipelines do occur, but are not always reported. Accidents are bound to happen in an industrial environment or during the transport of chemicals or hazardous waste. The resulting spills must be immediately cleaned up by experienced and well-trained crews with the proper equipment, before the chemicals soak into the soil and contaminate groundwater. Spills of chemicals and hazardous materials from accidents involving tanker trucks and railroad cars normally are reported to the authorities. More dangerous are the unreported, intentional spills when hazardous liquids are discharged onto the ground illegally rather than being transported to collection facilities. Toxic liquids from spills and leaks contaminating groundwater are very troublesome, since remediation usually takes large amounts of time and money and may not always be successful.

3.6 Water mismanagement

Improper design and construction of infrastructural water works may lead to groundwater contamination. Infrastructural works may comprise dams and reservoirs, embankments along rivers, sluices, irrigation and drainage works, infiltration galleries, or water wells. The construction of these works interferes with the natural environment and may also have an effect on groundwater quality. In this guideline the emphasis is on the effects of water wells and well fields. The mismanagement of well fields does not have to create new sources for groundwater contamination, but it can aggravate the effects of existing contamination sources.

3.6.1 Improper well-field design

Well fields alter the local groundwater flow and chemical and biological conditions in the groundwater system. Groundwater flow directions may be altered or even reversed, the hydrochemistry of the aquifer changed, or the redox potential altered. In the case that well-field siting, well screening, and pumping are not done in a proper way, the hydrochemistry of groundwater may be changed to such an extent that groundwater quality is affected. For example, improper well siting and screening may change redox values in iron- and bacteria-rich groundwater, leading to the precipitation of iron, manganese, and slime in the groundwater and on the well screen and pump. Another example is improper well siting in that part of a groundwater system where man-induced contaminants like fertilisers or pesticides or liquid or solid waste are present. As a result of pumping, contaminants may move laterally into 'clean' areas of an aquifer and even end up in the well field. In addition, the downward penetration of contaminants through semi-confining layers may deteriorate groundwater quality in deeper aquifers and reach well screens. Thus, improper well siting and screening will worsen the effect of natural and man-induced contaminants and could be considered as a secondary mechanism of contamination.

3.6.2 Upconing of brackish water and seawater intrusion

A special case of groundwater contamination associated with improper well-field management is the upconing of brackish water. Brackish water also may be present in inland areas, not only near current seas or oceans. Brackish groundwater may be contained in deeper layers of the groundwater system, where it was trapped in the sediments of a previously marine environment (fossil water). Upconing may take place due to improper well-field layout, wrong screen depths, or high pumping rates. Once upconing has taken place and parts of the groundwater system have been affected by high salinity, it takes a very long time to reverse the process, and abandonment of the well field may often be the only choice.

Another case of groundwater contamination by improper well or well-field siting and/or pumping schedule is seawater intrusion, which is defined as an inland movement of saline water into fresh groundwater in coastal areas. As a result of overpumping, the wedge-shaped saline bottom part of the groundwater system connected with seawater extends inland, and the original interface between saline and fresh groundwater shifts toward the pumping wells (DeBreuck, 1991). The threat of the expanding saline wedge is in particular imminent when the pumping levels at the wells are well below sea level. Improper well-field siting, well screening, and in particular, excessive pumping has caused seawater intrusion in practically all populated coastal areas around the world.

3.6.3 Faulty well construction

Another source of groundwater contamination is an improperly constructed well. First, the annular space between well casing and rock may not be properly sealed. In case the space near the surface is not properly cemented or otherwise sealed, contaminants from the land surface may enter the groundwater system along the well casing. Also, an inadequate seal or a lack of seal of the annular space in a confining layer may cause the mixing of groundwater in adjoining aquifers. This process, which is referred to as an *aquifer interchange,* may cause the transfer of contaminants between two aquifers. Second, well casing (steel) may not be properly welded or subject to corrosion, which results in the development of holes in a well-casing column. In this way shortcuts are created that may allow the entry of contaminated water at higher levels in a pumped well. Although a TV camera may inspect conditions of the well casing from the inside, groundwater contamination may be hard to confirm. The risk of groundwater contamination is especially high in developing countries where incorrect well design, insufficient sealing of wells, and poor craftsmanship during well construction has resulted in many cases of local groundwater contamination.

3.6.4 Abandoned wells and holes

Abandoned production or observation wells and exploration boreholes may act as vertical conduits for the transport of undesirable substances. In case the wells and holes are left unplugged, local people may use them for the dumping of waste or consider them as public latrines. Abandoned wells may be damaged by vehicles or badly deteriorate when corrosion or aggressive groundwater destroys the well casing and screen. The migration of water from one aquifer to another (aquifer interchange) is then stimulated.

3.6.5 Uncontrolled land development and irrigation practices

Two examples of water mismanagement, which are not directly related to wells include improper land development in areas with pyrite-rich soils and poorly managed irrigation schemes in semi-arid or arid regions. Pyrite in coastal soils may oxidise as a result of water level changes, resulting in sulfate-rich and acid groundwater. Development of such areas often includes the installation of drainage systems. In case these systems are not properly managed, groundwater levels may be substantially lowered. Substantial declines of the water table result in high pyrite oxidation rates yielding high concentrations of sulfate and high levels of acidity. The upper part of the water system can then be contaminated and water supply sources, such as shallow wells may have to be abandoned.

Mismanaged irrigation schemes may cause serious groundwater contamination. Even properly managed irrigation schemes may result in contamination (see para. 3.3.4), but poorly managed irrigation schemes carry a more serious risk. Such schemes usually suffer from a lack of properly installed drainage systems. Salts in excess irrigation water accumulate in shallow groundwater as a result of high evapotranspiration rates and poor drainage. As a consequence, highly saline water may migrate down and contaminate groundwater in nearby wells.

3.7 Miscellaneous sources

There are a number of other potential sources of groundwater contamination that do not fit into one of the above categories. Five of them have been selected for discussion: airborne contaminants, surface water, the transport sector, natural disasters, and cemeteries.

Contaminants that are transferred through the air may originate from a large number of sources. Industrialised and mining areas, urban areas, and road systems produce hazardous substances that may be carried over very large distances through the air. Acid rain is caused by power stations and other industries, by burning the sulfide-rich coal in homes, and by automobile exhausts. Airborne contaminants released by these and other activities include nitrates, sulfates, and trace metals (Keeler and Pirrone, 1996). After travelling through the air, contaminants dissolved in rainwater (wet deposition) or as solid particles (dry deposition) reach the land surface. Washing the contaminants down to the water table may pose a threat to groundwater quality. Fortunately, acid rain is often buffered (neutralised) by the soil and rocks and thus groundwater is protected from the impacts of acid rain.

Surface water may act as a secondary source of groundwater contamination. As indicated in previous sections, agricultural contaminants, urban and industrial liquid waste, wastewater, and leachate may enter open water courses. Rivers and streams contaminated by hazardous and resistant substances form potential line sources of contamination for influent groundwater systems located along their courses. Contaminated surface water in rivers and streams may be carried downstream over considerable distances. For example, industrial inorganic and organic contaminants accidentally released into the Rhine River in Germany infiltrated into a sandy groundwater system located about 200 km downstream, near the town of Zwolle in the Netherlands. The infiltrated contaminants affected the local well field (Wang et al., 1998).

Spills and leaks associated with the transport sector, including the transport of hazardous liquids, are widely known. Spills and leaks may occur from tanker trucks and railroad tankers, from cross-country pipelines, and from tanks at petrol stations along highways and at airports. For example, the spillage of diesel and jet fuel has received wide attention in England and the United States (Zaporozec, 1981). Although the industry sector is aware of the potential risk of contamination, accidents still happen and may threaten groundwater quality.

Natural disasters include earthquakes, landslides, storms, etc. These natural disasters may damage urban or industrial treatment facilities for liquid waste or tanks for storage of toxic materials. In addition, earthquakes and landslides may disrupt buried pipes, oil and water wells, and infiltration galleries. These incidents can cause the release of contaminants that may affect the groundwater system.

At cemeteries, the dead are buried and left in the unsaturated zone for many years. Leachate from graves may cause groundwater contamination, although such cases are not well documented. Most recently, Engelbrecht (1998) described how groundwater in some sections of graveyards near Cape Town, South Africa, was contaminated by rising water table during wet seasons.

4 Contamination source inventory

Alexander Zaporozec

In order to assess the existing or potential impacts of human activities on groundwater, it is necessary to document, in an orderly fashion, all existing and potential sources of contamination – their location, type, characteristics, and estimated magnitude of impact on groundwater – and the contamination already caused by the existing sources. The process by which the necessary information is collected is called a contamination source inventory.

The inventory of possible sources of contamination should be an integral part of any groundwater protection program. An assessment of both the existing and potential sources of contamination and the spatial extent of the existing groundwater contamination is needed before considering methods to prevent future groundwater quality problems.

Although this process is usually tailored to the specific needs and available resources, it is possible to outline, in general terms, the basic steps in the design, structure, implementation, and evaluation of the inventory. It is our intention to present in this chapter a list of examples of inventory methods and possible sources of data, from which a person charged with conducting the inventory can select those methods suitable for a given task and for available financial and personnel resources.

4.1 Planning the inventory

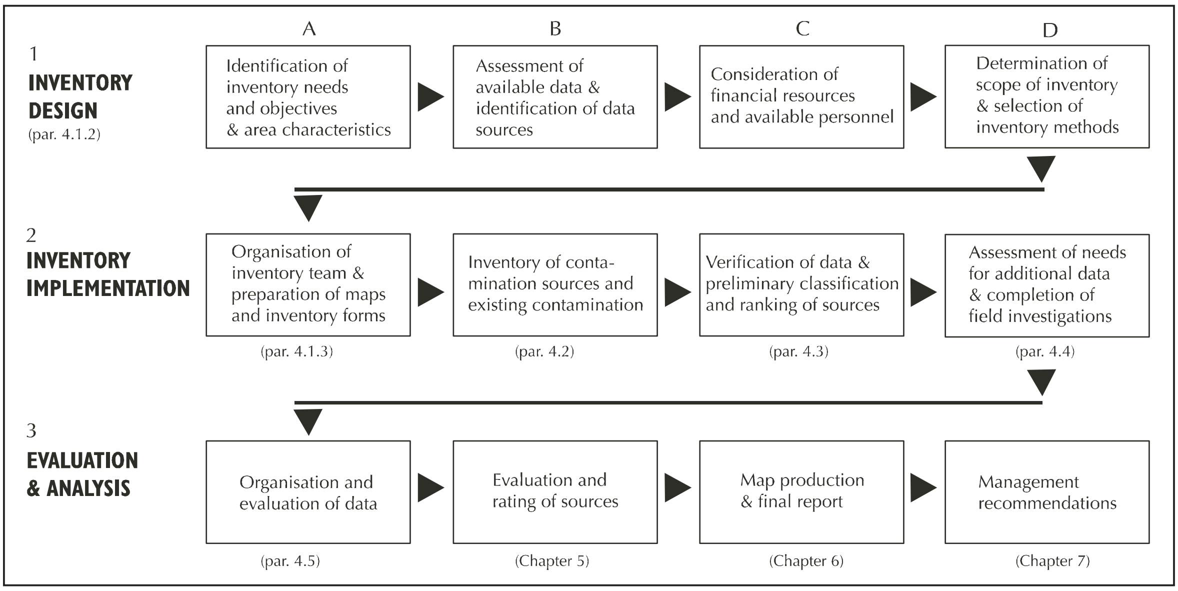
4.1.1 Inventory process

The inventory of contamination sources is a systematical, detailed process by which the potential threats to groundwater quality can be evaluated. This process usually includes three major phases outlined in Fig. 4.1. Elements of inventory design (Phase 1) are summarized in para. 4.1.2. The second phase, inventory implementation, is described in paras. 4.1.3, 4.2, 4.3, and 4.4. And the last phase, containing the evaluation and analysis elements of groundwater contamination inventory, is discussed in the remainder of Chapter 4 (para. 4.5) and in Chapters 5, 6, and 7.

4.1.2 Inventory design

The first step in designing a source inventory is to understand the needs of the inventory and the unique characteristics of the area to be inventoried (local geography, size of communities, transportation network, land use, etc.) and to define objectives of the inventory (Fig. 4.1-1A). Groundwater contamination inventory is primarily needed for the assessment of potential threats to groundwater quality, for groundwater protection planning, and for the design of cleanup methods and technology. The scale (size of the area) plays the primary role in the selection of source inventory methods. One area may be located outside of town, possibly in farm land, whereas another one may be found in the centre of a city. These areas will have vastly different

Figure 4.1 Major phases of a groundwater contamination inventory



demands on the inventory. Objectives of the inventory, in most cases, will be based on the specifications given by the user of the inventory, who may have specific concerns, needs, or special requirements, such as the focus on a particular source of contamination or group of sources. Designing the inventory also involves preliminary evaluation of the quantity and quality of available data (the number and type of contamination sources) and identification of primary sources of available information (Fig. 4.1-1B). Finally, personnel responsible for conducting the inventory have to take into account budgetary constraints, which in turn determine the detail of the inventory and the number and level of training of staff (Fig. 4.1-1C). If the inventory does not have proper resources, both financial and personnel, it is likely to be unsatisfactory.

After considering all these factors, the scope of the inventory can be determined and methods for implementing the inventory selected (Fig. 4.1-1D). The scope of an inventory can range in detail from very elementary to quite complex; from a simple office study with limited staff to an extensive inventory involving a large amount of field work and investigations. What data should be collected depends highly on the objective and degree of detail of the inventory. Whatever the level of detail selected, the source inventory process should incorporate the basic steps in gathering and interpreting information as outlined below.

At the beginning of a contamination source inventory, it should be assumed that there are many potential contamination sources within the study area. An effort needs to be made to locate all the possible sources of contamination that lie within the area. Therefore, it is beneficial to compile a checklist of sources expected to be located within the study area (see example in Table 4.1). Although not all of the sources that are found will necessarily be a threat to groundwater, all sources need to be noted regardless.

The actual design of the inventory will primarily depend on the availability of data, which can range from a satisfactory amount of available data to almost nonexistent data. The best scenario would be a large amount of existing data. Then, no new information is necessary and the inventory can be done primarily by inspecting existing agency files and published material. However, data gaps and information needs probably will exist in certain areas and a limited amount of new data may have to be collected in areas where the available data are scarce. The worst scenario would be the complete lack of data, which would require the employment of a variety of inventory techniques, a field survey, or a hydrogeological investigation to collect new data.

An example of a simple scenario may include an inventory of possible sources of contamination within a proposed wellhead protection area (WHPA) for a medium-size, well- established community in an environmentally aware state/province. In this case, the size of the WHPA will be relatively small (several square kilometers) and all the necessary data may already be available in

TABLE 4.1 Example of a checklist for the inventory of potential contamination source

1 ____	Abandoned well	23____	Manure spreading
2 ____	Aboveground storage tank	24____	Mine tailing pile
3 ____	Agricultural fertiliser use	25____	Mining operation (gravel pit, quarry,open mine, underground mine)
4 ____	Agricultural pesticide use	26 ____	Natural source of contamination (identify): ______________________________
5 ____	Airport/air field		
6 ____	Animal feedlot or waste storage pit	27____	Municipal sewer
7 ____	Auto repair and/or body shop	28____	Oil or gas pipeline
8 ____	Cemetery	29____	Plastics manufacturing
9 ____	Cesspool, latrine, septic system	30____	Private well
10____	Chemical production or storage	31____	Production or other well
11____	Drainage or disposal well	32____	Salt water intrusion
12____	Dump	33____	Service or petrol station
13____	Electroplating/metal refinishing factory	34____	Sewage treatment plant
14____	Fertiliser/pesticide storage, mixing, loading, or production facility	35____	Spill site (chemical or waste)
15____	Hazardous waste site	36____	Stockpile (chemical, road salt, etc.)
16____	Industrial complex	37____	Storage tank farm
17____	Injection well	38____	Underground storage tank
18____	Irrigation system (agricultural, golf course)	39____	Urban fertiliser/pesticide use
19____	Junk yard/Salvage yard	40____	Wastewater lagoon/pond
20____	Land disposal/spreading of wastewater, sludge, or septage	41____	Well construction
		42____	Wood preserving facility
21____	Landfill (active or abandoned)	43____	Other (specify):
22____	Machine shop	_________________________________	

Note: Check the identified source off, locate it on the map using the corresponding number from the list above and a letter (A, B, …) denoting a unique location, and include the map number on the line next to the item number (e.g. 2 A, 16 A, B). Then fill in a survey inventory form for each source (see examples in Table 4.2 and 4.3).

the files of the local planning, engineering, health, or zoning offices; local library and historical society; and the state/provincial governmental agencies. The inventory task will then simply be an office study with limited staff (1–2 persons), consisting of collecting and analysing the available data. Examples of more complex inventories requiring more sophisticated inventory methods and field work are included in case studies of the state of São Paulo, Brasil and the city of Managua, Nicaragua (Chapter 8).

4.1.3 Organization of the inventory

A successful inventory requires attention to many administrative details. Inventories typically generate large amounts of data, which officials must collect, compile, and manage in an organized manner. (For a discussion of data management, see para. 4.5.) The staff responsible for conducting the inventory must be identified and trained. If volunteers are to be used for portions of the inventory, other staff must be identified or recruited to train them. It is particularly important that the inventory be well organized when volunteer workers are used. Officials must communicate accurately and clearly their goals and instructions on how to properly conduct the inventory to their staff. Failures in communicating instructions are a prime cause of implementation failures.

Each inventory should have a project manager or a group who is responsible for planning and management of the inventory, its implementation and evaluation, keeping the inventory within budget, and final products (maps and report). In the initial stages, the following steps should be taken:

- organize an inventory team;
- take care of team member training;
- select base map(s);
- compile a checklist of potential contamination sources for inventory staff (Table 4.1);
- identify sources of information and data, and compile a list of their addresses (both the mail and e-mail) and telephone numbers;
- select source identification method(s);
- prepare inventory forms (sample forms are included in Tables 4.2 and 4.3);
- order the necessary equipment and facilities (cars, computers, etc.);
- select data recording and processing system;
- appoint data base manager;
- discuss how the data will be presented;
- issue identification cards to all team members;
- notify local law enforcement authorities about conducting the inventory to avoid potential problems when people may be suspicious of strangers asking questions;
- secure landowners permission to enter their property.

The inventory team may consist of professionals and volunteers. Professionals with expertise would in particular be engaged in complex inventories requiring detailed field investigations. The use of volunteers available from various public service organizations and local interest groups should always be considered, especially when financial resources are a major issue in designing an effective source inventory program. For example, the city of El Paso, Texas, USA, implemented an inventory project that utilised community members through the local chapter of the Retired Senior Volunteer Program (RSVP). The RSVP is a national program administered by the national organization ACTION. Volunteers were trained by local officials to conduct field surveys within the community's wellhead protection area (WHPA). These volunteers completed this task successfully by collecting a vast amount of good information about what existed within the WHPA (U.S. EPA, 1991a).

An additional benefit of employing such or similar group of volunteers is the amount of anectodal information that they have regarding the historical land uses within their community. Their local knowledge may help in locating old petrol stations (underground petroleum storage tanks); old, abandoned wells (possible direct conduits for contaminants); abandoned industrial sites (chemicals used in production); or old, abandoned dumps or landfills, which may not be obvious or shown on any current map.

It is important to use a standardised form for the data collection from the very beginnings of the inventory. Two types of inventory forms may be needed: 1) a simple form for recording data from agency files, archives, literature, etc. (Table 4.2) and 2) a more detailed form for the on-site description of a source and potential problems (Table 4.3). If some kind of rating of contamination sources is aimed at (see Chapter 5), the necessary questions for this purpose must be included in the form. Tables 4.2 and 4.3 are general examples. For specific contamination sources or cases, a special form must be created.

TABLE 4.2 Sample form for office inventory

Source ID number ________________ Date of inventory ____________________

Map ID number ________________ Inventory person ____________________

INVENTORY FORM

Landowner/Company/Facility name ____

Address ____

Contact person ________________________ Phone number ______________

Type of property: Residential _____ Commercial _____ Industrial _____
Agricultural _____ Governmental _____ Other (Specify) _____

Potential contamination source

Type ____

Areal extent ____

Unregulated/regulated by ____

Material(s)/Waste used/stored/disposed (check one)

Type ________________________________ Quantity ________________

History of any releases or contamination incidents ________________________

____

Source of information: Agency file _____ Archives _____ Literature/report _____

Name ____

Address ____

Contact person ________________________ Phone number ______________

TABLE 4.3 Sample survey form

Source ID number ________________ Date of site visit ____________________

Map ID number ________________ Inventory person ____________________

Location: coordinates____

how determined (topo map, surveying, GPS) ___________________________

distance from roads and dwellings _____________________________________

SURVEY INVENTORY FORM

Landowner/Company/Facility name ____

Address ____

Contact person _____________________ Phone number _______________

Physical setting of the site ____

Number and location of contamination sites _______________________________________

____

Description of contamination source(s)

Type ____

Characteristics/Appearance ____

Maintenance/Operation ____

Description of contaminant(s)

Type ____

Amount ____

Nature of release ____

Protective measures/controls ____

Apparent problems ____

History of any discharges or contamination incidents ______________________________

____

Area(s) affected by contamination ____

Remediation efforts ____

It is strongly recommended that the decision be made at the very outset of planning the inventory how the inventory data will be organized, managed, and presented. If the collection of inventory data is carefully planned, the conversion to a mapped representation (Chapter 6) needs the minimum of interpretation. Therefore, cooperation of the inventory team and the map-making team is an important part of the inventory process (see Fig. 6.1).

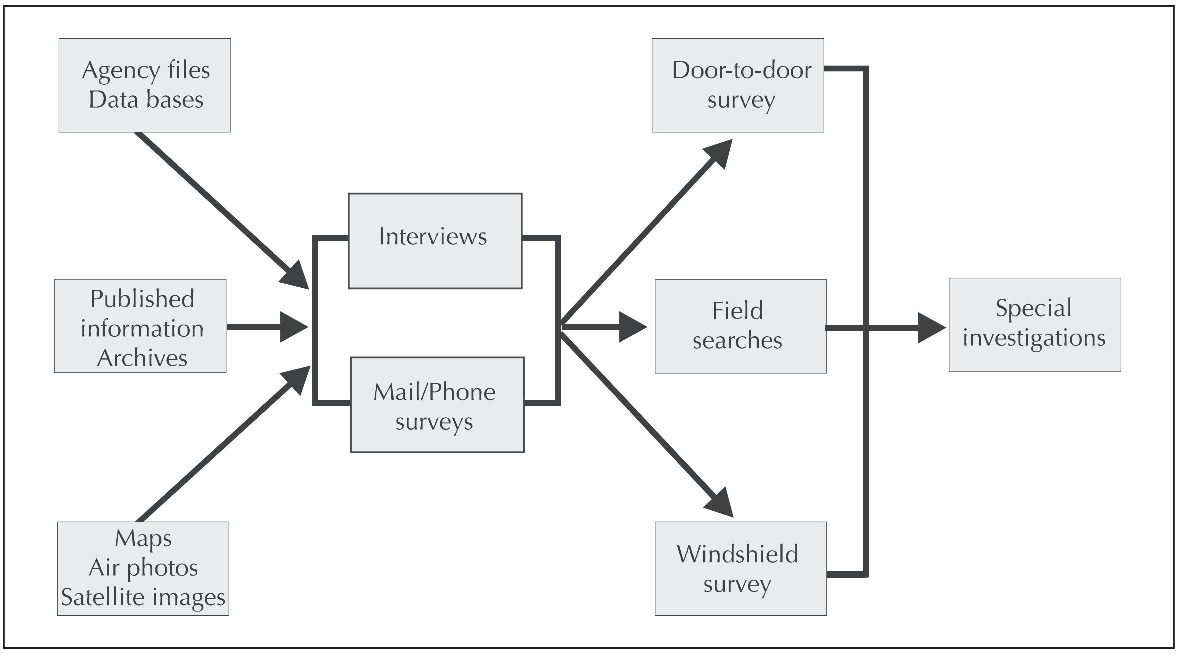
Budgetary concerns are also important. As noted above (para. 4.1.2), the design of inventory involves a consideration of the amount of resources available to conduct the inventory. During the inventory process, the project will require supervision in order to keep it within budget. The calculations of a source inventory budget must take into account the expenditure of resources required to set up and maintain the inventory data management system, as well as to conduct the inventory and produce final products (maps, reports, etc.).

4.2 Source identification methods

The implementation of a contamination source inventory requires not only careful, advance planning, but also appropriate selection of one or more of source identification methods. A thorough source inventory can be conducted in a progression of steps, using the simpler methods during the first steps and the more costly and labour intensive methods in the later steps (Fig. 4.2). The importance of the different steps will depend on the objective, scale, and degree of detail of the inventory; number and type of contamination sources; availability of data; competence of staff; and budgetary constraints.

The identification of contamination sources means to find and locate them, and is necessary for all kinds of inventories regardless of their purpose and scope. Various methods used for this purpose are outlined in paras. 4.2.1 and 4.2.3. The description of the identified sources is a detailed process and the methodology used will vary widely depending on the purpose, objective, and scope of the inventory.

FIGURE 4.2 Sequence of methods used for source identification (*Adapted from:* U.S. EPA, 1991a)



4.2.1 Office identification of sources

The first phase of the source identification process is largely an office (file) study. Much of the information on contamination sources probably may already be available, but in scattered locations. Availability of data sources will depend on the legal and institutional framework, dependence on groundwater for water supply, degree of development, tradition, etc. The quantity and quality of available information as well as the accessibility to this information may vary substantially.

(i) Custodians of information on existing contamination sources

A substantial amount of information on existing contamination sources may be found in the form of routine records or documents recorded or assembled in the day-to-day operations of agencies at various levels of government (local, regional, state, provincial, or national). These agencies also may have inventories of and statistics on potential contamination sources or files with permits issued for potentially contaminating discharges or activities. Examples of such agencies are the environmental, health, sanitation, planning, and water agencies. Other possible organizations with useful data include:

- water supply companies and organizations;
- geological survey organizations;
- research institutions;
- consulting companies;
- resource exploration companies;
- statistical and census authorities.

Information documenting past and present land uses also may be maintained at the local level. This information is primarily of three types: 1) local registries of commercial and industrial activities; 2) property transfer records, titles, and deeds; and 3) historical perspectives, such as revised and updated ('before-and-after') air photos and interviews of or statements from senior citizens living in the area for long periods of time, including verification of anecdotal evidence ('storytelling') related to past activities in the area that could be a source of contamination.

Important information can be obtained by literature and historical searches. Sources of information may be the published studies in literature, unpublished studies conducted by consulting companies or research institutions, unpublished theses of university students, records or historical documents in archives, maps, air photos, or satellite images.

Remote sensing from aircraft or satellite is a valuable tool for the identification of sources in areas of scarce data or for screening large areas for follow-up investigations. Air photos and satellite images can be useful particularly for surveying large geographical areas or areas that are not easily accessible on foot or by vehicle. Air photos can be found in files of geological survey organizations, soil survey organizations, and topographic map-makers or in the local historical archives. The newer remote-sensing, satellite-vectored systems (e.g. LANDSAT, SPOT, or IKONOS) carry relatively high resolution devices that give magnifiable images. Particular land uses identified from the air photos or satellite images can be checked against the list of potential sources to determine if they merit additional consideration. A review of updated air photos and satellite images should be performed to develop a historical perspective of the changes in surface features of a given area and to reveal new locations of sources or activities that may contribute to groundwater contamination. Remote sensing is especially valuable when land use maps do not exist or when these are old. Urban development and changes in agriculture (areas, crop rotation, etc.) and wetlands or forested lands are typical examples of information that can be obtained from remote sensing.

(ii) Custodians of information on potential sources of contamination

Information on the potential sources of contamination (see Chapter 3) usually is more difficult to gather. Potential data sources and their custodians for the following contamination sources are listed below:

- Agricultural and forestry practices

  Governmental agricultural units, farmer organizations, fertiliser and pesticide distributors (statistics on crops, livestock, animal waste storage facilities, fertilisers, pesticides, and permits issued for specific activities and practices).
- Urbanisation

  Urban planning, water, sanitation, environmental, and health agencies; waste management companies; and local fire brigades (solid waste disposal, sewage systems, on-site sanitation, wastewater storage and treatment, and underground storage tanks).

- Mining and industrial activities

Planning and environmental agencies (mine tailings, acid mine water, wastewater effluent, disposal and injection wells, and spills and leaks); branch organizations (solid and liquid waste); and industry owners (records and files on storage and handling of waste and hazardous materials).

- Transportation

Governmental departments of transportation or environmental protection (statistics on traffic and transportation of hazardous materials, spills of hazardous materials, road salting, and salt storage) and public utilities (oil and gas lines).

(iii) Spatial extent of existing groundwater contamination

Conceptually, the contaminated groundwater consists of two distinct parts (NRC, 1994): 1) contamination source area and 2) the plume of dissolved contaminants. The contamination source covers a small area relative to the plume of contamination, which extends far beyond the source area. In many cases, information gathered during the office phase of the inventory would be insufficient especially for the assessment of the extent of contamination in the subsurface, and field investigation would be necessary for proper site characterisation (para. 4.4.2).

The extent of existing groundwater contamination should be clarified especially around the suspected natural and anthropogenic sources of contamination or in heavily industrialised areas. Many governmental agencies are charged with groundwater quality control, e.g. for public and private drinking water supplies and for control of compliance with groundwater quality regulations. They may have on file the results of mandatory monitoring around regulated contamination sources (e.g. landfills) or of monitoring on water quality observation networks. They also may be involved in collecting and documenting incidents of groundwater contamination. Consulting companies and research institutions may have valuable information from specific investigations or research projects. Typically the files may include information on (potential custodians are indicated in parentheses):

- areas with naturally contaminated groundwater due to the mineral composition of the aquifer material, e.g. arsenic, fluoride, radionuclides (geological surveys, natural resource agencies, environmental protection agencies, water authorities, water supply companies).
- areas affected by diffuse contamination sources, such as leakage of nutrients and pesticides from arable land or acidification from atmospheric deposition (agricultural, environmental, and health agencies, water authorities, water supply companies).
- extent of point source contamination from agricultural activities, e.g. inadequate manure, fertiliser, or pesticide storage and handling (agricultural and environmental protection agencies).
- areas of contamination spreading from potential contamination sources, such as waste disposal sites, wastewater treatment plants, mine drainage, and industries handling hazardous materials (environmental protection agencies).
- spills of hazardous materials and leaks from tanks storing chemicals, e.g. location, amount, and type of spilled substance; attempted cleanup measures; estimated release of contaminant(s) into groundwater or the environment (environmental protection agencies, governmental departments of transportation, fire brigades).

It should be also noted whether the contamination is a) an integral design feature (for systems or activities designed to discharge waste or wastewater to the land or groundwater); b) incidental (in case of industrial accidents, technology failures, and spills during traffic accidents); c) accidental (such as carelessness, mismanagement, or poor operation); or d) intentional (involving illegal dumping of waste or hazardous materials).

4.2.2 Refining the design of the inventory

The initial information-gathering phase of the source inventory may have a number of results in terms of existing and potential contamination sources or contamination. In most cases, however, it is likely that existing data and information will simply indicate that the source or activity may be (or may become) a problem. At this point, the original goals of the inventory should be re-examined and the design revised to reflect the findings. The purpose and objectives of the inventory must be kept in mind. The re-design of the inventory has to be a trade-off between the purpose and objective of the inventory, number and type of contamination sources, and financial and personnel resources (U.S. EPA, 1991a). An evaluation of possibilities to reach the original goal of the inventory within financial limitations must be carried out. If it is not possible to reach the goal, it needs to be determined what partial results can be reached and what would be the additional cost to reach the original goal. Preliminary classification and ranking of identified contamination sources (para. 4.3.2) in terms of their impact on groundwater will help decide whether partial results are adequate or inadequate.

4.2.3 Field identification of sources

After completing the office phase of the inventory (para. 4.2.1), investigators will likely have identified most known sources of contamination or incidents of groundwater contamination, i.e. sources and contamination incidents that are already known to authorities or that are available in published literature or historical records and in files or data bases. If this information is not sufficient, additional data and information must be collected in the field. The need for additional information should be carefully assessed and additional means of obtaining this information selected (Fig. 4.2). These additional steps in the inventory process will help identify information on sources that were unknown due to oversight, lack of regulatory controls, or lack of concern. Collecting information on unknown sources generally requires some type of direct contact with landowners as they are likely to be the only ones who know about a source. This contact can be in the form of personal interviews or surveys (mail, phone, or door-to-door).

Although interviews and surveys are a relatively straightforward means of identifying potential contamination sources or contamination incidents, they are subject to certain deficiencies. For example, data obtained through mail and telephone surveys or personal interviews may be tainted by response bias (U.S. EPA, 1991a). People who have an interest in responding to surveyors' questions will respond adequately, but those who feel they may be affected adversely by the results of the survey will not respond in full. Another problem is that a survey will be only as complete as its list of contacts. For example, if the list of addresses for a mail survey includes only residences and not commercial or industrial facilities, a large sector of potential contamination sources may be missed. Conversely, a list of only commercial establishments could miss such potential sources as public works garages or many private-home activities.

Therefore, the interviews and surveys may be complemented by field inspections and searches of some or all of the area being inventoried. Field inspections allow the inventory staff to look at the inventory area themselves to determine if potential sources are present, without relying on landowners to identify and provide information about sources. The field inspections usually include field searches or windshield surveys (i.e. vehicle-based surveys).

Probably there would be no need to conduct all of these methods – interviews; mail, phone, and door-to-door surveys; and field inspections (Fig. 4.2) – as this would gather a large amount of repetitious information. The choice of a particular configuration of methods will depend on the resources available for the inventory. If resources are not available for some of the more labour intensive methods (e.g. surveying all landowners and businesses in a given area), various means may be used to reduce the efforts without losing their value (e.g. pare down the survey contact list or area). Also the use of volunteer organizations or local public service groups should always be considered when resources are a major issue.

(i) Interviews of key persons

Personal interviews are an extremely valuable source of information. Interviews could be scheduled with various local officials, health inspectors, facility managers or operators, area business people, farmers, local interest groups, and long-term residents. Local officials can often supply names of other contacts. The advantage of conducting personal interviews is that a large amount of useful information may be obtained that is not available from any other sources. It may, however, require several contacts to find the most helpful people to interview, and a fair amount of time may need to be spent making preliminary contacts. It is important to clearly explain the purpose of the inventory, the need for information, and the value of the information that can be supplied by the interviewed person (U.S. EPA, 1991a). Understanding and trust is the basis for the possibilities to obtain reliable information.

(ii) Questionnaires

Mail and phone surveys have the advantage of reaching a large number of people at relatively low cost and of obtaining information on sources that were previously unknown. Addresses and phone numbers can be obtained from a number of sources, e.g. telephone directories, tax assessor's lists, utility records, voter registration lists, real estate registers, or permit applications. Questionnaires should be simple and clear and the questions asked should be adapted to the anticipated level of knowledge of the target group. Contact by phone before and after the distribution of questionnaires is necessary. The direct contact with the public, which is involved in conducting these types of surveys, can also promote public education about the potential for groundwater contamination. One of the possible means is advertising in local newspapers. Media involvement can increase the survey response rate by preparing the public for the survey and explaining its purpose.

(iii) Door-to-door surveys

These surveys generally involve canvassing the residences, businesses, and industries within the inventory area to determine the activities and materials that exist in the area of concern. Their design can be much like the design of mail/phone surveys, although it can be far more extensive (U.S. EPA, 1991a). Their advantages include the accuracy and uniformity of data, the opportunity to promote public education about groundwater contamination, and the likelihood of identifying previously unknown sources. However, door-to-door surveys are time-consuming and require a staff of trained surveyors or volunteers. These surveys are particularly suited for relatively small study areas.

(iv) Field searches

Field inspections and searches are conducted much like door-to-door surveys and require the same amount of planning, but often require more time to complete. They consist of an extensive foot survey of an area, and are often used when a particular situation calls for a detailed inspection of land uses or specific sources. Much like door-to-door surveys, field searches can be costly and labour intensive and are best used in relatively small areas.

(v) Windshield (vehicle-based) surveys

Windshield surveys can be conducted in much less time than field inspections and searches and can be effective in areas where most of the sources can be located from the road. To conduct a windshield survey, the surveyors obtain detailed maps of the study area and drive through all or parts of the area by automobile, recording the potential sources of contamination that they observe through windows. Conducting a windshield survey requires a vehicle and preferably two people (driver and observer). The windshield surveys are less time-demanding and less labour intensive than field searches and can identify a large percentage of potential contamination sources in an area. They are more difficult to conduct and less effective in rough terrains or some rural areas where many sources will not be visible from the road (U.S. EPA, 1991a).

4.3 Preliminary evaluation of results

After the field phase of the inventory, another assessment, and eventually revision, of the original goals of the inventory should be undertaken (see para. 4.2.2.). If the need for further data is suggested in the assessment, a decision should be made whether the value of the new information would justify additional expenditures for gathering the information. Collected data should be verified, and the identified contamination sources classified and ranked.

4.3.1 Verification of data

After a carefully conducted inventory, the assembled data should be verified and evaluated. The data should be considered in terms of quality, accuracy, uncertainty, and reliability. The best way to assure accuracy of information gathered during contamination inventories is to 'ground-truth', or field check, the assembled data. In the case of air photos of early or unknown age, updating photo files is an accurate (but costly) option. Follow-up telephone confirmation is inexpensive, and can be used to verify mail survey questionnaire information. Telephone confirmation also can be useful where access to a property or facility is denied (e.g. for purposes of national security), or where the facility or activity is unmanned (e.g. remote oil-well pumping stations).

Information gathered by personal interviews can also be verified by an actual site visit. Field checks and interviews are important for the confirmation of questionable data or for obtaining additional information on important or potentially important contamination sources and on existing contamination, where uncertainties prevail. If the contamination sources or contaminating activities are regulated and controlled by a governmental agency, this agency should be informed and should, if feasible, be used as a backup when contacting land/facility owners. Sometimes it is difficult to get permission for inspections without such backup.

4.3.2 Preliminary classification and ranking of contamination sources

Based on existing data and gathering of additional data and information using the means described above, a preliminary classification and ranking of contamination sources should be made before deciding on the next, more time-consuming step of the inventory: field investigations. The purpose of the preliminary classification and ranking is to establish the basis for prioritisation of field investigations according to the importance and level of concern of contamination sources and to the need for verification of reliability and accuracy of data. The classification of the identified sources could be preferably arranged as an organizational procedure where the contamination sources are divided into groups. Various classification schemes are discussed in Chapter 3.

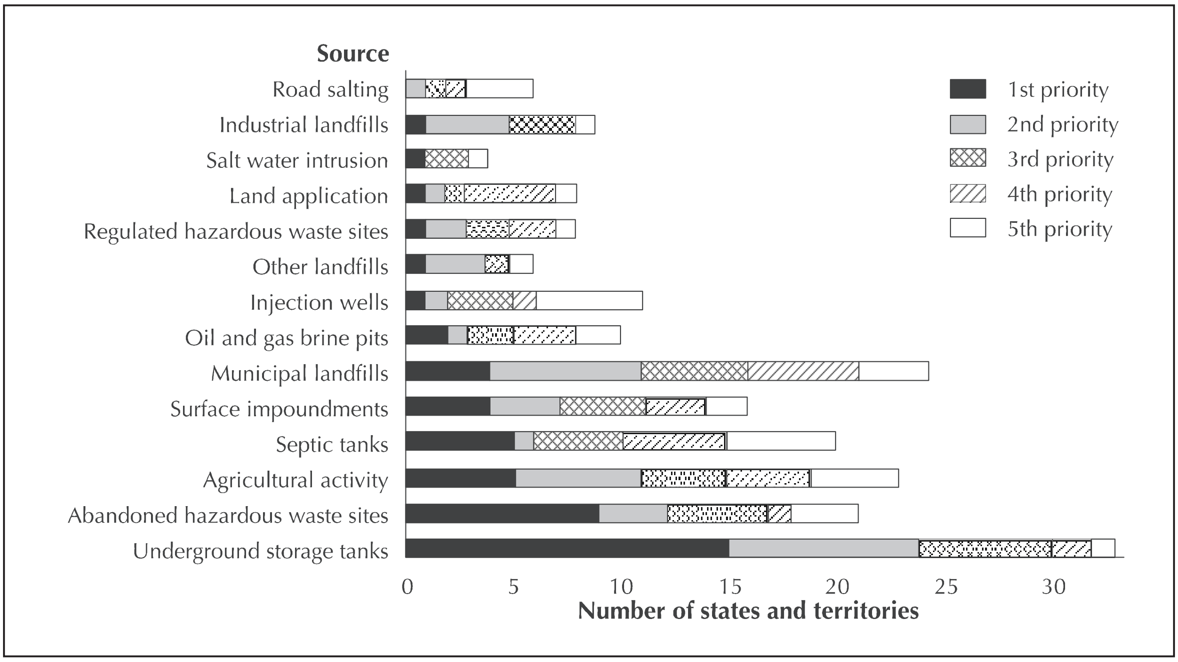
Although there are many potential sources of groundwater contamination, some pose much more of a threat to groundwater than others. For a preliminary estimate of the contamination threat, the identified contamination sources may be ranked according to their impact on groundwater determined by any of the general-approach rating methods listed in Chapter 5. Results of the preliminary ranking can be used for prioritising field investigations and detailed site specific studies. The degree of the level of confidence (para. 5.3.3) should be used together with the ranking of importance and level of concern of the contamination source for the final prioritisation of field investigations.

An example of priority rankings of contamination sources in the United States is shown in Fig. 4.3. These priority rankings are taken from the 1988 reports submitted to the U.S. Environmental Protection Agency by the states on the sources of groundwater contamination and the type of contaminants observed (U.S. EPA, 1990). The states could give a priority ranking from 1 to 5 (1 being the highest priority) for the various contamination sources.

4.4 Field investigations

Field investigations are the last, most costly and time-consuming methods of a contamination source inventory. They may be needed primarily for the studies of probable naturally-occurring contamination sources and for a detailed description of the known important anthropogenic contamination sources (e.g. heavy industries or mining activities). Other goals may include the field verification of data collected during the inventory, the design of a monitoring network for defining the extent and direction of movement of a contaminant plume, or the quantification of contaminant loading from a known source.

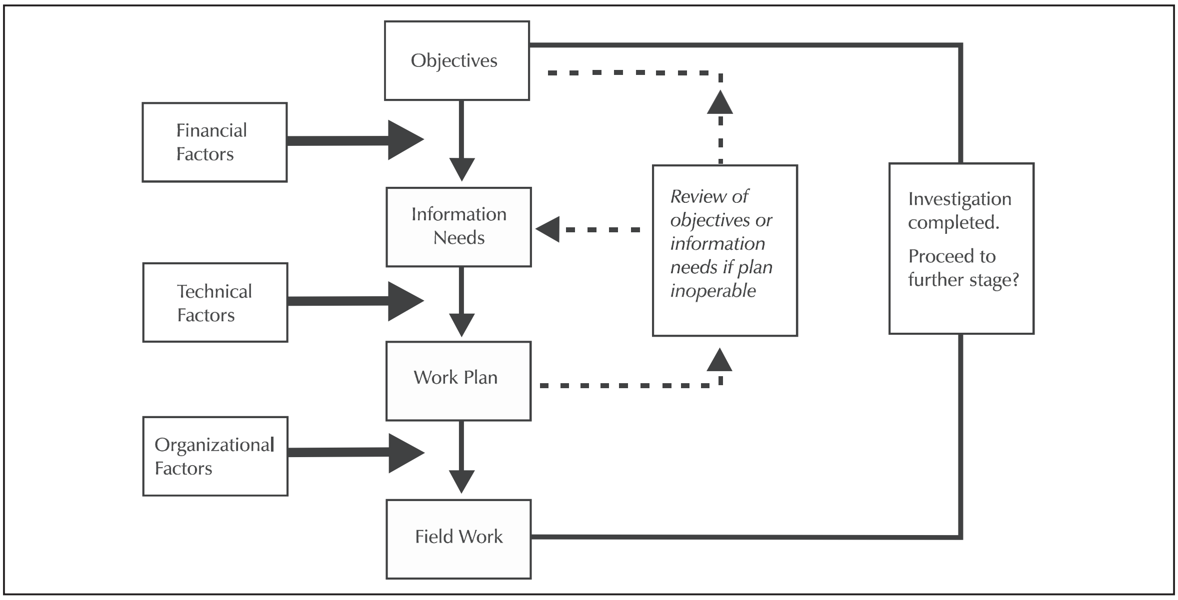
FIGURE 4.3 Priority ranking of contamination sources considered by more than ten states and territories of the United States to be a major threat to groundwater quality (*Source:* U.S. EPA, 1990)



4.4.1 *Planning the investigation*

The plan must be well-conceived and practically achievable. Although each investigation is unique and the detailed design of an investigation will be dictated by its specific purpose, general guidelines need to be followed for all of them (Fig. 4.4). The investigator must first clearly define the objectives and scope, review the existing data and previous studies, determine information needs (purpose of investigation), develop a work plan and time frame, specify the technical and personnel needs, and prepare a budget. Other common elements of field investigations include field work, laboratory analyses, data interpretation and conclusions, and report preparation and recommendations. A balance must be struck between the data demands and the financial, technical, and organizational factors involved (Fig. 4.4).

FIGURE 4.4 A framework for field investigation planning (*Adapted from:* Skinner, 1983)



(i) Objectives

The planning process begins with the definition of objectives (Fig. 4.4). Establishing objectives is essential to a successful and cost-effective investigation. The objectives will vary widely depending on the type of investigation, as described above, but they are always necessary to ensure that the correct information needs are identified (Skinner, 1983). The objectives will also determine the complexity, time span, and cost of the investigation. All interested parties should clearly agree upon these objectives.

(ii) Review of existing data

As much information as possible should be reviewed in order to determine information needs and effectively plan the field work. This includes inventory data, information on site history, site specific knowledge of geological conditions (which control the site groundwater flow and contaminant movement), and information on contaminant characteristics (type and concentration, and type, amount, and rate of release). Possible sources of information are:

- inventory forms and other documentation;
- published reports and maps about soils, geology, and hydrology of the area;
- unpublished data in agency and organization files, such as well logs, water level measurements, or water quality monitoring;
- air photos (especially important in fractured rock terranes).

(iii) Work plan

A work plan provides the overall administrative framework for an investigation and should be responsive to the defined objectives, using existing data and information to the fullest extent possible. The work plan should specify the technical needs, equipment, methods and techniques of investigation, necessary personnel, and data recording system. Unlike the goals and objectives of the investigation, which are fixed, the work plan needs to be flexible. For example, the position of test wells or sampling points cannot entirely be determined at the start of an investigation.

Significant financial savings can be achieved by attention to the structure of field work (Skinner, 1983). Investigations carried out in stages, with an opportunity for data analysis between stages, will have the benefit that the design of later stages can be refined according to results gained from the first stage, which usually is the most intensive and important part of the investigation.

(iv) Resources needed

Before any work begins, the investigator must determine the number and qualifications of staff required to accomplish the tasks and determine the types of services and equipment needed to execute the field work. Any outside services needed, for example drilling, should be scheduled to ensure that a drilling contractor will be available when needed. Laboratories should be alerted to expect samples for analyses. Support services, such as computer work, cartography, or GIS processing should also be specified and reserved.

(v) Budget

There is very little information on the way in which budgets for investigations are set or on any objective assessment of how objectives may be compared with costs (Skinner, 1983). A budget should be set realistically, with the objectives and information needs in mind. The budget includes a breakdown of anticipated costs for each activity. This budget then specifies the level of staff effort and other resources that need to be used to complete the required work.

A high, and often ignored cost of field investigations is the operational cost. A large part of this cost is in manpower time. Any methods that can be used to improve the productivity of manpower, particularly if at the same time they can reduce human error, should be adopted. The most expensive single element of the budget normally is borehole drilling, and any means of reducing this without unreasonably compromising on the informational needs will provide additional resources for other parts of the program. Full use should be made of existing boreholes and it will often be worthwhile rehabilitating unused boreholes to contribute to the investigation.

(vi) Field work

The investigator is responsible for getting people and equipment to the site for field work. This always involves numerous logistical considerations and problems, such as site access, borehole and well permitting, site clearance, and the execution of the work within the time and budget limits. These can have a direct bearing on the success of the investigation.

Site access and permits needed for subsurface work are usually combined tasks because they precede the actual field work. Often, well installation permits may be required by the local regulatory agency, which may want to review and approve the well installation prior to starting work. Other access permits may be required by local laws and regulations (e.g. encroachment, public easements, or right-of-ways), which can require letters of authorisation or fees. Site clearance involves identifying overhead and buried utility lines, which must be marked to avoid costly repairs and to prevent injury for the field crew. Also great care must be given to reduce ecological damage to a minimum.

(vii) Data collection and analysis

The data recording system should be specified in the work plan. Even a moderate-to small-sized site, a limited-scope investigation can result in the collection of a great amount of data. In order to avoid the time loss and frustration during data interpretation, the amounts and types of data should be anticipated early in the investigation planning. Provisions should be made for the continuous input of collected data as the work progresses. The use of computers greatly facilitates data processing, and a work plan should include specifications of the data handling system (para. 4.5). To ease report preparation, the graphic displays and maps needed for reports should be anticipated and provided for in the work plan.

4.4.2 Site characterisation

Characterisation of sites with groundwater contamination is a very important part of field investigations because it will determine the extent and nature of contamination and help select the type of remedial activities and the costs associated with them (NRC, 1994). Site characterisation consists of investigation of the 1) nature, extent, and distribution of contaminants; 2) potential receptors and risks posed by contaminated ground water; and 3) hydrogeological and contaminant properties. Site characterisation has two major components: 1) assessment of the groundwater flow system and 2) assessment of contamination in the groundwater (U.S. EPA, 1991b).

For the groundwater flow system assessment, a broad description of the hydrogeological setting (the stratigraphy, lithology, and continuity of aquifers) is required. Hydrogeological data to be collected include the depth to groundwater and its fluctuations, hydraulic properties of aquifers (porosity, hydraulic conductivity, and hydraulic gradients), aquifer boundary conditions, rate and direction of groundwater flow, and groundwater recharge and discharge. Hydrogeological characterisation methods are usually most successful when used in conjunction with one another. These methods may include drilling, surface and borehole geophysical measurements, aquifer tests, tracer tests, and other methods, as described in para. 4.4.3.

Important goals of contaminant characterisation include: 1) delineation of contaminant source areas and characterisation of the nature of releases; 2) determination of the nature, concentration, and extent of contamination, both in the horizontal and vertical direction; and 3) characterisation of contaminant transport pathways, processes, and rates (NRC, 1994; U.S. EPA, 1991b). Contamination source areas and downgradient contamination plume areas (para. 4.2.1 *(iii)*) should be delineated early during the characterisation process to clarify site remediation strategies (see Chapter 7). A brief outline of techniques that can be employed for contaminant characterisation is presented below.

4.4.3 Investigation techniques

Well-executed field work is the key to obtaining reliable and good quality data needed for an understanding of the basic geology and hydrogeology of the site and of the types of contaminants and their behaviour in the subsurface. Techniques that can be used to accomplish the objectives of the investigation include, among others, site reconnaissance, drilling, borehole and well testing, groundwater sampling, and field measurements and tests. This chapter provides only an overview of the available techniques. For details, the reader is referred to standard texts, such as *Soil, vadose zone, and ground-water contamination* (Boulding, 1995), *Groundwater and wells* (Driscoll, 1986), or *Principles of contaminant hydrogeology* (Palmer, 1996), from which this overview was prepared.

(i) Site reconnaissance

As a precursor to more expensive techniques, a quick and relatively inexpensive reconnaissance can help obtain preliminary data needed for the location of test boreholes, monitoring wells, and sampling points. Several approaches can be used: geological mapping, geophysical survey, soil vapour sampling, and shallow groundwater sampling.

Geological mapping indicates consolidated and unconsolidated materials in the area being investigated. The maps show the rock types and the distribution of geological structures. Geological mapping can also be used for a specific purpose; for example, for the identification of geological materials that may contain potentially contaminating substances.

Geophysical surveys can help investigators characterise the site conditions and contamination (Zohdy et al., 1974). Geophysical techniques are rapid and non-disruptive to the site, and less expensive and less time-consuming than drilling. The following five techniques are commonly used in groundwater investigations: ground-penetrating radar (GPR), electromagnetic conductivity (EM), electrical resistivity (ER), seismic refraction (SR), and magnetometry (MM) (Table 4.4).

New geophysical exploration techniques are being introduced all the time. For example, a relatively new technique is the nuclear magnetic resonance (NMR), also referred to as magnetic resonance sounding (MRS), which is used to determine water saturation directly with depth in unconfined or semi-confined aquifers to depths of approximately 100 m (Roy and Lubczynski, 2000).

Soil vapour sampling is one of the 'newer' reconnaissance techniques used to locate and sample volatile contaminants (Boulding, 1995). It is accomplished by pushing a thin-wall, small-diameter tube into the subsurface (generally 1.5 to 3 m, and up to 6 m), above the water table, using a one-way drive point. Once the desired depth is reached, the tube is pulled back slightly

TABLE 4.4 Application of surface geophysical techniques in groundwater investigations

Application	*Geophysical technique*				
	GPR	*EM*	*ER*	*SR*	*MM*
Changes in stratigraphy and lithology		•	•	●	
Depth to bedrock			●	•	
Fracture detection	•	●	•		
Karst features (cavities, sinkholes, etc.)	●	•			
Depth to water table			●	•	
Detection of plumes		•	●		
Location of buried objects (drums, UST, etc.)	•		•		●
Location of buried pipes	●	•	•		•
Location of abandoned wells	•				●

Note: ● primary technique, • secondary technique.

and the vapor in the tube is evacuated to induce soil vapour to fill the tube. A sample is drawn into a syringe to transfer it to a portable gas analyser or to a laboratory.

Shallow groundwater sampling is a powerful tool for rapid assessment, especially in difficult locations, such as in roads or alleys or in buildings. Essentially, it is a variant of the soil vapour technique. A thin-wall tube is pushed to the water table and slightly below it. A sample is collected and analysed either in the field or in a laboratory. Although deep penetration is possible, the recommended maximum depth is about 5 to 8 m depending on sediment type (Palmer, 1996).

(ii) Drilling

A number of drilling techniques are available for subsurface exploration and monitoring. There is no universal drilling technique applicable for all subsurface conditions and well installations. In most cases, the drilling contractor is best qualified to select the particular drilling procedure for a given set of parameters. However, the investigator should have a strong working understanding of the drilling techniques in order to stay within given time and budget, especially if unforeseen problems occur. Basically, three techniques are commonly used: auger drilling, rotary drilling, and cable-tool drilling (Driscoll, 1986). Their principal characteristics are summarised in Table 4.5. The most common are auger drilling (for shallow holes) and rotary drilling (for deeper holes). Although cable- tool rigs are used less commonly in developed countries, they are still widely used in many parts of the world.

TABLE 4.5 Principal test drilling techniques (*Source:* Driscoll, 1986)

Drilling technique	*Common depth (m)*	*Geological material*	*Formation sampling capability*	*Drilling speed*
Auger drilling	15–45	Unconsolidated	Reliable samples	Rapid penetration
Rotary drilling (hydraulic or air)	100+	All types	Representative samples relatively difficult to collect	Fairly fast penetration
Cable-tool (percussion) drilling	20–100	Unconsolidated, caving formations, hard rock	Good samples	Slow penetration

(iii) Borehole and well testing

Geophysical borehole logging is usually carried out after collecting the soil and rock samples for determining lithology. The logs aid in filling the gaps between intervals of sampling and in revealing fine details of the subsurface strata. Geophysical logs also can be used to estimate hydrogeological characteristics. Most of the geophysical logs are done in the open uncased borehole. Only rarely is a single logging method used. Multiple logs provide more information than individual logs, and many logs require other logs for interpretation. The logs are usually made as pen-and-ink strip charts. This gives a continuous record, which is most useful. Interpretation of logs requires considerable training and skill. From the many borehole logging methods available, six are of major use in groundwater investigations (Table 4.6).

Hydraulic conductivity of a formation is an important aquifer parameter needed in many contamination studies. Normally, hydraulic conductivity can be determined by a pumping test, when the water level is measured prior to starting the pump and its drawdown during the pumping. In wells drilled into formations with low permeability or equipped with small-diameter casing, a so-called *slug test* can be performed. During the test, the response of water levels in wells

TABLE 4.6 Major borehole geophysical methods used in groundwater investigations and their application (*Source:* Boulding, 1995; Palmer, 1996)

Logging method	*Hydrogeological application*
Resistivity (normal or single-point)	Generally determine the character and thickness of the various strata; identify porous (sand) sediment; indicate water quality and possible contamination.
Spontaneous potential (SP)	Distinguish clay/shale and sand/sandstone lithology or fresh and brackish water.
Natural gamma (in both uncased and cased holes)	A qualitative guide for stratigraphic correlation and permeability or for estimating rock type.
Caliper	Measure the borehole diameter; determine casing depth; locate cavities; indicate joints in carbonate aquifers.
Flow meter	Determine source and movement of water in a well (especially, fractures producing water and zones of high permeability); locate intervals of leakage in artesian wells; trace casing leaks or plugged screen.
Fluid temperature	Trace the movement of the water injected into an aquifer and the dispersion, dilution, and movement of contaminants.

to adding or removing a volume of water is measured. The response can be interpreted in terms of hydraulic conductivity, using various methods, such as Bouwer-Rice (1976), Cooper-Bredehoeft-Papadopulos (1967), Hvorslev (1951), and Nguyen-Pinder (1984).

Pumping tests to determine the capacity of an aquifer to yield water usually are not performed in contamination studies. However, they do produce more accurate results than the slug or bailer test methods. If they are needed, their description can be found in groundwater hydrology textbooks (e.g. Driscoll, 1986; Fetter, 1994).

(iv) Groundwater sampling

Groundwater sampling is one of the most important tasks performed during a contamination investigation. Well sampling provides the geochemical and contaminant chemistry information for the problem under consideration. Together, the borehole log and the water quality information provide the two basic sources of observed subsurface data.

There are two fundamental considerations that are common to most groundwater quality sampling programs: 1) the establishment of individual sampling points (i.e. in space and time) and 2) the elements of the water sampling protocol (Barcelona et al., 1987).

The placement and number of sampling points will depend on the complexity of the hydrogeological setting and the degree of spatial and temporal detail needed to meet the information needs. It is better to start with fewer points and a low sampling frequency. The placement and number of sampling points can be phased to gradually increase the scale of the monitoring program.

Usually, a sampling plan and procedures, commonly called the *sampling protocol*, are prepared prior to field investigations. A sampling protocol may be given by government guidance documents or it may be written specifically for a given investigation type or contaminant type. Generally, the sampling protocol would address:

- water level measurements made prior to sampling;
- well purging (the volume of stagnant water that should be removed from the well or borehole);

- sample collection, preservation, and handling;
- quality assurance and control;
- sample storage and transport;
- chain-of-custody record.

Representative sampling is the result of the execution of a carefully planned sampling protocol, well-trained staff, and good field-laboratory communication. A representative water sample may be defined as: 'a minimally disturbed sample taken after proper well purging, which will allow the determination of the chemical constituents of interest at predetermined levels of accuracy and precision' (Barcelona et al., 1987).

A wide variety of devices and installations are available for the sampling of groundwater (Weaver, 1992). They can be broadly classified as portable well samplers (used in permanently installed and screened wells) and in-situ samplers, which do not require cased monitoring wells (Boulding, 1995). Portable samplers include either suction devices or non-suction devices (Table 4.7). Schematic diagrams of the most commonly used portable samplers are shown on Fig. 4.5.

In-situ sampling probes are relatively new devices, which are either portable, used for rapid collection of samples without the installation of permanent wells, or left in place for continued monitoring. In monitoring wells, dedicated (left-in-place) sampling equipment can be used to minimise the potential for cross-contamination of samples between wells as well as the amount of equipment cleaning needed between wells. Dedicated sampling equipment is installed in a well and is used only for sampling that well. The initial purchase of dedicated sampling equipment for each well is more expensive than buying one portable equipment for an entire site. However, the time and money spent moving and cleaning equipment would be greatly reduced.

TABLE 4.7 Commonly used groundwater sampling devices (*Source:* Boulding, 1995; Lindorff et al., 1987)

Sampling device	*Min. well diameter (cm)*	*Max. sampling depth (m)*	*Sample delivery rate (l/s)*	*Potential for chemical alteration*	*Ease of operating and maintenance*
Suction devices					
Peristaltic pump	1.3	8	0.15–125	Slight-moderate	Easy
Centrifugal pump	2.5	5	15–400	Moderate-high	Moderately difficult
Non-suction devices					
Bailer	1.3	Unlimited	Variable	Slight-moderate	Easy
Bladder pump	3.8	120–300	8–50	Minimum-slight	Easy
Gas displacement pump	2.5	90	2–160	Moderate-high	Easy
Syringe sampler	3.8	Unlimited	3	Minimum-slight	Easy
Electric submersible pump (helical rotor)	5.1	60	8–25	Slight-moderate	Moderately difficult

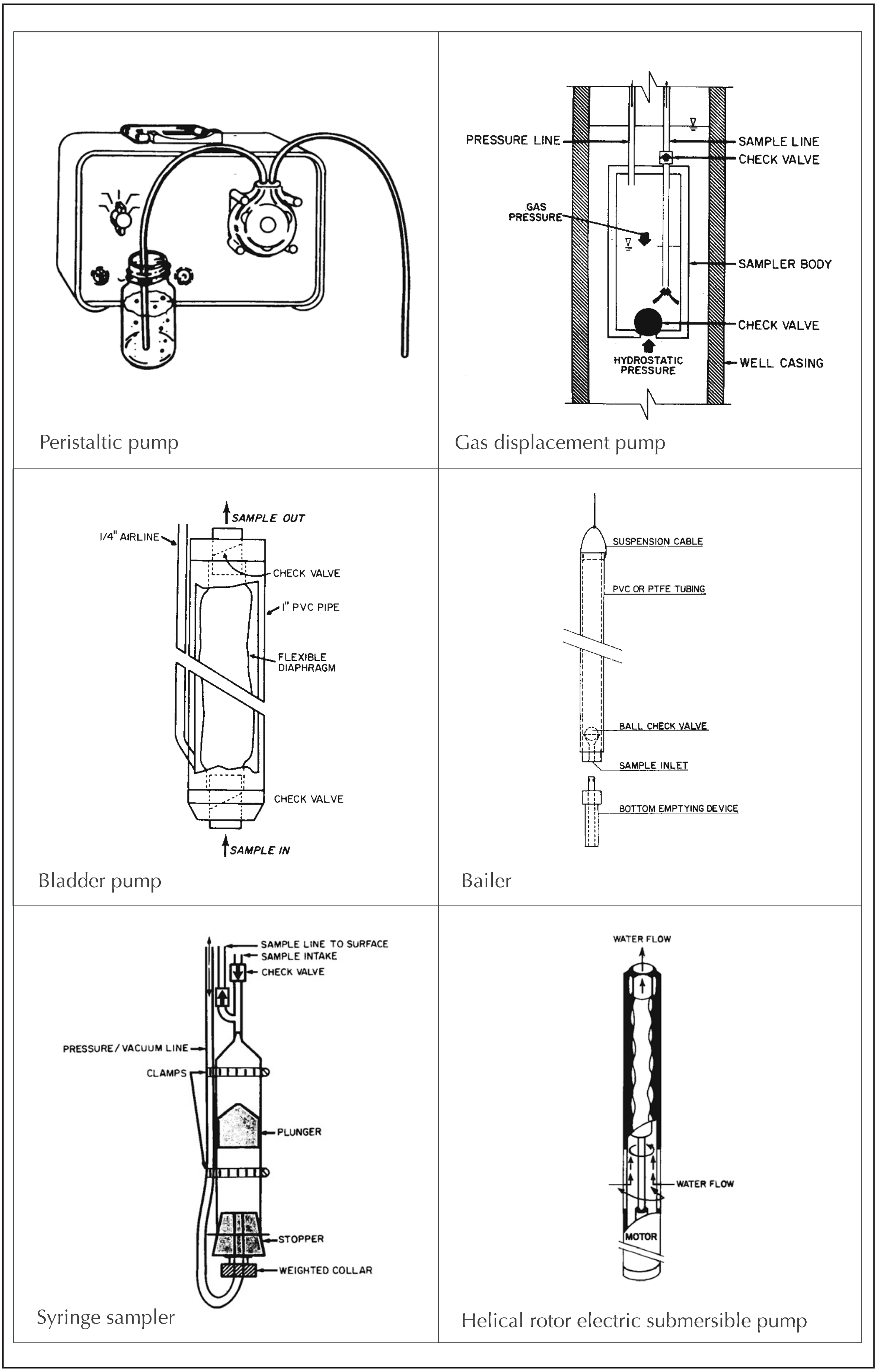
Note: Schematics of sampling devices are included in Fig. 4.5.

(v) Other characterisation methods

Field investigations include a variety of other measurements and tests performed in the field, such as water level measurements, tracer tests, fracture characterisation, and fracture traces.

A field investigation normally begins with measuring water levels in the monitoring wells and existing wells in the area. In addition to recording water levels prior to well purging and sample collection, the measurements also provide the basic data for a potentiometric map. The depth to water is typically measured manually with a steel tape, electric probe, or pressure

FIGURE 4.5 Schematic diagrams of the most commonly used sampling devices (*Source:* Lindorff et al., 1987)



inducer. The air-line method is useful in pumped wells where water turbulence may preclude using a more precise method.

Tracer tests can be used to measure or estimate the various hydrogeological parameters, most commonly the direction and velocity of flow and dispersion, or to identify sources, velocity, and direction of movement of contaminants. The variety of tracer tests is almost infinite, considering the various combinations of tracer types, geological settings, hydrogeological conditions, and injection and sampling methods (Käss, 1998). No one ideal tracer has been found. Because of the complexity of natural environment and a wide variety of tracers, the selection and use of tracers is almost as much an art as it is a science (Barcelona et al., 1987). The purpose and practical constraints of a planned tracer test must be specified prior to the actual planning of the test. The more common types of tracer tests include single-well technique (injection/withdrawal and borehole dilution) and two-well technique (one testing for uniform flow and another for radial flow). The most commonly used tracers can be grouped into six general categories (Boulding, 1995): ions, dyes, gases, isotopes, water temperature, and solid particles.

In fractured rock terranes, the first step usually involves determining the spacing, orientation, depth, and length of fractures. The methods employed to gain this information depend on the surface or outcrop expression of fractures, type of material, depth of unconsolidated material over the aquifer, and fracture orientation (vertical and horizontal). Besides manual measurements, azimuthal seismic survey is another possible method for detecting fracture orientation. Fracture trace and lineament analysis using air photos or satellite images is a useful starting point for identifying possible areas of concentration and preferential direction of groundwater flow. In favourable conditions, fracture expressions may be visible even during field reconnaissance. For example, during periods of dry weather, in croplands underlain by shallow bedrock, crop growth is more vigorous over fractures filled with fine-grained soil, which holds more moisture than surrounding rocks. A basic understanding of a site's tectonic history and fracture orientation would contribute to better understanding of potential contaminant pathways.

4.5 Data management

The foundation for any successful groundwater contamination inventory is the collection, storage, and management of data – a data management system. Data management is the process of maintaining data in a logical fashion to facilitate information retrieval and analysis. Data management begins with a set of procedures for entering the data in a systematic fashion and for checking, sorting, and classifying data. Data are the raw material from which information is generated.

Conceptually, data are assembled into records and files for management purposes (U.S. EPA, 1991a). A data record is made up of a small group of related data items, and a collection of data records is known as a data file or data set. A data record that belongs to a particular data file also can be cross-referenced to other data files that contain additional information (relational data bases). For example, land use categories can be linked to a file containing typical chemicals found within these categories. An orderly collection of data files forms a data base.

Whatever its purpose and detail, the groundwater contamination inventory should incorporate the basic steps in gathering and interpreting data as outlined below. The purpose of this section is to provide an overview and a working guideline for recording and managing data collected for the contamination inventory process.

4.5.1 Data recording

Appropriate, standardised forms for recording data should be prepared to be used by all staff and volunteers involved in the inventory. If field notebooks are used during field searches or surveys, all field notes should be transferred to standardised inventory forms. Examples of inventory forms are shown in Tables 4.2 and 4.3. The completed forms are filed in an organised and easily retrievable manner.

The selection of a uniform base map, on which the information obtained during the inventory will be recorded, is a very important step. Each data point is plotted on topographical maps or on specially selected and prepared base maps. Each map has an assigned unique identification (ID) number. There are many types of maps available for the purpose of the inventory. Preferably, standard topographic quadrangle maps of the large scale (1:25,000 or larger) should be used. These maps are easily reproduced, provide enough detail to determine streets and boundaries, and will make the eventual transfer to a digital, computer-based format possible. They are available from the official national/state topographic mapping agencies or from certified topographic map dealers. Other regional or local maps may be available from urban and regional planning agencies or city/village offices.

All data points need to be entered into a data base, updated, and maintained at a central location, either in a manual or, preferably, in a computerised form. In order to enter data into the data base, each data point needs to have a unique ID number, which is also recorded on the inventory forms; geolocator; and the ID number of a map on which it is plotted. The types and qualities of data that are to be incorporated into the data base need to be specified and evaluated. Location and source attribute information must be verified to meet established data standards.

4.5.2 Creating a data base

The inventory process requires an accurate, appropriate, and sufficient system for the collection, review, storage, and retrieval of data for later use – a data base. A data base is a collection of data records and files that are logically organised to facilitate the manipulation of data. It makes no difference whether the data are in a field notebook, in a filing cabinet, or on a computer disk, as long as the collection of data is logically consistent with the objectives and goals of the inventory. The primary objective of developing a data base is to enable the processing, analysis, and retrieval of data. The function of a data base is to organize a volume of data and to make the data accessible, so that they become information. Various approaches to the design and management of geological data bases and examples of their uses are included in Giles (1995). The development of a data base would typically follow a series of procedures such as:

1) formulation of data base specifications;
2) designation of data base operator and/or manager;
3) data collection and recording;
4) data investigation;
5) data base design (or selection of a commercially available one);
6) data base implementation;
7) data base evaluation and modification.

4.5.3 Data storage, access, and maintenance

The inventoried data can be either filed manually or stored in a computer. Although computer storage and manipulation of data is preferable, the high costs of digitalisation and manipulation of data, hardware and software needs, and training of personnel may preclude the use of a computer in some cases or in some parts of the world.

For a small amount data, a manual filing system may well be adequate. A manual system is inexpensive and does not require special equipment and specialised training. As long as the data base is not going to be shared or updated frequently, a manual filing system is generally sufficient to manage a limited volume of data from a source inventory. Its disadvantages are: cannot be easily shared, inflexibility, possibility of data redundancy, slow retrieval, and limited data analysis and processing capabilities. In addition, the manual filing system is often too labour intensive for an individual to manually cross-reference even a small number of data files in a timely manner.

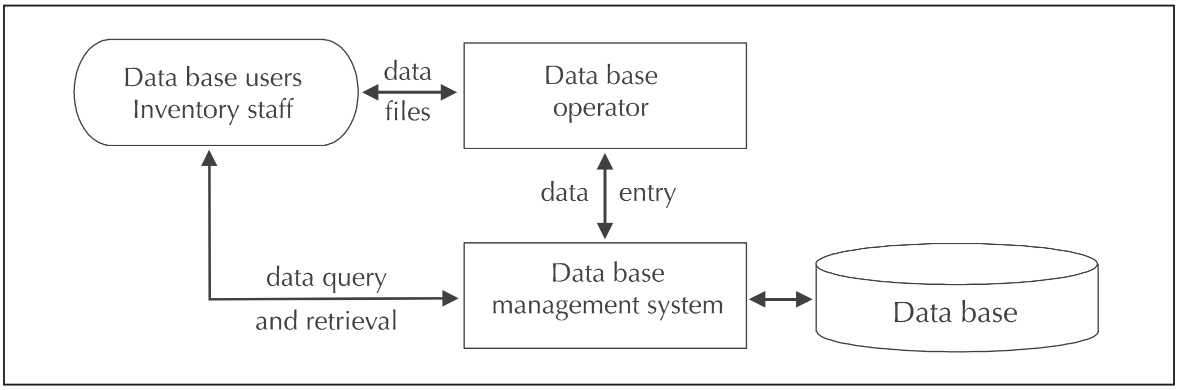
When dealing with a larger amount of data, a computerised data base is ideal because it can deal with a large quantity of data and perform complex data processing tasks. Its advantages are: great flexibility in data analysis, easy accessibility and retrieval of data, and centralised control of data, which help ensure the integrity of the data base and data security. The disadvantages include: costs of hardware and software acquisition and maintenance, specialised training, and risk of losing or corrupting data if backup protocols are inadequate or lacking (U.S. EPA, 1991a).

Under a proper data management scheme, the data must be securely stored to minimise any chances of accidental destruction or gradual degradation over time. It should also not be possible for any unauthorised person to alter the contents of the data. Access to data bases should be available to all inventory staff, but data entry and corrections should be made only by an appointed data base operator or manager (Fig. 4.6). A data manager is an essential element of a data base. The data manager's role is critical especially in ensuring data quality. The single most important reason for the failure of data bases is the absence of a data manager.

All data management systems require some sort of periodic maintenance. Once an inventory has been completed, the data must continue to be updated. Through data base verification and updating, a computerised data management system can be fine-tuned and modified to increase the effectiveness and efficiency of the system for data retrieval and analysis. Maintenance of a computerised data base also can involve training of new users and updating the skills of previous users whenever modifications are made to the system. In addition, backup and recovery procedures should be well established to minimise the risk of losing data due to error or malfunction (U.S. EPA, 1991a).

Data Base Management Systems (DBMS) provide storage, maintenance, and access capabilities for large amounts of data. Storing the data in a DBMS with adequate access capabilities would allow the data to be reused without extensive reformatting. Fig. 4.6 illustrates the proper access to data bases. Users want to use the inventory data for many types of analyses. They can access the data base directly through DBMS utilities and query the data base, using a data query language, or retrieve the data. However, if the users (inventory staff) want to enter new data or correct the old ones, they have to forward the data or corrections to the data base operator.

FIGURE 4.6 Proper access to a data base (*Adapted from:* Dodson, 1993)



4.5.4 *Data processing and presentation*

Electronic spreadsheets, non-relational data bases, or structured DBMS can be used for processing the data. Spreadsheets are designed for the entry and display of numerical data in a grid pattern. Although spreadsheets have limited processing capabilities, they are effective enough for small data set analyses. Non-relational data bases (such as dBase) are sufficient for most purposes but they do not have a good control in exporting of data. Structured DBMS (such as ORACLE), which show the interrelationships between attributes, fields, etc., are more complicated and expensive. However, the long-term benefits of using such systems can easily outweigh the costs, because these systems provide a much better basis for complex data processing, decision-making support, and cross program integration.

Results of the contamination source inventory should be tabulated and displayed on maps according to the predetermined source categories. All sources should be properly located, accurately referenced spatially, and plotted on maps. The scale of maps should be compatible with the scale of other maps constructed for the project. Various types of maps resulting from the contamination source inventory are described in Chapter 6.

Several types of graphic applications are available for presentation of data (Dodson, 1993):

- Computer-Assisted Drafting and Design (CADD) programs;
- Image Processing Systems (IMS);
- Geographical Information Systems (GIS).

CADD programs provide powerful tools for the input of inventory and field survey data. The most widely used is the AutoCAD™ program, which can be used for mapping and general technical drawing. CADD programs generally deal with vector data (points, lines, and arcs). They do not include capabilities for displaying or editing raster data (e.g. data files from scanners).

Image processing systems store, enhance, analyse, and display digitised images such as those received from high-altitude photography and other forms of remote sensing. Image processing systems are based on raster data.

A geographical information system (GIS) is a powerful computer-based tool for integrating and analysing data obtained from a wide range of sources. It is explained in more detail in Chapter 6 (para. 6.3). GIS is an example of an integrated data base management system. It presents a graphic picture of the location of contamination sources in relation to other data elements. GIS contains a base map and several layers of data. GIS may deal with vector data as well as raster data. Once stored, the data can be easily validated, analysed, extracted, reformatted, updated, and mapped.

5 Rating of groundwater contamination sources

Per-Olof Johansson and Ricardo Hirata

5.1 Introduction

The purpose of a groundwater contamination source inventory could vary, ranging from the identification of major sources on a national level to the detailed description of sources within a local area, for example, a wellhead protection area. In most cases, to make the maximum use of the data gathered in an inventory, some kind of classification, ranking, and/or rating of the contamination sources is desirable. Various classification schemes are presented in Chapter 3 and a classification based on origin is advocated. Such a classification does not explicitly tell anything about the potential hazard of the type of source or of the single object. However, in general, different types of contamination sources are known to pose more or less serious threats to groundwater.

The term *ranking* in this guideline is used for the relative, subjective arrangement of contamination sources from the most to the least hazardous or by any other priority. Ranking of contamination sources usually is done by government officials or decision-makers based on local preferences, and is briefly addressed in para. 4.3.2 and Chapter 7. The term *rating* is used for a procedure where contamination sources are given a quantitative or qualitative measure of the potential hazard they pose to groundwater. A quantitative value could, for example, be a quantity or a concentration, e.g. quantity of deposition of airborne acidifying substances or concentration of pesticides leaching from the root zone. A qualitative measure of the contamination potential could be expressed as ranging from high to low or as a numerical index. Rating of contamination sources is the focus of this chapter.

Rankings and ratings are useful to give an indication of the size of the problem and to make priorities for more detailed studies as well as for areas and objects to be considered for regulatory and engineering measures. The ranking and rating can be based on varying degrees of information and can also be used during the inventory to prioritise contamination sources to be studied in more detail.

Groundwater contamination is to a great extent controlled by the type and volume of the contaminant and its mode of disposition. However, the usefulness of the rating of groundwater contamination sources as a planning tool will increase if it is combined with assessments of the vulnerability and aquifer value (see Chapter 6, case study 8.4, and Johansson et al., 1999). In a long-term sustainability context, the vulnerability is less important when dealing with very mobile and persistent contaminants.

5.2 Practical constraints

Although methods for rating of existing and potential groundwater contamination sources can be considered to be very useful tools in groundwater protection programs, the complexity involved in the form of diversity of human activities (substances, quantities, and handling of raw material, products, and solid and liquid waste) raises questions concerning the applicability of simple rating schemes. To find the balance between a very general approach and a detailed assessment is difficult but necessary for practical purposes. It is important to try to find an optimal level based on the objective of the inventory, the area to be covered, number of contamination sources, competence of the inventory team, and available time and money.

Problems can occur if the available information shows strong spatial variation within the study area. The decision to be taken is between increasing the level of information in areas with less information or accepting the fact that in some areas much more information is available than in others. In the latter case, the difference in data density should be indicated in the text and on the inventory maps.

A major concern, when rating groundwater contamination sources based on limited information, is the risk of underestimating sources posing a substantial threat to groundwater. On the other hand, too conservative an approach will inevitably lead to high rating of a great number of sources not posing any real threat, meaning risk for misallocation of resources for detailed investigations and measures. A probable but 'bad' situation is recommended to be the basis for the rating. To make a correct judgment in this sense is not an easy task. It is not necessarily the largest activities that generate the largest subsurface contamination load. For these activities, chemical handling and waste and effluent disposal, in many cases, are better controlled and monitored than for smaller activities. Small services and industries are widely scattered, often use considerable quantities of potentially toxic substances, and the waste and effluent disposal may not be subject to strict control.

Particularly in developing countries, the urban areas grow very fast. Numerous industrial and commercial facilities are often established, and they close or reduce their production processes and volumes again during periods of economic recession. To keep a data base up-to-date when the study area includes a high number of changing activities is often a very difficult task. A simple rating method often has in this aspect a clear advantage since the requirements on data are less demanding.

5.3 Rating approaches

5.3.1 Overview of methods

The idea of rating existing and potential groundwater contamination sources is not new. However, the number of comprehensive methods specifically directed to groundwater contamination is limited. Several methods have been developed for more general contamination source rating, including risk assessments for spreading contaminants to air, land, surface water, and groundwater (e.g. Canadian Council of Ministers of the Environment, 1992; Swedish EPA, 1999; WHO, 1982). The general character of these methods means that the specific aspects of groundwater contamination are not treated in detail. Several methods have also been developed for groundwater contamination from specific classes of activities (Table 5.1): solid waste disposal (e.g. ISal, 1991; LeGrand, 1964; 1983; Parsons and Jolly, 1994; C. Phillips et al., 1977; Swedish EPA, 1990); oil exploration (e.g. WMU, 1981); pesticide application (e.g. Carsel et al., 1985; Jarvis et al., 1997; Mullins et al., 1993; Rao et al., 1985); deposition of acidifying substances (e.g. Holmberg et al., 1990; Warfvinge and Sverdrup, 1992); or contaminated land (e.g. Canadian Council of Ministers of the Environment, 1992; Swedish EPA, 1999).

One of the first comprehensive and simple methods for the rating of different types of contamination sources within the same framework was developed by Mazurek (1979). It was basically a list of activities that were rated in 9 classes (1–9, from low to high groundwater contamination risk). The rating was based on the handling of hazardous materials and substances present in solid and liquid wastes. Foster (1987) and Foster and Hirata (1988) also proposed comprehensive methods for rating of different types of sources within the same framework. Modified versions of these methods are described in more detail in para. 5.3.3. Table 5.1 contains examples of existing methods for rating of groundwater contamination sources.

TABLE 5.1 Examples of methods for rating existing and potential groundwater contamination sources

Method	*Type of source*	*Approach according to subdivision in para. 5.3.1*	*Principle*	*Reference*
Danish EPA*	general	general screening	qualitative, 3 classes	Danish EPA, 1995
Foster-Hirata*	general	general screening	qualitative, 4 classes	Foster and Hirata, 1988
Rao et al*	pesticides	general screening	quantitative, equation	Rao et al., 1985
Swedish EPA*	contaminated land	general screening	qualitative, 4 classes	Swedish EPA, 1995
MACRO-DB	pesticides	general screening or object-specific	quantitative, simulation model	Jarvis et al., 1997
PRZM/ PRZM-2	pesticides	general screening or object-specific	quantitative, simulation model	Carsel et al., 1985; Mullins et al., 1993
PROFILE	acidification	general screening or object-specific	quantitative, simulation model	Warfvinge and Sverdrup, 1992
Foster-Hirata*	general	object-specific	qualitative, numerical index	Foster and Hirata, 1988
Hirata*	general	object-specific	qualitative, high to low	Hirata, 1994
Mazurek*	general	object-specific	qualitative, numerical index	Mazurek, 1979
ISAL	waste disposal	object-specific	qualitative, numerical index	ISal, 1991
LeGrand	waste disposal	object-specific	qualitative, numerical index	LeGrand, 1964 and 1983
Phillips*	waste disposal	object-specific	semi-quantitative	C. Phillips et al., 1977
Visual HELP	waste disposal	object-specific	quantitative, simulation model	Waterloo Hydro-geologic, 2000
WASP	waste disposal	object-specific	qualitative, numerical index	Parsons and Jolly, 1994
Hirata*	nitrate, pesticides	object-specific	semi-quantitative	Hirata et al., 1993
MIFO	contaminated land	object-specific	qualitative, 4 classes	Swedish EPA, 1999
Swedish Nat. Road Adm.*	road accidents	object-specific	quantitative, probability and consequence in monetary units	Swedish Nat. Road Adm. and Swedish Rescue Service Agency, 1998

* No formal name given.

Many of the above-mentioned methods for contamination source rating also involve an evaluation of the possibilities for contamination spreading in the subsurface (vulnerability assessment), either as an integral part of the method (for example, the LeGrand, 1964, method) or in a separate step (Foster and Hirata, 1988). In a risk assessment, where risk is defined as *probability x consequence,* the combined rating of the contamination source and the possibility of the spreading into and in the groundwater could be interpreted as the probability for groundwater contamination, both in quantitative or qualitative terms depending on the method used (Chapter 6 and para. 8.4 of this guideline and Johansson et al., 1999). Including an assessment of the groundwater value in the rating process invites possibilities for evaluating the *consequence* part of the risk assessment.

Methods for rating groundwater contamination sources can be categorised in several ways, for example, according to:

- type of source that can be assessed,
- need for information (general, object-specific, degree of detail),
- principle of the evaluation (e.g. aggregation of indicators or structural simulation models), and
- type of result (quantitative, qualitative).

The selection of a rating method for a specific inventory involves a number of considerations to be addressed early in the planning phase of the inventory. Key aspects are:

- objective of the rating and desirable results,
- available information (existing or to be gathered during the inventory),
- number and complexity of contamination sources to be covered related to available time and money, and
- competence of the evaluation team.

In the following paragraphs, approaches to rating are subdivided into two major categories: 1) general screening approaches and 2) object-specific approaches. In the first category, general knowledge of the threat to groundwater posed by the type of contamination source is used. For the second category of approaches, site-specific information on the potential contamination source is needed. Indirectly, these two categories can often be coupled to the size of the area and the number of contamination sources to be studied. The general approaches are usually applied on a national or regional level; the detailed object-specific approaches are applied in small areas, for example, within wellhead protection areas.

In addition, risk-based approaches are described separately (para. 5.3.4). In a risk analysis, the probability and consequence of a contamination event are estimated. The analysis usually includes both the properties of the contamination source and the hydrogeological environment.

5.3.2 General screening approaches

General and quite simple methods for rating of groundwater contamination sources can be very useful to raise awareness and to put groundwater protection on the agenda in general decision- and policy-making and in the physical planning process. Besides awareness-raising, the general methods can be used to identify and prioritise contamination sources or areas in which more detailed studies should be applied. Presented as overlays on supporting maps, the ratings can, for example, highlight areas where major existing or potential contamination sources overlay important and vulnerable groundwater resources.

In principle, this kind of approaches includes a contamination source identification and classification while the rating is based on expert judgement. The methods are fast and easy to apply and only require a small technical team. Data requirements are minimal and normally enough data are readily available for this approach. Already, a representation on a map of a classification of the contamination sources as presented in Chapter 3 is valuable in this context, although the degree of hazard posed by the sources is not explicitly expressed. To supply decision-makers and planners with more information, a qualitative rating of the sources based on general knowledge of the type of activity (type and quantity of substances used, or solid and liquid wastes produced) can be made.

A general method for screening contamination sources, adapted to the origin-based contamination source classification of Chapter 3 is presented in Fig. 5.1. A subdivision is made into sources given high, moderate, and low contamination potential rating. For more examples of general screening methods, the reader is referred back to Table 5.1.

5.3.3 Object-specific approaches

When a more detailed approach is necessary, object-specific information is needed. Normally, methods belonging to this category require field surveys or field investigations, although a very important part of the information can be obtained from authorities and public and private organizations. For the object-specific rating of contamination sources the following aspects should be considered:

- type of potential contaminants (toxicity, mobility, persistence),
- amount of potential contaminants (quantities, concentrations),
- handling and storage of potential contaminants,
- treatment and disposal of solid and liquid wastes, and
- areas affected by contaminants.

The most important information for the rating is probably that on the presence of hazardous materials (potential contaminants). If toxic substances are used or produced, there is a risk for contamination, even if the activity is well managed and has proper handling and treatment of solid and liquid wastes. One problem is to establish the minimum quantity of substance that can generate a contamination. Toxic liquids, like solvents, can cause serious groundwater contamination even in very small volumes (Mackay and Cherry, 1989).

Because of the individual analysis of each object (i.e. contamination source), it is also possible to get a historical perspective of groundwater contamination incidents. For some objects, monitoring records and sporadic water analyses may be available.

For all object-specific approaches, an indication of the degree of confidence of the rating is recommended. For example, due to the quantity and quality of the available information, the following indicators can be used:

a) detailed data available, including field studies;
b) some data available, limited field studies; or
c) no or very limited data available.

The complexity of an object-specific rating method can vary substantially. Examples of simple rating methods for industries, effluent lagoons, and waste disposal developed by Hirata (1994), are presented in Fig. 5.2a and 5.2b. According to these schemes, the potential contaminant load rating is based on: a) the volume and type of hazardous substances manipulated and b) the volume of effluent generated by the activity, calculated indirectly from the size of the facility (area of a lagoon, for example). The volume of hazardous substances suggested in Fig. 5.2a, and size of the facilities in Fig. 5b, were established taking into account typical value distributions of activities studied by the author. To adapt the method for other areas, new cut-off values should be defined based on the universe of activities of a specific region.

The results typically can be used for regional and general municipal planning and as a first step in an evaluation of contamination sources for groundwater management and protection purposes. These methods can also be used for prioritisation of contamination sources and areas for more detailed field surveys and field investigations, according to importance and level of concern of the contamination source and need for verification of accuracy of available data.

To further increase the reliability of the rating, more detailed field surveys and field investigations are needed. This is usually only possible for a restricted number of contamination sources and smaller areas. The results could typically be used in municipal and urban planning and in wellhead protection area programs. This category of methods typically requires detailed information about raw materials; processes; intermediate and final products; and storage, treatment, and disposal of solid and liquid wastes. The requirements on the competence of the evaluation team are also higher. Good competence in processes and practices of individual activities and in chemistry is desirable as well as knowledge of mobility and persistence of different substances in the subsurface.

FIGURE 5.1 A general rating system of groundwater contamination sources based on the classification by origin presented in Chapter 3 (H, M and L = high, moderate and low potential groundwater contamination load, respectively)

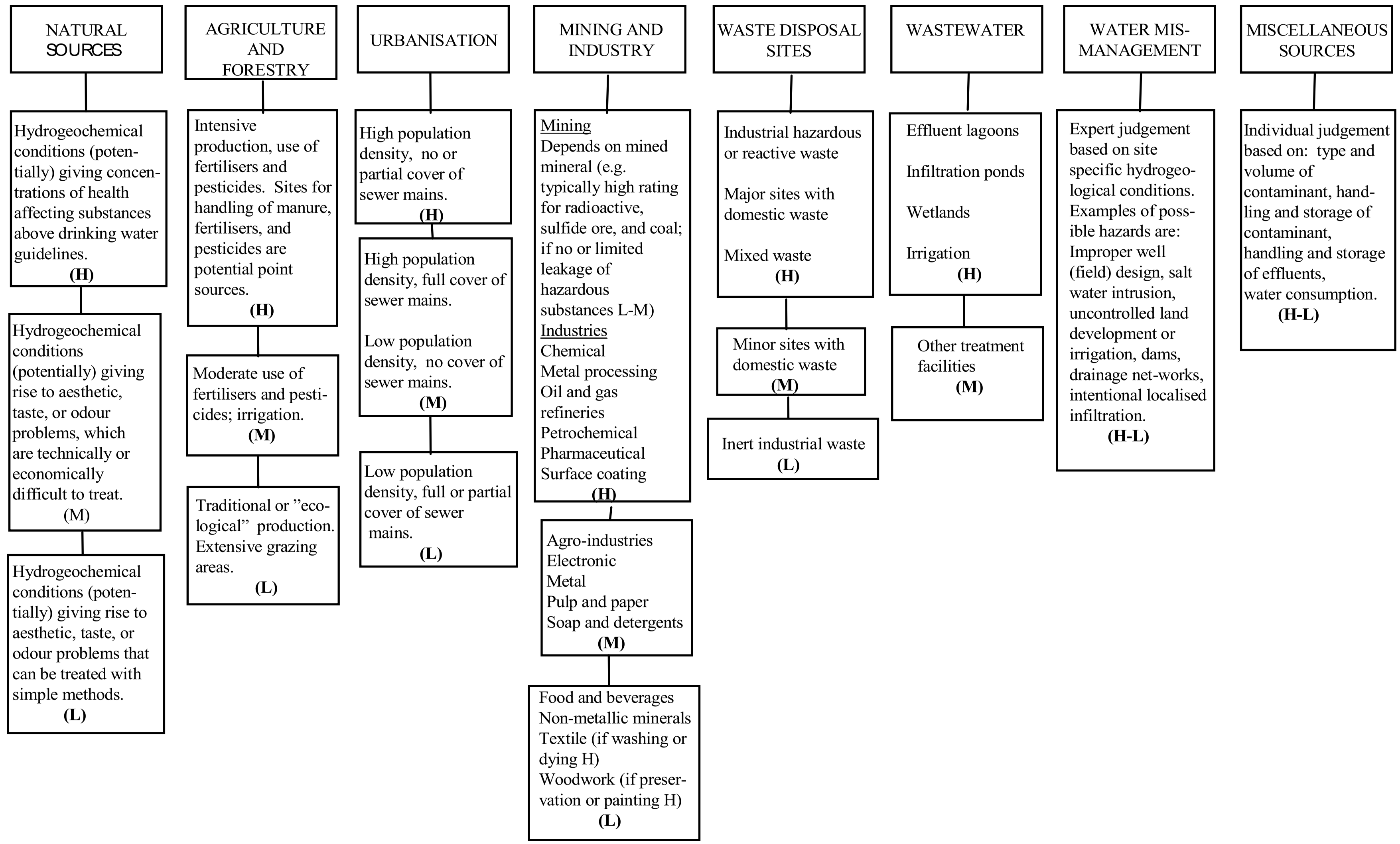


Figure 5.2a Example of a simple object-specific rating method for industries. High, moderate, and low refers to the potential groundwater contamination load (*Source:* Hirata, 1994)

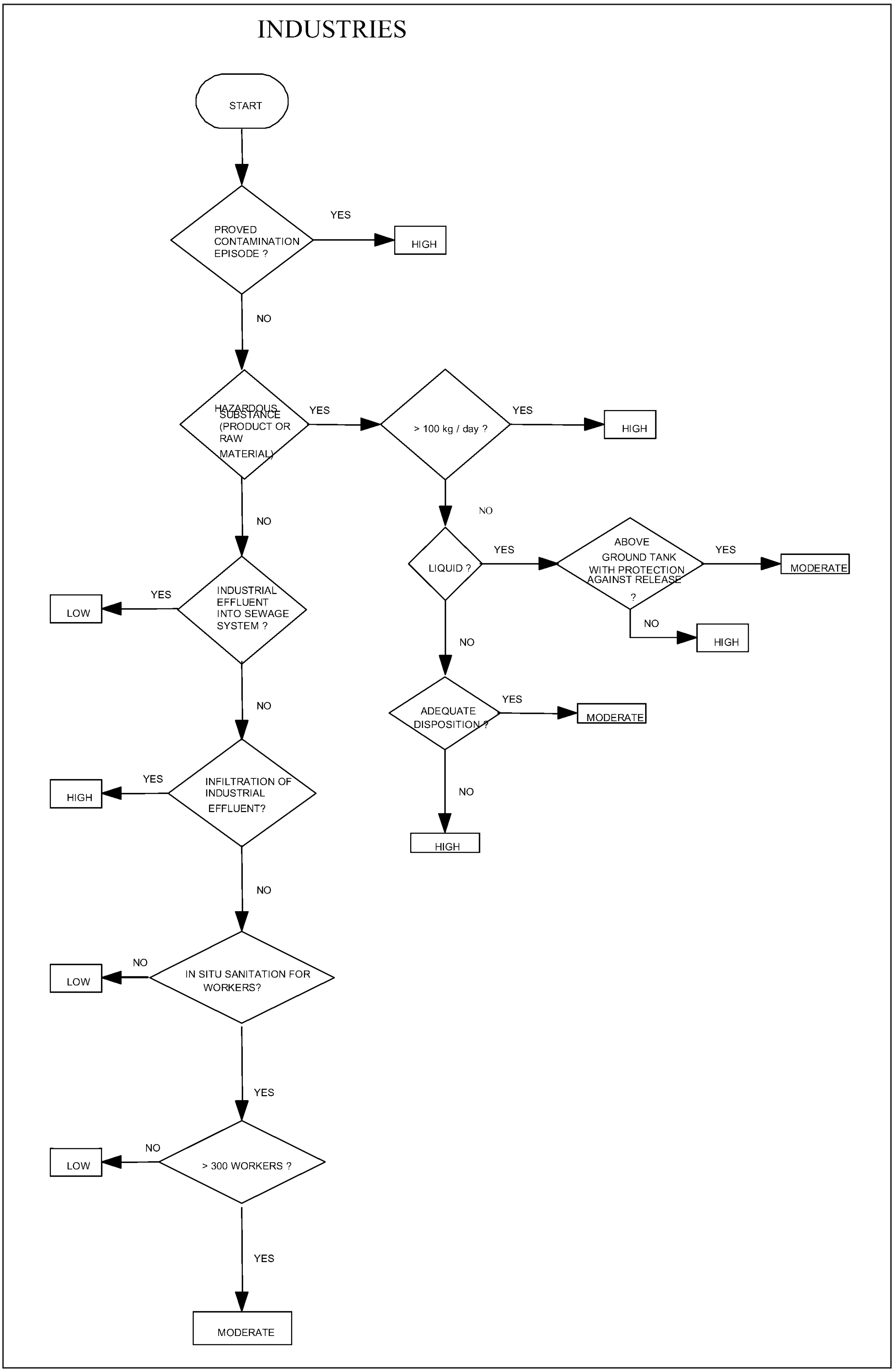
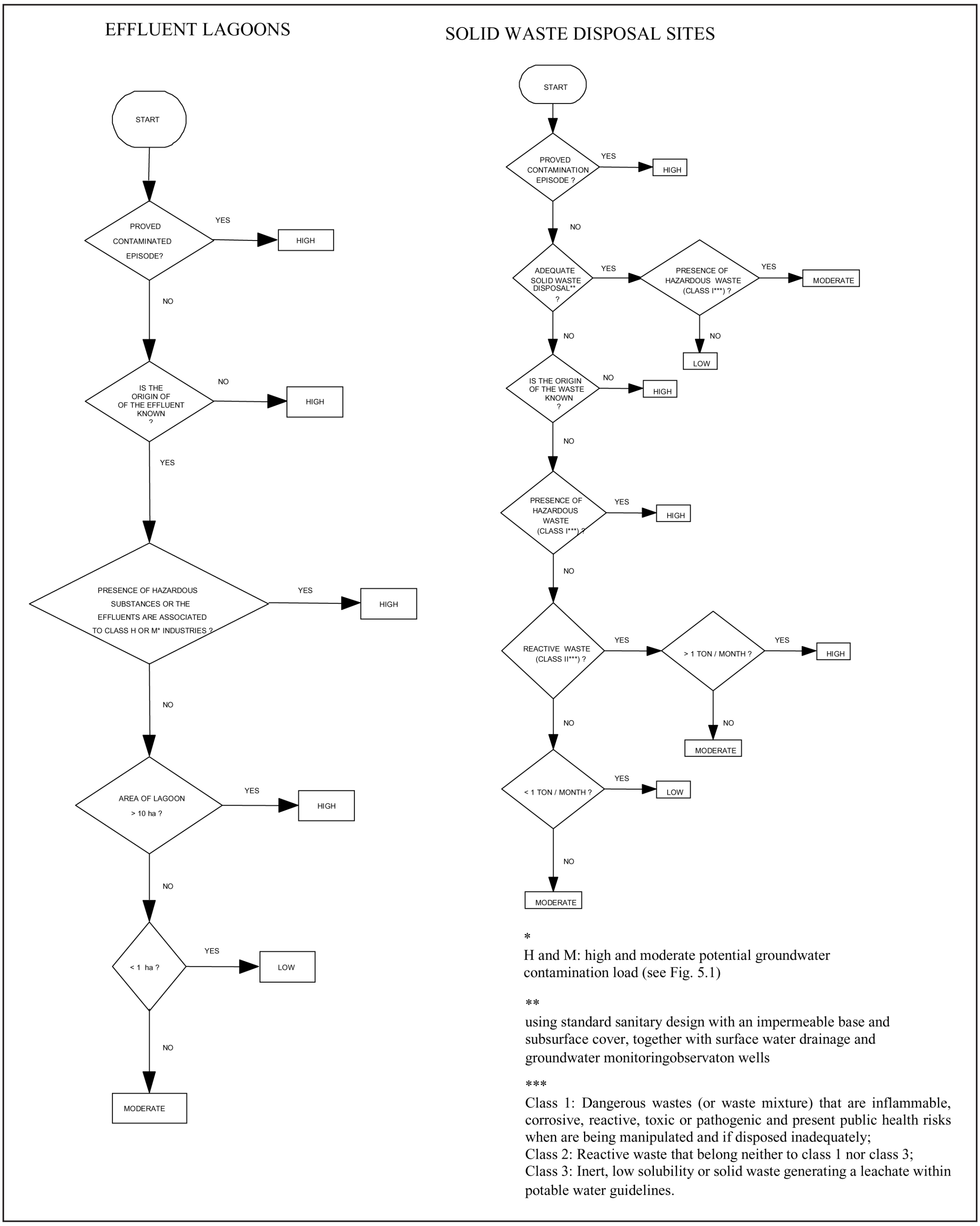


FIGURE 5.2b Example of a simple object-specific rating method for effluent lagoons and solid waste disposal sites (*Source:* Hirata, 1994)



Foster (1987) and Foster and Hirata (1988) developed a rating method for a common evaluation of various anthropogenic contamination sources. The rating system is based on the evaluation of four key characteristics of the groundwater contamination source:

1) contaminant class,
2) mode of disposition,
3) relative contaminant load, and
4) duration of contaminant load.

A rating of the key characteristics is made graphically in matrices. The ratings vary between 0 and 1 (see Chapter 8, case study 8.4). Only the characteristics of the contamination source are rated. The vulnerability of the groundwater system is supposed to be assessed separately (by the GOD method: Foster, 1987).

A modified version of the Foster-Hirata (1988) method (elaborated by P.-O. Johansson) is presented in Fig. 5.3. A relative rating of the potential groundwater contaminant load – in three classes: high, moderate, and low – is made stepwise by three evaluation matrices. The stepwise pro cedure, described below, promotes better understanding of the evaluation process. The user may evaluate the result of the combination of two parameters at the time and the idea is to give each combination a physical meaning. If a source contains more than one contaminant, the contaminant obtaining the highest rating is used for the final rating of the source.

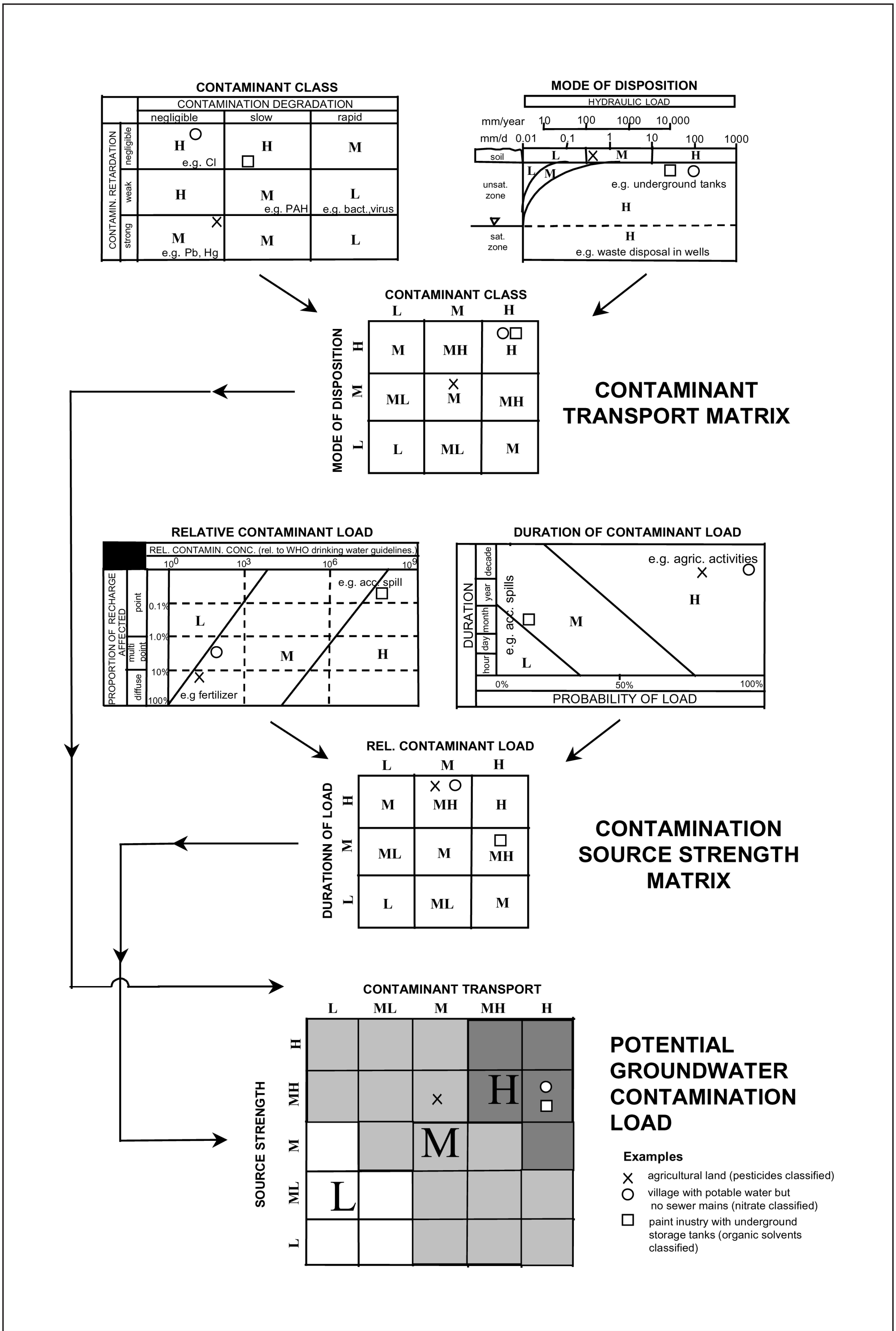
In the *contaminant class diagram* (Fig. 5.3), the persistence and the mobility of the contaminant in the subsurface is classified. Highly mobile and persistent contaminants are classified as of high contamination potential. Contaminants that are strongly retained and rapidly degrading are classified as of low contamination potential. In the second diagram, *the mode of disposition* of the contaminant in terms of the depth of introduction in the groundwater system and the hydraulic load is evaluated. An introduction of the contaminant at the ground surface results in a relatively low rating due to possibilities for retention and degradation of the contaminant before entering the groundwater zone. The soil zone especially is important in this respect with a high biological activity and a high content of organic material and aluminium and iron (hydr)oxides. A high hydraulic load means more rapid transport of the contaminant and less time for degradation and retention processes. Furthermore, a high hydraulic load of ten results in a lower redox potential, at which degradation and retention are less effective for most contaminants. The worst mode of disposition is when a contaminant is introduced directly into the groundwater zone at a high hydraulic load. The results of the rating of contaminant class and mode of deposition are combined in a matrix to obtain the *contaminant transport characteristics* of the contamination source.

In the next step, the *relative contaminant load* is evaluated, based on the proportion of the groundwater recharge area that is affected and the contamination source intensity in terms of a concentration relative to the WHO drinking water guidelines (WHO, 1993). Diffuse sources, such as leakage of nutrients from agricultural land, may affect all of the recharge area, but usually the relative concentration is not very high. In the case of an accidental spill, the relative concentration may be very high, but only a very limited area is affected. In the *duration of contaminant load diagram*, the probability and the duration of a contaminant load is evaluated. For leakage from agricultural land, the probability of load (leakage of nutrients and/or pesticides) often is high and the duration of the load may be long; for an accidental spill, the probability often is low and the duration short. The results of the rating of the relative contaminant load and the duration of contaminant load are combined in a *contamination source strength matrix*.

In the last step, the ratings obtained from matrices for the contaminant transport and the contamination source strength are combined in a matrix to get the final classification of the *potential groundwater contamination load* of the contamination source (Fig. 5.3). The presented evaluation matrices are symmetrical. It could be argued that a greater weight should be given to a specific parameter, for example, contaminant class or relative contaminant load, which would result in an asymmetrical, skewed evaluation matrix. In Figure 5.3, examples of classification of three contamination sources are shown. The contamination sources are taken from a study in Nicaragua (see Chapter 8, case study 8.4), and include: 1) an agricultural area with use of pesticides, 2) a big village with potable water but no sewer mains, and 3) a paint industry with underground storage tanks for chemical solvents.

For diffuse contamination sources, several quantitative modelling tools have appeared. These models can be used both for general screening purposes and for object-specific assessments. Simulation of a number of typical combinations of groundwater recharge, irrigation, crop, soil, and fertiliser and pesticide application can be used for general screening, while detailed information on climatic factors, soils, and agricultural practices are required for object-specific assessments. Examples of such models are: for pesticides PRZM-2 (Mullins et al., 1993) and MACRO-DB (Jarvis et al., 1997), and for nitrate SOILN (Jansson et al., 1991) and DAISY (Danish EPA, 1990). An example of a quantitative model for the determination of critical load of acidifying substances is a model developed by Warfvinge and Sverdrup (1992).

FIGURE 5.3 System for detailed object-specific rating of potential groundwater contamination load (L, ML, M, MH, and H = low, moderate-low, moderate, moderate-high, and high, respectively) (*Based on* Foster and Hirata, 1988 *and elaborated for the guideline* by P.-O. Johansson)



5.3.4 Risk-based approaches

Relatively recently, methods for risk assessment based on probability and consequence of failure have come into use for the evaluation of groundwater contamination sources (e.g. Rosén and LeGrand, 1997). Usually these kinds of methods rely on Bayesian statistics, where both statistical hard data as well as soft data in the form of empirical knowledge are used. The analysis is usually performed in what can be illustrated as a decision tree (risk tree). Risk is defined as probability multiplied by consequence; and the consequence is described as a cost, for example, for remediation and an alternative water supply. (Actual health risks due to the presence of a particular contaminant in groundwater are not considered.) An example of such a risk analysis for a road accident involving petroleum transport is shown in Fig. 5.4. The circles illustrate that an event takes place with a specific probability (P). The probability of the complementary event are signified by $Q = 1 - P$. The squares represent the consequences (C) of an event.

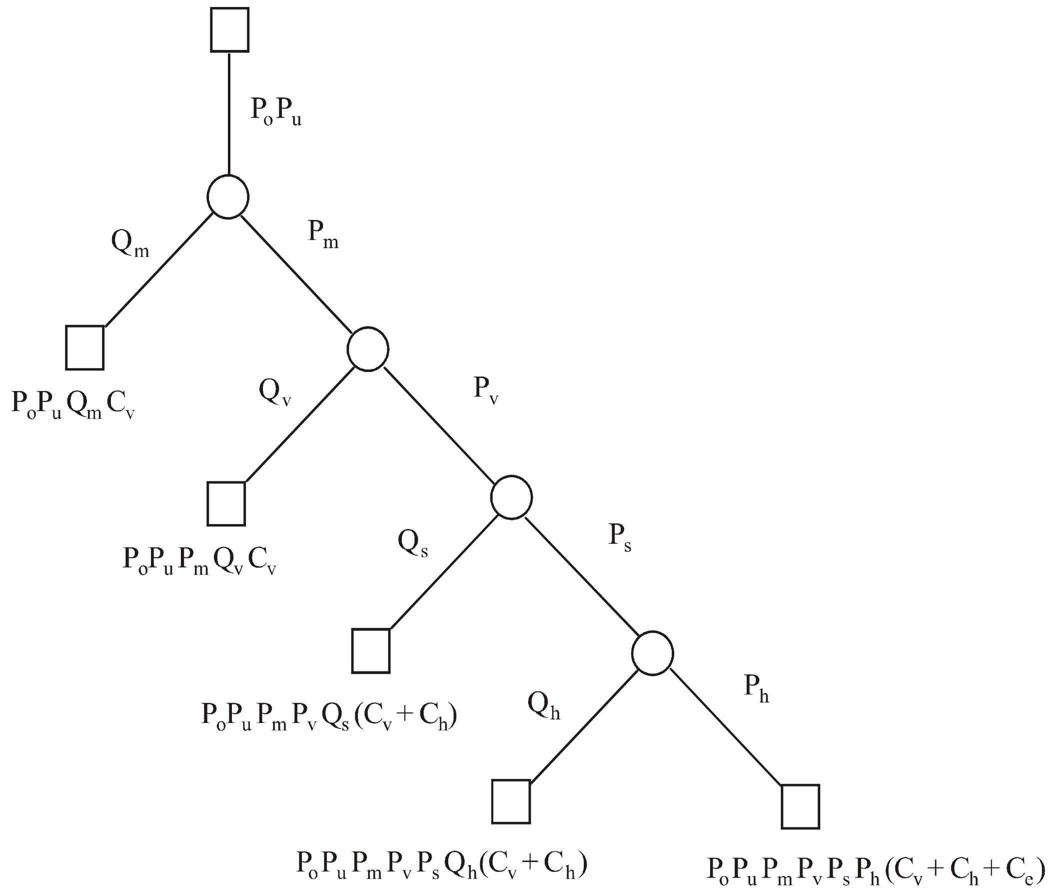
This kind of risk analysis has the advantage of a systematical procedure giving answers in monetary units. The major problems are to define realistic probabilities and to put value on the groundwater resource (for evaluation of groundwater resources, see NRC, 1997). However, the procedure is easily understood and a sensitivity analysis can be applied on the outcome of the evaluation. Even if the absolute cost of a failure can be questioned, the relative order of a number of contamination sources can be very useful as a decision-support tool.

This kind of risk analysis can be performed based on more or less detailed information and, of course, the degree of reliability of the evaluation will vary accordingly. More complex methods could be applied to calculate spreading of contaminants in the underground within this kind of risk-based approach (Freeze et al., 1990).

5.4 Concluding remarks

A number of rating approaches and methods have been presented above; from very simple general screening methods to relatively complex object-specific methods. The results are mainly qualitative and relative but some of the more detailed and complex methods give semi-quantitative or quantitative results (Table 5.1). However, regardless of the approach used, it is very important to stress dependence of good result on good input data. If possible, a measure of the reliability of the rating should be given; relatively as the a, b, c indicators proposed above in para. 5.3.3 or by a sensitivity analysis of the output to changes in input data. It should also be stressed that most of the presented methods should be seen as screening tools and not as a replacement for detailed investigations.

FIGURE 5.4 Decision tree for risk analysis for a road accident involving petroleum transport threatening a groundwater supply (*Source:* Swedish Nat. Road Adm. and Swedish Rescue Service Agency, 1998)



Total annual risk cost:

$$R = P_o P_u (C_v + P_m P_v C_h + P_m P_v P_s P_h C_e)$$

P_o = probability for an accident with petroleum transport vehicle
P_u = probability for leakage in case of an accident
P_m = probability for a rapid, vertical transport through the unsaturated zone
P_v = probability that the residence time in the unsaturated zone is shorter than required for remedial action
P_s = probability for unfavourable flow direction
P_h = probability that residence time in the groundwater zone is shorter than required for remedial action
Q = complementary probability to P: $Q = 1 - P$
C_v = sum of costs for remedial actions in the unsaturated zone
C_h = sum of costs for remedial actions in the saturated zone
C_e = cost for a new water supply

6 Map production

Julian Conrad, Simon Hughes and John Weaver

On completion of the groundwater contamination source inventory and the ranking and rating of the sources, the next step is to ensure that results are presented in a meaningful and responsible way. Project findings, conclusions, and recommendations are usually presented by means of a written report and maps. A well-presented map plays a significant role in the clear communication of the results and can influence actions that may result from the inventory. A map can assimilate a lot of data and present them in an easily understandable manner. It is, therefore, important that appropriate attention is given to map production.

The first part of this chapter discusses the design philosophy and practicalities, and stages of producing a groundwater contamination inventory map. The role and type of supporting maps are also discussed. The process for the compilation of a groundwater contamination risk map, which entails determining contamination sources, aquifer vulnerability, and aquifer value, is outlined. The second part of the chapter touches on the preferred technology for data collation, spatial analysis, and map production. The use of a Geographical Information System (GIS) is becoming widespread as software usability enhances, price decreases, and hardware performance dramatically improves. Different types of GIS are tabulated, and a discussion follows on the basic components and functions of a GIS, hardware requirements, available software, GIS advantages and disadvantages, integration with image processing software, and the use of the Internet for serving maps. Finally, a number of useful websites addresses are provided for referral purposes.

6.1 Groundwater contamination inventory map

6.1.1 Design philosophy

For as long as human beings have inhabited the earth they have asked, of travellers and strangers, what the rest of the world was like. It was a question more easily put than answered, because in any statement of the complexities of content and position, verbal description must soon have proved to be a tedious and limited form of communication. Moreover, there were powerful reasons – economic, political, even theological – for wanting to have such questions answered. Therefore, it is not surprising that maps, which developed to meet this need for precise, specific statements of 'what there is' and 'where it is', should have a history stretching back to antiquity (Dickinson, 1979).

With groundwater contamination inventory maps, experts wish to convey a message. Thus, before the task of map production is started, careful thoughts and decisions must be made regarding the design of the map. The questions that will influence the design will include:

- What is to be achieved with the map?
- What is the final message to be conveyed?

- Who are the end-users? What is their level of knowledge? How much can be taken for granted? If the map is for use by parties foreign to groundwater contamination mapping, what additional information is required?
- What level of accuracy will be required?
- Will the end product be a printed map or an electronic copy?
- If it is to be printed, will it be a few copies with limited distribution (report for decision-makers) or will it be widely distributed (schools, libraries, and the general public)?
- How will the map be distributed (as a stand-alone product, within an explanatory booklet, or via the World Wide Web)?

It is only once these factors have been considered that one should proceed with the practicalities of map production.

6.1.2 Design practicalities

(i) Scale

The scale of a map inevitably has a very strong control on map design. On large-scale maps (for example, 1:1,000) many features can be depicted and these can be shown to scale. In comparison, for small-scale maps (for example, 1:1,000,000) many of these features will have to be omitted and those that are retained will be shown using symbols or colours.

For a groundwater contamination inventory, the decision on scale will determine what can or cannot be depicted on the maps. Thus, large-scale maps will be special-purpose maps depicting the local contamination inventory and aquifer importance and vulnerability. These will more likely be maps included with reports for special investigations and will have limited circulation. Small-scale maps will tend to be overviews on a regional scale and will more often be directed towards planning and general public consumption. Vrba and Zaporozec (1994) developed a table of map types and scales for groundwater vulnerability maps, which could be easily applied to contamination inventory maps (Table 6.1).

TABLE 6.1 Classification of groundwater contamination inventory maps (*Adapted from:* Vrba and Zaporozec, 1994)

Type of map	*Scale*	*Purpose and content*	*Graphic representation*
General overview, synoptical	1:500,000 or larger	General planning, decision-making, and setting policies in contamination control and groundwater protection on national or international level; educational purposes. Synthetical maps showing the extent and spatial distribution of contamination and type of contaminants; local details are lost.	Usually stand-alone maps, with notes and supporting graphics on the margin of maps. Less detail is better.
Schematic	1:500,000 to 1:100,000	Regional planning, groundwater protection management and regulation, and assessment of diffuse contamination problems or saline water intrusion. Most of local details are still lost.	Often stand-alone maps, sometimes a series of complementary maps. Can contain some detail.
Operational	1:100,000 to 1:25,000	District land use planning and design of groundwater contamination control programs. Analytical maps depicting vulnerability of groundwater in areal extent in relation to the specific contaminant travel time, aquifer value, and contamination sources and their potential impacts.	Usually a series of supporting maps with one or more summary maps. Accompanying explanatory notes and report is standard.
Specific, special purpose	1:25,000 or smaller	Single-purpose and site-specific maps for local or city planning and well protection. Expresses local or point-source contamination problems. Detailed depiction and description of point sources is possible.	This map is usually part of a larger extensive and detailed report.

(ii) Social and natural features

A map will generally contain several different layers of information, these being the feature layer and the ancillary layers. The feature layer is the layer containing the principal information, i.e. the reason for which the map is being produced. The ancillary layers contain supporting information and orientation information. Supporting information are data that assist with the interpretation of the feature layer. Orientation information are data that assist the viewers in spatially orientating themselves with landmarks, i.e. roads or social and natural features. Essentially, it could be said that scale information, grids, graticules, and north arrows are also orientation information. For the purposes of this guideline, these objects will be referred to as cartographic elements. For the contamination inventory map, the source inventory is the feature layer, or the primary purpose of map production. Social and natural features exist only as ancillary information, assisting with orientation and interpretation.

The primary purpose of the contamination inventory map is that it must convey to the reader of the map the purpose and message of the inventory. Thus, the social and natural features that are shown on the map must support the message and not interfere with the message. Persons closely involved with the project will often want to put more on the map rather than less. This is because they are intimately familiar with the surveyed area and when reading the map, these extra features are 'invisible' to them. However, when an outsider reads the map, these 'invisible' features will be 'visible' and will detract the reader's attention from the message. Economy of map elements is the first step to map legibility.

Bearing in mind the previous discussion, it must be noted that the depiction of relevant social and natural features obviously plays a very important role in the contamination inventory map. The role that both have to play is orientation of the reader. Roads, rivers, railways, and similar semi-permanent linear features are the more common examples. Other point features that are of significance in the local context should also be included for orientation, for example, post offices, schools, town halls, hospitals, places of worship, etc. Consider that in sparsely populated areas all of these features could be included, whereas in densely populated areas an appropriate selection should be made to avoid clutter. The scale of the contamination inventory map will also influence which features are retained. Very-small-scale maps (1:1,000,000 and smaller) become very cluttered if they include every social feature. Thus, such maps may only show main roads and local government boundaries, whereas for large-scale contamination inventory maps, many more features may be included.

(iii) Contamination source inventory

After the field work for the contamination inventory has been completed (Chapter 4), the question is 'how to present this written and diagrammatical information on a map?' There are two main factors to be considered for representation, namely the type of potential contamination source (Chapter 3) and the potential contaminant load (Chapter 5). When designing a contamination inventory, a system for data collection and processing (para. 4.5) is usually selected in the early stages. Also, it must be assured that the inventory data base is designed to be compatible with the mapping software. It is strongly recommended that thought also be given to how the data will be presented. If the presentation of field data is carefully planned, their conversion to a mapped representation needs the minimum of interpretation. Therefore, early communication with the contamination inventory team is an important part of the map-making process. An example of a groundwater contamination inventory map is included in para. 6.1.4, Fig. 6.3.

(iv) Data sources for map production

Much has been written about the use of and methodologies for remote sensing for map production. A common misconception is that remotely sensed data are equated only with satellite imagery. It is true that advances in technology have resulted in a dramatic increase in the application of satellite remote sensing data and have, therefore, raised the profile of satellite systems (para. 4.2.1 *(i)*). However, all the methods – the aerial photography, digital orthophotos, digital aerial sensors, and satellite imagery – are important for map production and can be used as effective and informative backdrops in GIS map layouts. Satellite imagery offers the advantage of a small-scale synoptical view. Therefore, large, regional structural formations can be detected (either through immediate visual interpretation or as a result of image-processing techniques), which are not discernible during ground-based or even aerial surveys.

The golden rule for map production is to always collect rather too much data than to find out at the map printing stage that some previously unknown map with important data is available. Bear in mind that if a map is available, then a lot of work has already gone into its production and it is usually easier to build on the information contained in that map than to start from the beginning. Always ensure that the usage of a map is acceptable in terms of copyright and always acknowledge the source. Also ensure that the information being used is of a reliable nature and that the scale at which it was compiled is compatible with the data to be used in the project.

(v) Evaluation of data sources

All data (and their sources) that are to be used for contamination inventory mapping must be thoroughly considered in terms of quality, accuracy, certainty, and reliability.

Metadata can usually answer questions arising regarding these variables. Metadata should not be thought of as 'data about data' as is often cited, but rather as 'descriptive information about data'. The information can be stored in a number of different formats, such as data bases, text, digital files, or hard copy, and should accompany all spatial data. A number of formalised international standards exist for the collection and storage of spatial data sets, foremost of which is the Federal Geographic Data Committee (FGDC) standard. FGDC is an American system in use throughout the geospatial data community. It is being used as a basis to formalise a new International Standards Organization (ISO) standard. Several software packages have been developed to assist with metadata input. Some examples of these are MetaLite (USGS), Digest (NATO), and the National Oceanic and Atmospheric Administration (NOAA) metadata recording tool.

Where quality, accuracy, or origin are lacking, then improvements must be made or the data set must be replaced or recreated before map production commences. If improvements cannot be made, whether for budgetary or practical reasons, then allowance must be made during map production.

6.1.3 Stages of map production

When obtaining and preparing the data for map production, there is a certain order in which the various stages of map production are addressed. Many of these stages can be undertaken concurrently with the contamination inventory. Fig. 6.1 shows the various stages of map production and the corresponding stages of the contamination inventory (see Chapter 4) at which point in the project the map production stage can be undertaken. This figure can be used to help plan the project and develop a time schedule.

(i) Design

The design of the map is not the same as design of the layout. The map design process is essentially a user requirements analysis: What is to be achieved, what is the message to be conveyed, who are the end-users likely to be, and what format will the end product be in (para. 6.1.1). The map design should also be considered when the contamination inventory is being planned (Chapter 4) and during the rating of groundwater contamination sources (Chapter 5). The layout design is the actual design of the size and arrangement of a map sheet, and is further described in para. 6.1.3 *(viii)*.

(ii) Data audit, collection and input

An audit of necessary data must be performed. This audit will usually include checking through data archives to obtain listings of existing data. As discussed earlier (para. 6.1.2 *(iv)*), the data must be obtained from a reliable source, and recorded at an appropriate scale and in an accessible format. An example of inappropriate scale would be the use of river feature data obtained from 1:1,000,000 maps when the remainder of the data has been entered at 1:50,000 scale. The audit should also include a listing of what base maps are required and of how many of these are already held in archives. Analysis of these base data is essential to ascertain whether the scale or level of detail is sufficient to extract the required information. Cost-effective data entry is an important consideration, especially when budgetary constraints are tight. Entry of data must only extend as far as project parameters require. If a project is operating at a national scale (in a large country), entering, for example, surface water features at 1:5,000 scale will introduce an unnecessary element of complexity and increase the time necessary to enter data. Also, the input of data outside a study area, unless there are definite applications for the data outside the current project, is unnecessary.

All of the above issues need to be discussed with the contamination inventory project manager. Compatibility needs to exist between the data that is generated as a result of the inventory and the data/information systems that will be used to capture, analyse, and present the

FIGURE 6.1 Flow chart of the stages of map production and the corresponding stages of groundwater contamination inventory

Map production stage	*Task*	*Corresponding stage as shown in Figure 4.1*
DESIGN	Project based on required end product. See Chapter 4 and par. 6.1.1 and 6.1.2.	Inventory design (Stage 1A).
DATA COLLECTION AND CAPTURE	Selection of base maps. Data audit. See Chapter 4, par. 4.5.1 and 4.5.3.	Inventory design (Stage 1B) and inventory implementation (Stage 2B).
DATA EDITING	Application of attributes. Clipping away superfluous data. Start collection of metadata.	Inventory implementation (Stage 2D) and evaluation and analysis (Stage 3A).
DATA CONVERSION	Uniform spatial data base in chosen projection.	Evaluation and analysis (Stage 3A).
DATA VERIFICATION	Checking quality, accuracy, uncertainty, and reliability. Evaluation and improvement or allowance made.	Inventory implementation (Stage 2D). Evaluation and analysis (Stage 3A).
ANALYSIS	Data manipulation. Spatial analysis. Attribute analysis. Modelling.	Evaluation and analysis (Stage 3A and 3B).
RESULTS	Including uncertainty.	Evaluation and analysis (Stage 3C).
OUTPUT PRODUCTION	Layout, legend, and media.	Evaluation and analysis (Stage 3C).

data. During the planning and organisation of the inventory these issues need to be considered (para. 4.1.3). The data/information systems also play a valuable role in refining the design of the inventory and verification of the data (paras. 4.2.2 and 4.3.1, respectively). It is important for the cost-effective completion of a project that good communication is maintained between the inventory team responsible for the data collection and those responsible for the capture, analysis, and presentation of the results.

(iii) Data editing

Once the data have been entered, the attributes must be added to the digitised data. For example, waste volume, waste composition leachate concentration, etc. associated with a waste disposal site are considered as the attribute data (see Fig. 6.11). Most project parameters impose a geographical area of interest. If archive or third party data of a large volume are being utilised, it may be prudent to reduce the data, for example, to a study area. This has a number of advantages, the first of which is an increased drawing rate and analytical speed in digital packages. Second, and perhaps the most important, advantage is the reduction of storage space for the data and derivative data products. The data-editing phase is a good time to start the collection of metadata related to data that have been entered specifically for a project (para. 6.1.2 *(v)*). Remember to record the original scale and the source of the data for future referencing and accuracy assessment purposes (6.1.3 *(ii)*).

(iv) Data conversion

To ensure that the spatial data can be displayed in the same viewing window and co-registered for map-making and analysis, all data must be converted to a single uniform projection. A common procedure is to archive all data in geographical coordinates (longitude/latitude). The reasoning behind this is mainly to facilitate the transfer of data from one party to another, whilst not complicating the issue with projections. Both parties can then operate in whatever projection they choose. Also, many different project projections impose different demands upon spatial data. For both of the aforementioned reasons, geographical coordinates are a good archiving format. Most geographically enabled software is designed to work with, and transfer data between, a large number of internationally recognised projections. Further discussion concerning suitability of geodetical parameters could fill many volumes.

(v) Data verification

Errors can arise during the encoding and input of spatial and non-spatial data. The most common errors are (Burrough, 1990):

- spatial data are incomplete or repetitive,
- spatial data are in the wrong place,
- spatial data are at the wrong scale,
- spatial data are distorted,
- spatial data are linked to the wrong non-spatial data, and
- non-spatial data are incomplete.

Besides errors, the data may be over-defined, and may need to be reduced in volume. This commonly occurs with lines entered by stream digitising or with data obtained from scanner input.

The best way to check that the spatial data have been correctly digitised is to plot them out again, preferably on translucent, or in any case, thin paper, at the same scale as the original. The two maps can then be overlaid on a light table and compared visually, working systematically across the map.

Missing data, inaccurate location, and other errors should be clearly marked on the printout. Some of the better vector systems can also be instructed to print out the identification codes attached to each graphic entity. These too should be checked. If the map is a unique drawing, locational errors need only be considered within the map boundary. If the map is one of a series covering a larger area, then the spatial data must also be examined for spatial contiguity across map edges. Certain operations, such as polygon formation, may also indicate errors in the spatial data.

Non-spatial data can be visually checked and verified by simply printing out the files and checking these against the source data. A better method is to scan the data files with a computer program that can check for gross errors such as text instead of numbers, numbers exceeding a given range, and so on. Programs that link spatial and non-spatial data can also be used to check that all links have been properly made. The programs should be written in such a way that they flag only the errors.

Using patience and common sense, all major errors can easily be spotted in the spatial data. It is much more difficult to spot errors in non-spatial data when the values are syntactically acceptable yet still incorrect.

(vi) Analysis

Typically, information must be derived from the captured data through spatial analysis or data manipulation (intersecting data, dissolving data sets by attributes, sub-setting data sets, contouring point data, buffering of features, etc.). For deriving certain data sets (such as aquifer value and groundwater vulnerability), it will be necessary to carry out overlay analysis. This can often be more easily carried out using a cell-based modelling approach, rather than a vector-based approach. For anticipating or predicting the extent of contamination sources and associated impacts, as well as for testing the best remedial action to take in the case of contamination problems, the use of internationally accepted groundwater modelling software is recommended. All the analyses and results need to be completed and compiled prior to the map-making process.

(vii) Results

When all analyses have been performed and derivative data sets have been created, a further check is wise. Are the accuracy, quality, and origin of the data that have been collected and created acceptable in terms of the project objectives? Have the data audit, recording, conversion, and analysis yielded a seamless data base of sufficient spatial data to create the map? The results phase is a good time to complete a final accuracy assessment. Any data passing through to the next phase of the map production process will be utilised in the final map layout.

(viii) Output production – layout design

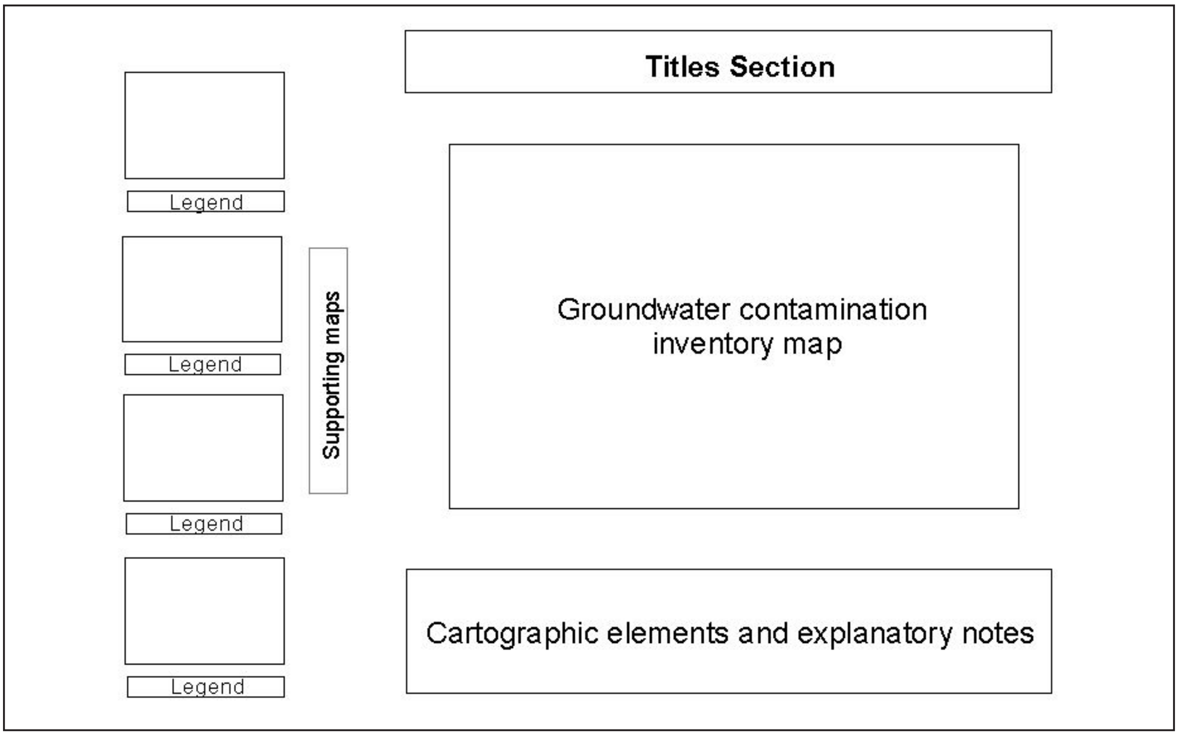
Keeping in mind the decisions that have been made so far (scale, detail, content, target audience, etc.), it is important to experiment with the different cartographic elements to obtain a comfortable balance within the map frame. Research to find an optimum size, or aspect ratio, indicates that maps look better with a width to height ratio of 4:3 (ESRI, 1994); however, this may vary depending on the outline of the study area. The map-maker must consider this outline to decide what shape and orientation will provide maximum clarity. If digital-mapping software is being utilised, the data can be displayed at various scales to assist with visualisation and also with selection of the appropriate scale. One of the simplest methods for pursuing this experimentation is manually sketching a variety of layout options. If a number of maps are to be produced in a set, it will be necessary to create a template that is appropriate for all the maps in the set. However, identical layouts for a set are not always possible or practical. Therefore, if different formats or orientations are necessary, then continuity of text and style throughout the set is essential.

In preparation of a groundwater contamination inventory map, the compiler should be aware that supporting maps are commonly included. This has layout implications for the cartographer to provide space on the map for the individual supporting maps (Fig. 6.2). Continuity in data preparation and view scale is imperative so as to provide an even presentation.

(ix) Output production – legend selection

Nowhere in a map production process is the concept of layers of information more important than in the selection of an effective set of legend colours, symbols, and patterns. There are many formal and international standards for legend selection. If creating a map in a specific field such as geology or hydrogeology, there are certain conventions in naming, labelling, colouring, patterns, and symbols. Many modern mapping software packages include international standard symbol sets. Further additions can either be extracted from other sources (for example, downloaded from the Internet) or created using icon creation/development options or font maps.

FIGURE 6.2 A suggested layout for the groundwater contamination inventory map



Field-specific symbol sets have been developed through time by international and national organizations in an effort to create a uniform understanding of maps and data (e.g. Struckmeier and Margat, 1995; Vrba and Zaporozec, 1994). If the circulation of the map being created is to include either educational/research institutions or parties that currently subscribe to recognised conventions, it will be expected that these conventions are followed. The key to a good legend is the elucidation of the critical information presented in the map whilst not dominating the map with bold, overbearing symbology that distracts the viewer during interpretation. Ancillary information, as discussed earlier, is presented only to assist with interpretation and orientation. The legend/symbology used should not distract the viewer from the intended message of the map. National and international standards exist for this part of the legend, raising the question of which standard to follow. This is, of course, entirely dependent upon the target audience and circulation. Standard sets are available from and used by national bodies such as the U.S. Geological Survey (USGS), the Ordinance Survey of Great Britain (OS), South African Directorate of Land, Surveys and Mapping, and other national mapping programs.

However, the design of derived, interpretive environmental maps, such as groundwater vulnerability maps, groundwater resource potential maps, or groundwater protection maps, still lacks international coordination, standardisation, and acceptance. Such maps are not comparable on the global scale and their international understanding is low. Therefore, the International Association of Hydrogeologists (IAH), within the framework of the International Hydrological Programme IHP-IV, Project M-1.2(a), suggested a model legend to facilitate the preparation of groundwater vulnerability maps in an internationally standardised form (Vrba and Zaporozec, 1994). A symbol set developed for this project is well suited for groundwater contamination inventory maps and the adapted version is included in Appendix C at the end of this guideline.

If a series of maps is to be produced, continuity throughout the set is imperative. But, if a series of maps is to be developed showing several different phenomena occurring in the same area, it is important to do both: to maintain continuity and to create legends that allow the interpreter/viewer to clearly discern the individual phenomena.

Care should be taken when inserting labels into maps. Typographic font selection and label position/orientation are the most important considerations in label application. Even the case (upper or lower) or font style (normal, bold, or italic) can greatly influence the legibility of a map. This can often be map specific, as text in one map could be extremely clear, but in another, the same text could be rendered illegible by the graphic content. Font style and selection are discussed at length by R. Phillips et al. (1977), showing examples of where tests were performed upon subjects searching for names on labeled maps. Results showed that the greatest success was achieved where labels were formatted to lower case with a large capital initial. Names set entirely in lower case take significantly longer to find than those set in small capitals with a large capital initial and so, emphasis given to the initial letter is clearly more important than word style (R. Phillips et al., 1977).

(x) Output production – explanatory notes

A standard map, such as a road map, a topographic map, or an aeronautical map does not have explanatory notes because the reader is expected to understand how to read and interpret the map. The groundwater contamination inventory map and groundwater contamination risk map, however, are special maps that convey a particular message. Thus in order to ensure that the map reader understands the maps, it is essential to have high quality and well-thought explanatory notes. These must be printed on the map sheet (Fig. 6.2), if possible, because if they are in a booklet, the map may be difficult to interpret when the booklet is lost. The explanatory notes must include the following:

- a description of what the map is, why it was prepared, and how it should be used. This is essentially an executive summary for the project;
- a detailed legend;
- a cautionary note regarding the map limitations and its intended use and purpose as well as a disclaimer on misuse of the map.

6.1.4 Supporting maps

In many instances, the major product of a groundwater contamination inventory is a map of the area that portrays the results of the project. Often, these maps, especially if they are stand-alone maps, oversimplify the results or include too much information, and therefore, confuse or mislead the user. The ineffective use of maps to portray results is due to a combination of poor definition of the purpose of the map, poor assessment of the knowledge of the user, poor cartographic skills of the map-maker, and the amount of time and effort it takes to prepare the complex and often multiple maps required to present the data (NRC, 1993). The effectiveness of the main message, which is shown by the main map, is enhanced if there are supporting maps presented to give more insight.

The value of including supporting maps with the presentation of the results is that they contribute to the overall assessment and understanding of the main concept being presented. The number of supporting maps to be included in a product is very much dependent on the objectives and scale of the project, the size of the final product, and the target audience. It is essential that the supporting maps are relevant to the purpose of the project and that they assist the target audience in understanding the presented main results.

Supporting maps should not be included just for the sake of making the final map colourful or for impressing target audiences with the number of data sets collected. This tends to clutter and confuse the results being presented and detracts from the desired effectiveness of the main product. Supporting maps also should not portray data already presented on the main map. However, it is very useful to have a common theme or feature, such as roads or rivers on the main map and all the supporting maps. This enables the audience to quickly locate and cross reference features from one map to another.

Supporting maps are typically smaller in size and scale than the main map and for these reasons should not be too detailed (yet, not over-simplified), nor multi-thematic. They need to be scaled, preferably all with the same scale factor. However, some supporting maps may serve the purpose of providing a zoomed-in or magnified view of a particular area. In this case the scale factor particularly needs to be included.

Each supporting map should have its own legend in close proximity and the data should be referenced. Fig. 6.2 shows how the supporting maps may be included in a layout of a groundwater contamination inventory map.

The types of supporting maps showing input parameters can be grouped into two main classes: those depicting natural resources (mainly groundwater conditions) and those depicting human activities. In addition, supporting maps may well portray the limitations and uncertainties associated with the final product. Supporting maps may include hydrogeological settings, important hydrological features, soils, etc. They also may include cross sections to provide further insight into hydrogeological settings. Groundwater maps that should be included would be those representing the aspects of groundwater that needed to be assessed for the final product. Other groundwater related features that could be included are aquifer importance (water use), groundwater resource quality and distribution, and groundwater protection zones. Additional natural resource maps may include weather and climate factors, surface water occurrence and quality, existing conditions of water bodies, and stream network density (Vrba and Zaporozec, 1994).

Anthropogenic data that may be of value to include on supporting maps are the extent of urban areas, location and type of industrial complexes and mines, potential contamination entries, main objects of protection (wells or other sources of water supply), and land cover connected to diffuse agricultural contamination.

The further use of supporting maps is that they can also show modelled and predictive 'what-if' scenarios for groundwater resource management purposes. Scenario prediction maps are very useful for adding further value to the main map. They are often valuable in emphasising the importance of taking certain management actions and can depict scenarios showing possible results of different levels of intervention. For example, if a contamination inventory indicates that there are potential contamination sources overlying a vulnerable aquifer, then scenario prediction maps can show what the consequences will be of changing urban plans, or of leaving the situation as is, or of allowing the situation to continue developing as it has over the past several years. If a risk-based approach is adopted, these type of scenario prediction maps can be valuable for providing decision-support to planners and resource managers.

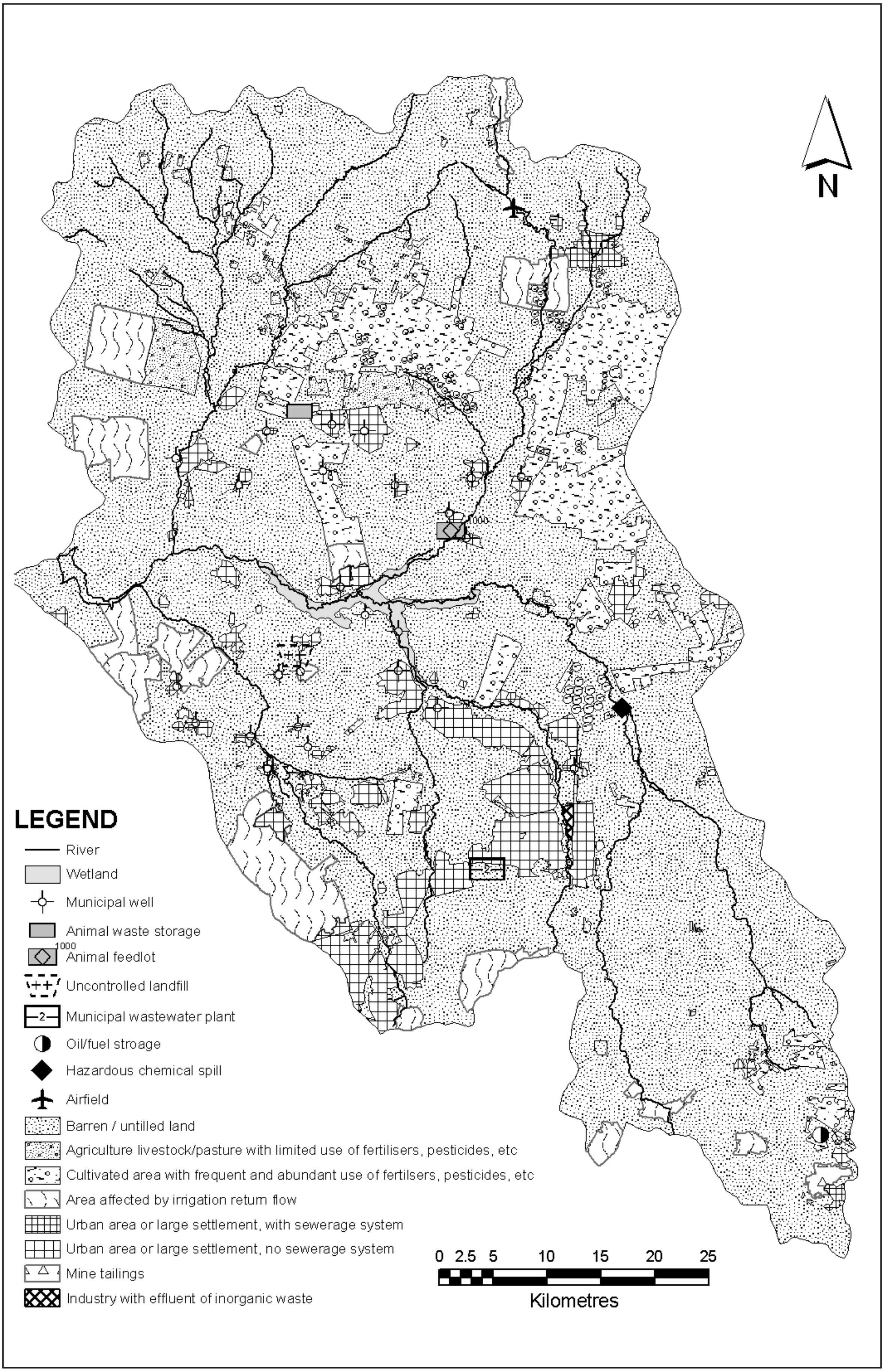
6.1.5 Example of a groundwater contamination inventory map

This example of a contamination inventory map (Fig. 6.3) is based on a study carried out in the Pienaar River catchment, South Africa – a mostly rural area with limited urban development. There is a large dependency on groundwater by the rural communities for their domestic water supplies. The inventory of potential contamination sources was done through field and windshield surveys. The potential contamination sources were mapped on 1:50,000-scale topocadastral maps, using the legend presented in Appendix C. The mapping included both the point sources and non-point sources. A dry-season Landsat5 multispectral image was obtained for the area, and was used to assist with the classification and more accurate delineation of contamination sources. The combination of field/windshield surveys and image processing significantly improved the accuracy of the contamination inventory mapping.

6.2 Groundwater contamination risk map

Methods for communicating the inventory results can vary widely. However, for resource managers and decision-managers, a risk-based approach is often preferred. The product that will assist in this process is a groundwater contamination risk map. A groundwater risk assessment can be performed if the probability for contamination and the consequence of contamination can be assessed (Chapter 5). (This risk assessment does not consider actual health risks due to the presence of a particular contaminant in groundwater.) The combination of the rating of the contamination source equates to the probability component and the rating of groundwater vulnerability and groundwater value equates to consequence. The risk that is described is thus the risk (or potential) of groundwater being contaminated. A high-risk value implies that the highly valuable groundwater resource will be impacted, or has already been impacted, due to the severity of the contamination source and/or the groundwater resource being easily accessible to contamination (for example, if a shallow water table exists, or the unsaturated zone has a poor

FIGURE 6.3 An example of a groundwater contamination inventory map



attenuation capacity). A low-risk value implies limited contamination sources and/or the groundwater naturally well protected from impacts and/or of limited value.

There are three factors that are required as input for producing a groundwater contamination risk map:

1) rating of the contamination source and the extent of existing contamination;
2) groundwater vulnerability rating;
3) groundwater value rating.

6.2.1 Contamination source rating

This is the first overlay that is prepared in order to produce the groundwater contamination risk map. The rating of the potential groundwater contamination load of an identified contamination source combines a number of key characteristics. These are extensively covered in Chapter 5, where several rating systems are presented (para. 5.3). After the contamination source has been evaluated, it will be rated, and the source will be assigned a category. On the map, the contamination sources and the areas of existing contamination will be labelled depending on whether they have been rated high, moderate, or low. A letter will indicate the rating of the source: H - high, M - moderate, and L - low potential contamination. The rating can also be based on a quantitative measure such as chemical concentration.

6.2.2 Groundwater vulnerability rating

Groundwater vulnerability to contamination varies depending on the degree of protection provided by the physical environment. In order to convey the degree of vulnerability (or the converse: what is the degree of protection of the aquifer provided by the physical environment), it is necessary to evaluate the various physical and hydrogeological conditions affecting the vulnerability. Results of this evaluation of the groundwater vulnerability will be the subdivision of an area into subareas that have different classes of vulnerability. These subdivisions show the relative vulnerability of a subarea to that of other subareas. Vulnerability ratings usually are relative, not absolute values.

Groundwater vulnerability and its rating was extensively discussed in the IAH publication *Guidebook on mapping groundwater vulnerability* (Vrba and Zaporozec, 1994). The definition of groundwater vulnerability is presented in the book as being 'an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts'. Special aspects of the vulnerability of shallow aquifers were addressed by Reynders (1994).

Various physical factors are used to assess groundwater vulnerability. The main factors are:

- recharge;
- unsaturated zone characteristics;
- the groundwater flow system.

Attributes of lesser importance include topography, ground/surface water interaction, and the nature of the underlying aquifer. All of these factors, as well as geochemical, biochemical, and physical processes affecting contaminant transport are described in Vrba and Zaporozec (1994).

The parameters listed above are used to evaluate the vulnerability of groundwater in a specific area to a particular contaminant or group of contaminants. Two or more adjacent areas can also be evaluated and compared. However, when larger areas comprising many subareas are evaluated, then additional techniques need to be used. A number of techniques have been developed and published, many of which are noted and discussed in the NCR report (1993) and in Vrba and Zaporozec (1994). These techniques are grouped into three basic groups: hydrogeological setting methods, parametric system methods, and analogic relations and numerical models. The parametric systems, which are the most used methods, include a variety of systems that can be divided into matrix systems, rating systems, and point count systems.

The matrix systems are based on a limited number of carefully chosen parameters, arranged in a simple matrix with numerical classification. For example, the system used in central England for the areas under the jurisdiction of the Severn-Trent Water Authority (Palmer, 1988) is based on a matrix of four types of soil leaching characteristics and three aquifer settings as shown in Fig. 6.4.

FIGURE 6.4 The matrix system used for groundwater vulnerability classification on Map 2 - Matlock, England (*Source:* Palmer, 1988)

Aquifer classification type	*Soil leaching class*			
	1	*2*	*3*	*4*
1	Extreme	High	Moderate	Low
2	High	Moderate	Low	Low
3	Low	Low	Low	Low

Rating systems take into account all the parameters that are judged necessary for an aquifer vulnerability assessment. A fixed range is identified for each parameter and rated. The sum of rating points gives an evaluation for the subarea or site being evaluated. The final numerical score is then divided into sections and each section describes the relative degree of vulnerability, in numbers ranging from a low (or nil) vulnerability to a high degree of vulnerability. A good example of rating systems is the GOD empirical system for the rapid assessment of groundwater vulnerability to contamination developed by Foster (1987).

Parsons and Jolly (1994) used the following four parameters in rating the impact of waste disposal on groundwater: the hydraulic conductivity and porosity of the unsaturated zone, the thickness of the unsaturated zone, the attenuation potential of the soil and unsaturated zone, and the hydraulic gradient across the barrier, to develop a formula for estimating travel time for contamination-bearing water to reach an aquifer. This travel time is then rated from 1 to 10 and used for site-specific investigations of the threat that a waste site poses to the groundwater (i.e. groundwater vulnerability).

The point count system models, which are also called 'parameter weighting and rating methods', introduce additional aspects to the rating system method. These methods recognise that some parameters carry more weight than others and for these a multiplier is added. The most well-known method is DRASTIC (Aller et al., 1987), which was developed for the U.S. Environmental Protection Agency. In this system each parameter is rated from 1 to 10 and weighted from 1 to 5, with 5 being the most significant. The depth to water table and the rock type of the aquifer are regarded as the most significant and are thus both weighted 5, whereas topography (angle of slope) is regarded as the least significant of the seven parameters used and is thus weighted 1.

6.2.3 Groundwater value rating

Groundwater is difficult to value; and as a result, economic valuation and future considerations have historically played almost no part in decision-making. Most groundwater studies to date have focussed only on the valuation of limited production-related services provided by groundwater, and not on a more comprehensive review of production and ecological services (NRC, 1997). A fundamental step in valuing groundwater resources is recognising and quantifying the resource's total economic value. Knowing the resource's total economic value is crucial for determining the net benefits of policies and management actions. The total economic value comprises 'extractive value' and 'in-situ value'. Extractive values are derived from municipal, industrial, commercial, and agricultural demands met by groundwater. In-situ values include, for example, the capacity of groundwater to 1) buffer against periodic shortages in surface water supplies; 2) prevent or minimise subsidence of the land surface from groundwater abstraction; 3) protect against seawater intrusion; 4) protect water quality by maintaining the capacity to dilute and assimilate groundwater contaminants; 5) facilitate habitat and ecological diversity; and 6) provide discharge to support recreational activities.

It is important to recognise the value even when one cannot develop specific quantitative separations of the various components. Even a partial or inexact measurement of economic value can greatly aid decision-making by providing insight into how economic value changes with a policy or management decision. The reader is referred to the work of the U.S. National Research Council (NRC, 1997) for more detail on valuing groundwater. Groundwater valuation is a complex process and a number of issues with high uncertainty have to be addressed. The groundwater value rating is presented in this guideline as an example of the evaluation of an important component of the groundwater contamination risk map, although we recognise that it includes an incomplete process. The approach is based on aquifer classification as a basis for groundwater value rating. Usually such a rating is developed using a matrix combining an aquifer classification system and a second, user-defined variable.

(i) Aquifer classification system

Parsons (1995) reviewed international aquifer classification systems and then developed a system for South Africa. The following discussion is adapted from his report. An aquifer classification system may be developed for a number of reasons. On a general and national scale these include: prioritising aquifers, developing and implementing policies and regulations, allocating limited groundwater management resources, setting water quality standards, defining monitoring requirements, and educating the general public. More detailed applications at a larger scale could include: providing information for policy formulation and implementation, setting of controls regarding groundwater abstraction, regional physical and land use planning, urban zoning, and setting of permitting and siting requirements.

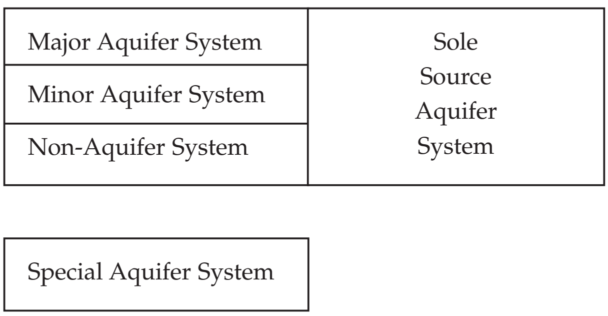
On evaluating aquifer classifications used elsewhere in the world, a number of common features were readily apparent. Most systems use between 3 and 5 classes; a wide range of criteria are used, many of which are related to aspects of aquifer usage considerations as opposed to the physical characteristics of the aquifer itself; the classifications tend to be quite general, with only total dissolved solids content being used quite specifically; and most systems appeared to be geared toward general decision-making (national scale) with more detail being required for more focussed judgments (local scale).

Three levels of aquifer systems emerged from the literature, namely: highly productive aquifers; aquifers of lower potential, but of local importance to their existing or potential user; and poor aquifers. This grouping conforms to that of the British Geological Survey (NRA, 1992).

Parsons (1995) noted that there were a number of positive attributes making this equally applicable to South Africa, especially that the grouping can accommodate both *major and minor aquifers* as well as *poor aquifers*. In addition to these three, he included *sole source aquifers* and *special aquifer systems* in his classification system. These five types of aquifers are shown schematically in Fig. 6.5.

The aquifer classification scheme described above has been developed for South Africa, which has mainly fractured rock aquifers and minor primary porosity aquifers. It focuses primaril on abstraction value. However, the classification could also include water use, water quality, or ecological value of groundwater, for example, spring or river baseflow contribution or support of ecosystems. In any case, a classification system should reflect the situation that exists at the study

FIGURE 6.5 South African aquifer classification system (*Source:* Parsons, 1995)



site. Such a system can be either the existing aquifer classification scheme for that country, an adaptation if the scheme is not quite suitable, or a new scheme.

There are a number of other groundwater resource or aquifer classification systems. For example, the state of Connecticut in USA adopted in 1980 'Water quality standards and criteria', which included a groundwater classification system (NRC, 1986). Connecticut is generally underlain by a shallow bedrock and water wells are commonly drilled in the alluvial aquifers to depths less than 30 m. Development of the system was prompted by concerns about the effects of wastewater discharges on groundwater. The system is based on use standards rather than quality standards. All of the state's groundwater was classified into one of the four classes established (Table 6.2).

The use standards are intended to restore or maintain the quality of groundwater to a quality consistent with its use for drinking without treatment. All groundwater shall be restored to the extent possible to a quality consistent with class GA, except where groundwater is designated as class GB or class GC. Other examples of aquifer/groundwater classification systems developed by the states in USA are summarised in Pye et al. (1983).

TABLE 6.2 Groundwater classification system of the state of Connecticut, USA (*Source:* NRC, 1986)

Class	*Groundwater use*	*Discharge allowed*
GAA	Public and private drinking water supplies without treatment.	Wastewater of human or animal origin and other minor cooling and clean water discharges.
GA	Private drinking water supplies without treatment.	Wastewater of predominantly human, animal, or natural origin that poses no threat to untreated drinking water supplies.
GB	May not be suitable for potable use unless treated.	All the above plus certain treated industrial wastewater, which shall not cause degradation of groundwater that could preclude its future use for drinking without treatment.
GC	More suitable for receiving permitted discharges then for development of public or private water supply.	All the above plus other industrial discharges that do not result in surface water quality degradation below established goals.

(ii) Groundwater value rating

Once an aquifer classification system has been defined (para. 6.2.3 *(i)*), then a rating of the groundwater value can be assigned. Table 6.3 shows two possible ratings for the South African aquifer classification system, which is described in the previous section. A sole source aquifer is given the highest rating because of the consequences to the dependant community should the aquifer be 'lost' for use. A special aquifer system can be any of the aquifer classes; it is merely an aquifer that

TABLE 6.3 Example of two possible ratings applied to the South African aquifer classification system

Aquifer class	*Numerical rating*	*Qualitative rating*
Sole Source Aquifer System	10	High value
Major Aquifer System	8	High value
Minor Aquifer System	5	Medium value
Poor Aquifer System	2	Low value
Special Aquifer System	2–10	Low, medium, or high value

has a differing legal status because it has been designated as such by ministerial decree of the Minister of Water Affairs.

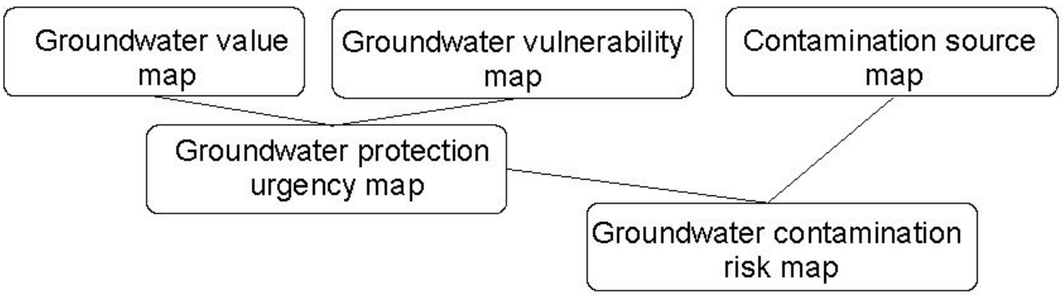
6.2.4 Compilation of groundwater contamination risk map

The final stage of production of the groundwater contamination risk map is to combine various overlays to produce the final product. At this stage, the various maps that have been assembled are:

- a contamination source rating map,
- a groundwater vulnerability rating map, and
- a groundwater value rating map.

These can be combined in various ways. One combination is described below. This combination includes the groundwater value and groundwater vulnerability rating, which results in the level of protection and the associated urgency that is needed for protection of the aquifer. The resultant groundwater protection urgency map is then combined with the contamination source rating (potential groundwater contamination load) map to produce the groundwater contamination risk map. This is shown schematically in Fig. 6.6.

FIGURE 6.6 The stages of combining various rating maps to produce the groundwater contamination risk map



For the combination of the ratings displayed on maps, a matrix approach can be adopted. In this approach, various matrices set up for contamination sources, vulnerability, and groundwater value are combined. The combination of matrices recommended for the derivation of a groundwater contamination risk map is in the figures below. This is a two-step process. The first matrix (Fig. 6.7) is used to obtain the groundwater protection urgency. The second matrix (Fig. 6.8) is used for the derivation of the groundwater contamination risk.

The approach presented will result in a qualitative assessment of groundwater contamination risk. It will enable decision-makers and planners to identify areas of priority. It is recommended, when compiling the report and final map, that the input maps are also included. A map layout is shown in Fig. 6.9. A proposed legend for the groundwater contamination risk map is presented in Appendix C.

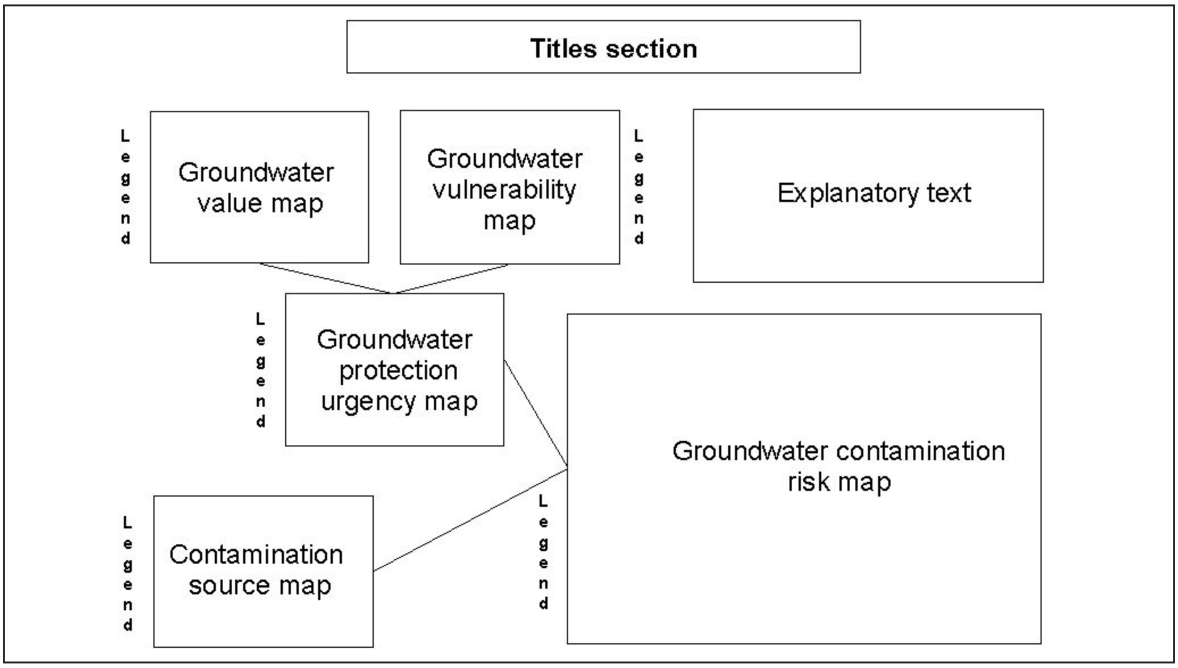
FIGURE 6.7 Groundwater protection urgency matrix (for groundwater value ratings see Tables 6.2 and 6.3)

Groundwater protection urgency		*Groundwater vulnerability rating*		
		Low	*Moderate*	*High*
Groundwater value rating	*Poor/GC*	Moderate	High	High
	Minor/GB	Low	Moderate	High
	Major/GAA or GA	Low	Low	Moderate

FIGURE 6.8 Groundwater contamination risk matrix

Groundwater contamination risk		*Groundwater protection urgency*		
		Low	*Moderate*	*High*
Contamination source rating	*Low*	Low risk	Low risk	Moderate risk
	Moderate	Low risk	Moderate risk	High risk
	High	Moderate risk	High risk	High risk

FIGURE 6.9 A proposed layout for the groundwater contamination risk map



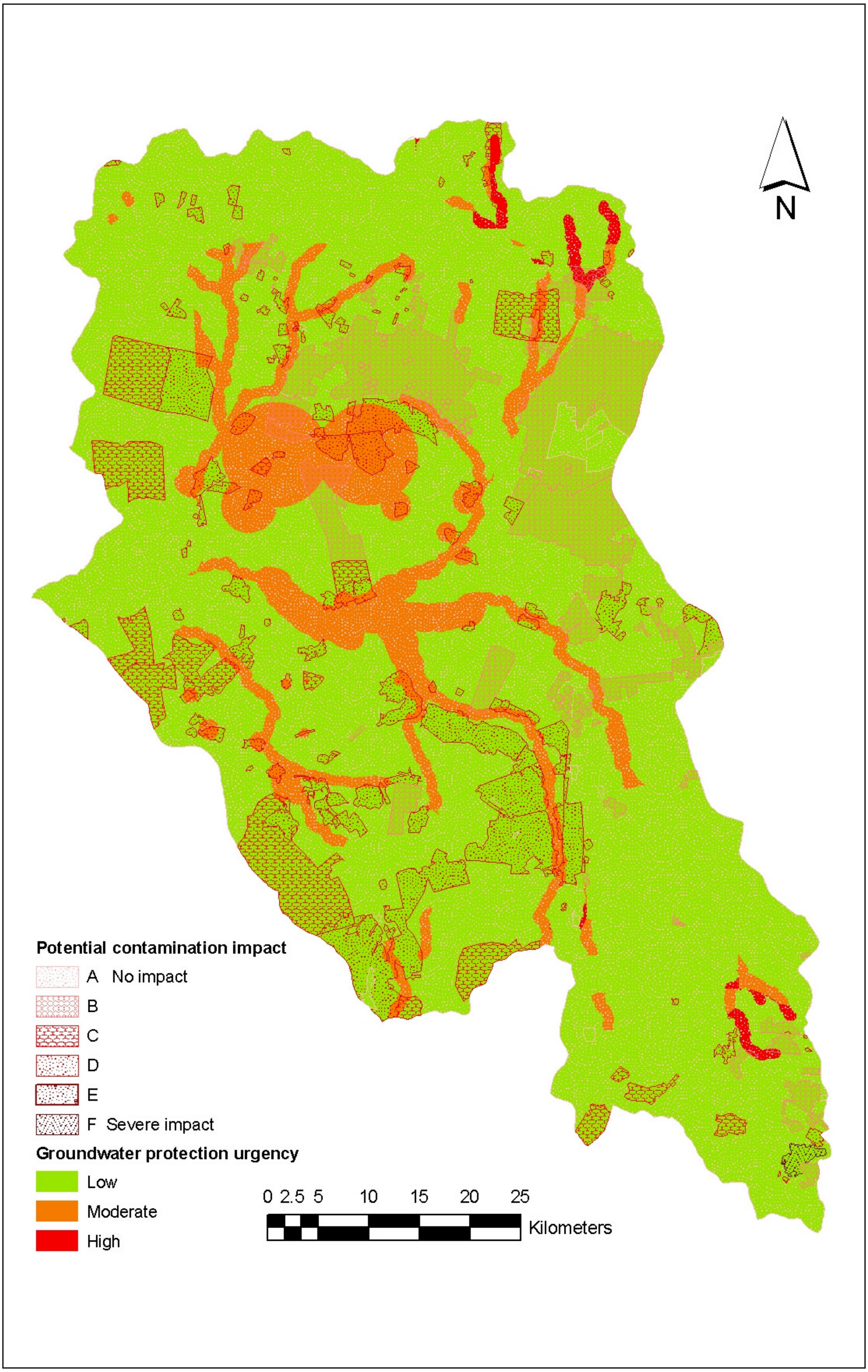
6.2.5 Example of a groundwater contamination risk map

A groundwater contamination risk map is the resultant map produced by overlaying results of the groundwater contamination inventory (potential contamination impact) upon the groundwater protection urgency map (Fig. 6.9). The potential contamination impact, or load, is derived from the rating of contamination sources identified in the inventory. The groundwater contamination risk map in this example (Fig. 6.10) is based on the example in para. 6.1.5 (Fig. 6.3). The contamination risk map is of particular importance to relevant authorities, decision-makers, and planners as it helps identify the priority areas for protecting groundwater and the activities that need to be properly managed and controlled. It also provides guidance for the design of groundwater monitoring systems. In Appendix C, recommendations are made as to the choice of symbols and colours to ensure the groundwater contamination risk map is easily interpretable.

6.2.6 Modelling existing and future scenarios

The groundwater contamination risk map can be used as it is for many purposes, including education and informing the public and decision-makers about dangers to the water supply sources. However, action will need to be taken in order to solve, reduce, or prevent contamination that threatens the groundwater resource. In order to do this, a decision-support needs to be provided to the relevant bodies that will be initiating the action. Thus, the next stage, after producing the groundwater contamination risk map, will be to model existing and future scenarios. This modelling can be, for example, of the contamination plume movement. The movement of the

FIGURE 6.10 An example of a groundwater contamination risk map



plume will be modelled first as if there is no intervention and then as if intervention took place. Intervention would be actions such as wellhead protection zones, leachate treatment, pump and treat, and installing impermeable linings.

The modelling will develop future scenarios and these can be shown in map format. For example, two sets of maps can be produced:

1) No intervention, i.e. what will the situation be in 10, 20, 50, etc. years;
2) With intervention, i.e. what will the situation be in 10, 20, 50, etc. years.

These future scenario maps can be included on the main map sheet accompanied by their own explanatory notes or can be included in the supporting document. Communication of these scenario predictions can be greatly enhanced if these are, in addition to the printed maps, animated on the computer screen by using the 3-D and time visualisation tools that are available for GIS (para. 6.4.4).

6.3 Geographical Information System in map production

Maps can be compiled manually or by computer, depending on the size of a project and the financial and staff resources of a map-maker. Although the Geographical Information System (GIS) is the system of choice nowadays, considerations of cost, time, and professional resources may limit the production of maps in a GIS format. For example, if the study is not part of a long-term assessment or program, or if only a small area is studied, then the use of manual techniques Zaporozec, 1994). However, for large projects with a great amount of data, mapping may be more efficiently conducted by using a GIS.

6.3.1 GIS components and functions

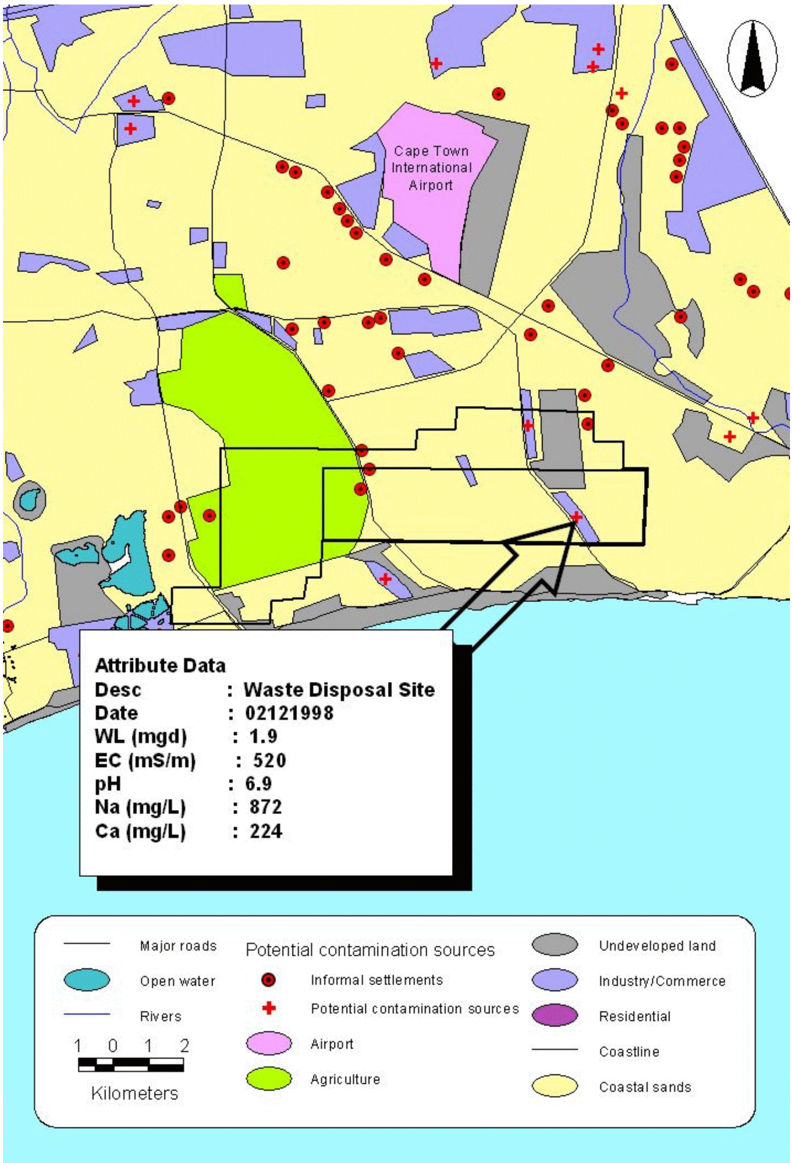
The most common form of digital mapping technology used today is the Geographical Information System (GIS), which can be very helpful by rapidly providing systematical information. Simply put, GIS is a user interface for spatial data bases. This technology makes it possible to combine layers of digital data from different sources and to manipulate and analyse how the different layers relate to each other. An alternative description of GIS is: 'an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture (record), store, update, manipulate, analyse, and display all forms of geographically referenced information' (ESRI, 1994).

Major advances in the availability and functionality of GIS software have seen this highly practical and user-friendly mapping technique being implemented throughout the world. Foreign aid programs, government surveying departments, and environmental organizations across Africa, Asia, and Latin America have increasingly taken up GIS as the mapping tool of choice in a wide variety of disciplines. Many of these organizations, some utilising remote sensing technology, have completed many projects in fields that include transportation, environmental science, ecology, meteorology, and geology, which parallel and in some cases exceed those completed in the developed world.

Digital spatial data are commonly a vector graphic in the form of a point, line (arc), or polygon with attributes attached in a standard data base file. This spatial information is often digitised from existing maps or remotely sensed data. The attributes are either joined from a look-up table or manually input into the data base. These attributes can vary from a simple identification number (ID) to many fields of descriptive information. The GIS will commonly feature a Graphical User Interface (GUI) to assist the user in manipulating the data. The layers can be combined into a viewing window and the order within the layering system changed to assist with analysis. The attributes allow the user to query or classify the digital data in a display according to specific criteria. For example, if point contamination sites are digitised from a map, attributes can be applied to each section point either during the digitising process or at a later stage. These attributes can be used to describe each contamination source (Fig. 6.11). Features or elements in the view can also be labelled in specific styles using the attributes.

An integral part of most contemporary GIS software packages is a layout or map-making

FIGURE 6.11 Vector attributes in spatial data and associated attribute data



option. This allows the user to compile maps from the data views that they have created. More complex products automate the addition of cartographic elements such as scale bars, north arrows, and measuring grids/graticules. Dynamic links between the digital features in the data view and the map layout not only allow the data to be shown in their predefined format, but assist in the creation of legend keys on the map. Used correctly, these functions allow the creation of complex maps whilst eliminating human error. Whether used in government, business, military, or a host of other applications, a GIS provides the means to examine, and to map, relationships in ways never before possible. Further assistance to the cartographer exists in GIS packages in the form of a wide variety of national and international geodetical standards, map unit presets, and view/layout scale relationships.

6.3.2 Hardware requirements for GIS

Spatial data sets are commonly not large digital entities in comparison to image (raster) data. The graphics element and index to the data base are relatively small, usually less than 1 Megabyte (Mb) in size, depending on the complexity of the feature they represent. The number of fields and records of the data base element usually determines the overall size of the spatial data set.

Complex data sets can be in the range of 10–20 Mb. Hence, if manipulating numerous layers of information in a GIS, disk storage space is an important consideration. If data input is necessary, a digitising. tablet will be required to transfer hard copy information into digital data.

As GIS packages now feature more complex display and analysis features, they are often processor-intensive, often requiring a minimum of a Pentium microprocessor and 64 Mb of RAM. Refresh rates of the GUI are improved with the use of more capable microprocessors and better graphics cards and memory. Relational Database Management Systems (RDBMS) serving data to a large group of GIS users require very large storage capacity and fast computer servers.

6.3.3 GIS software packages

There is an ever-increasing market for GIS software packages ranging from desktop products to large process-intensive systems and spatial data base engines (Table 6.4). As with many sectors of the software development industry, the GIS packages currently available exhibit similar capabilities, differing mainly in the data models upon which they rely.

In keeping up with current trends in information technology, ease of use is a common feature of GIS software design. A user with a good knowledge of the fundamentals of GIS theory will be able to create simple and effective maps with little problem.

Most contemporary packages also include a macro or scripting language allowing the development of applications required for spatial analysis or the automation of mundane, repetitive tasks. Apart from removing the necessity for operator participation in batch processing or mapping function, macros/scripts also remove the element of human error from these processes.

Basic GIS software can range in price from as little as US$ 500 to US$ 1,300 for desktop products and in excess of US$ 10,000 for industrial GIS and DBMS products. These prices are approximate and do not include extensions or add-ons. These must be purchased separately.

6.3.4 Additional extensions of GIS

Most GIS software packages now feature additional extension operations that expand the analytical and processing capabilities of the GIS environment. Only some of these facilities are pertinent to groundwater contamination mapping. Whilst some extensions allow the GIS to handle additional data types (raster and image data), some take GIS mapping into a third (z value) and even a fourth dimension (time). Three-dimensional (3-D) visualisation tools can be valuable in the development of an alternate perspective. These 3-D and time tools hold a lot of promise for presenting to decision-makers the results of scenario modelling and predictions.

6.3.5 Advantages and disadvantages of GIS versus other mapping techniques

The primary advantage GIS holds over other mapping techniques is its enormous capacity for attribute information and ability to accurately encapsulate spatial relationships. Computer Aided Design (CAD) software is perhaps the product closest to GIS. It can handle digital spatial data, but is limited in its ability to handle attribute information and has little or no geodetical capability. CAD spatial capabilities only extend as far as line and point data; and data are exclusively entered and stored in metric units. GIS can also process, display, and project all areal information and all vector formats (lines, points, and polygons).

Dynamic links between GIS software and data bases allow the creation of predefined query environments, in which, as data base attributes are changed through external data base input forms, the map layouts in the query environment respond.

Physical space is another major consideration. A map-server computer can be used to store many thousands of digital data sets that can be served to GIS users through client-server technology over a network. Hence, the equivalent of many thousands of paper maps can be stored on a central server, thus saving space, centralising data storage, and standardising data set use.

A disadvantage of these mapping techniques is the misconception that because the operator is working in a digital environment, accuracy is maintained throughout. There are many factors to

TABLE 6.4 Selected GIS and mapping software

Company	*Prodcut/Description*	*Website address*	*Price*
CadCorp	SIS A suite of integrated modules covering desktop mapping to corporate GIS.	www.cadcorp.co.uk	POA
	SIS ActiveX A suite of modules for embedding within 3rd party applications.		POA
Clark Labs	Idrisi32 High-end, raster GIS and image processing for advanced spatial modelling.	www.clarklabs.org	From $250
	CartaLinx Easy-to-use tools for vector data input, editing, and export.		From $200
ComGrafix	MapGrafix GIS The first GIS on the desk top with digitising, printing/plotting, and analytical tools.	www.comgrafix.com	$990
ERDAS, Inc.	IMAGINE A full suite of products for image mapping, visualisation, and processing.	www.erdas.com	POA
	ArcView extensions Easy-to-use geographic imaging for ArcView users.		POA
ESRI, Inc.	ArcInfo High-end GIS with new open development environment for customisation.	www.esri.com	POA
	ArcView Intuitive desktop mapping and Internet GIS package with unique extensible architecture.		£1 095
GGP Systems	GGP WIN GIS GIS for local authorities; ideal as corporate networked solutions linking to data bases.	www.gppsystems.co.uk	£995–£1,495
MetaMAP, Inc.	MetaMAP A full-featured PC-based GIS; includes several graphic and non-graphic data translators.	www.metamapgis.com	POA
Survey Supplies	FASTMAP GIS for Windows Easy-to-use, fast, fully customisable GIS.	www.surveysupplies.co.uk	£2,500
ThinkSpace, Inc.	MFWorks Easy-to-use raster-based GIS for spacial analysis, mapping, and image processing.	www.thinkspace.com	$900
XYZ Digital Map Co. Ltd	MAPUBLISHER Turns freehand illustrator into GIS; ideal for quality map production.	www.xyzmaps.com	£260

POA: Price on application.

Note: Software listed in this table is given as an example for information purposes only. The list is not an endorsement of any company or its products.

consider when working with digital data, the most important of which is data integrity. If a standardised level of data recording and handling is maintained throughout the mapping process, the end product should, to all intents and purposes, engender an equal level of accuracy. Caution should be exhibited when using spatial data of unknown or undocumented origin or accuracy. It only takes one data set of questionable integrity combined with data of a known standard to create results of a false nature. This is a common theme arising in current literature and debate surrounding concerns such as metadata and spatial data standards.

With sufficient support from its hardware environment, a GIS user can manipulate vast quantities of data efficiently and effectively. When considering the cost benefits of available techniques in financial outlay, professional input, resources, and time, no other map-making process can match the speed, accuracy, and reliability of GIS.

To maximise efficiency and capability, training in GIS theory and software use are essential. A correct introduction to the concepts of GIS and a formal explanation of the data models involved are invaluable when working with spatial data. Such training is usually offered by vendors of software and can often be tailored to the needs of a specific client. These courses can be costly, but if they are prepared correctly and involve the manipulation and mapping of groundwater contamination data, a lot of time and money can be saved.

6.3.6 Image processing software/GIS relationship

Many modern image processing software packages include some GIS functionality, either in the ability to export to GIS-software-supported image formats or actually allowing the use and creation and editing of vector GIS data in their analysis and mapping functions.

Current trends in three-dimensional visualisation are influencing this field. Image drapes, pioneered by image processing software packages, have recently been taken one step further with the ability of some software packages to display spatial vector data and raster data together in a 3-D environment. These processes can reap rich rewards in the identification of relationships not clear in two dimensions.

6.3.7 Serving map data on the Internet

The last few years of the 20th century have seen enormous advances in communications technology. Moving to the forefront of this field is the Internet and its related technologies. Initially designed to deliver text, the browsing technology has been developed to now include graphics, animations, and even stand-alone programs that run within the Web page (Fig. 6.12).

Several of the larger GIS software companies have developed software to drive map-serving over both company Intranets and the Internet. This technology enables:

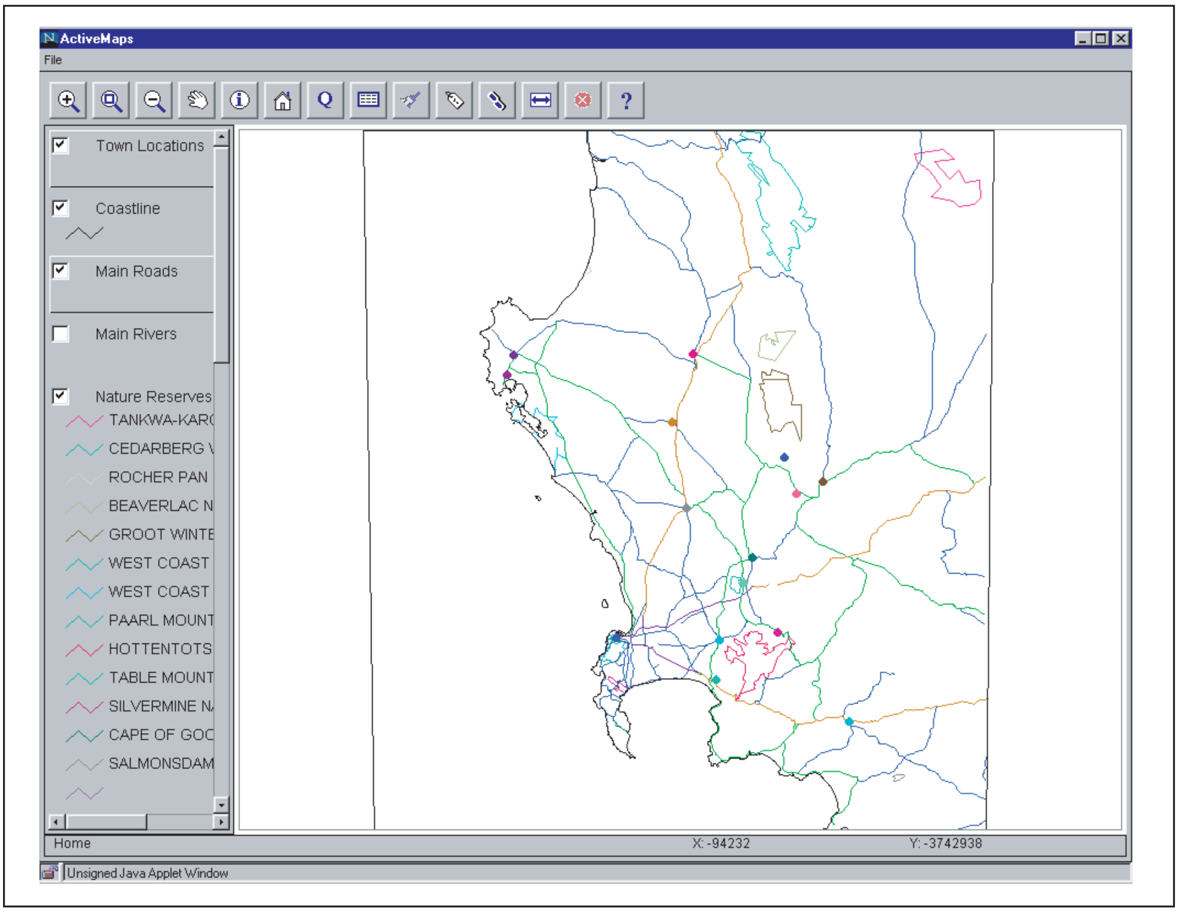
- searching for specific site locations;
- displaying and viewing multiple data sets;
- conducting query-based analysis;
- performing data purchases;
- retrieving specialised data services (ESRI,1994).

Internet map-serving allows the production of a map in a digital format. It also allows interactive manipulation of geographical data, similar to a normal GIS graphical user interface.

6.3.8 Useful websites addresses for map production

http://www.usgs.org/mac/isb/pubs/booklets/topo/topo.html
http://www.usgs.org/mac/isb/pubs/factsheets/fs05698.html
http://www.usgs.org/mac/isb/pubs/factsheets/fs07896.html
http://www.utexas/edu/depts/grg/gcraft/notes/cartocom/cartocom.html
http://www.nottingham.ac.uk/education/maps
http://www.esri.com
http://www.mapinfo.com
http://www.innovativegis.com

FIGURE 6.12 A Web-page embedded Java applet that allows display of shape files



7 Using results of the inventory to protect groundwater

Erik Romijn and Alexander Zaporozec

7.1 Groundwater protection, a question of priorities

Hydrologists have been involved in the protection of groundwater against contamination, especially with respect to drinking water, for a long time. In France, for example, hydrologists were officially appointed as advisors since 1900. The involvement became more intensive during the rapid economic development in the second half of the last century, especially in the industrialised countries, where both the number of groundwater abstractions and contamination accidents increased. The UN Conference on the Human Environment, held in Stockholm in 1972, led to the creation of the UN Environment Programme, and gave a major impulse to environmental thinking and public concern.

Protection of the environment, including the groundwater, comprises both resource and waste management. As to waste management, the commonly accepted priority sequence is:

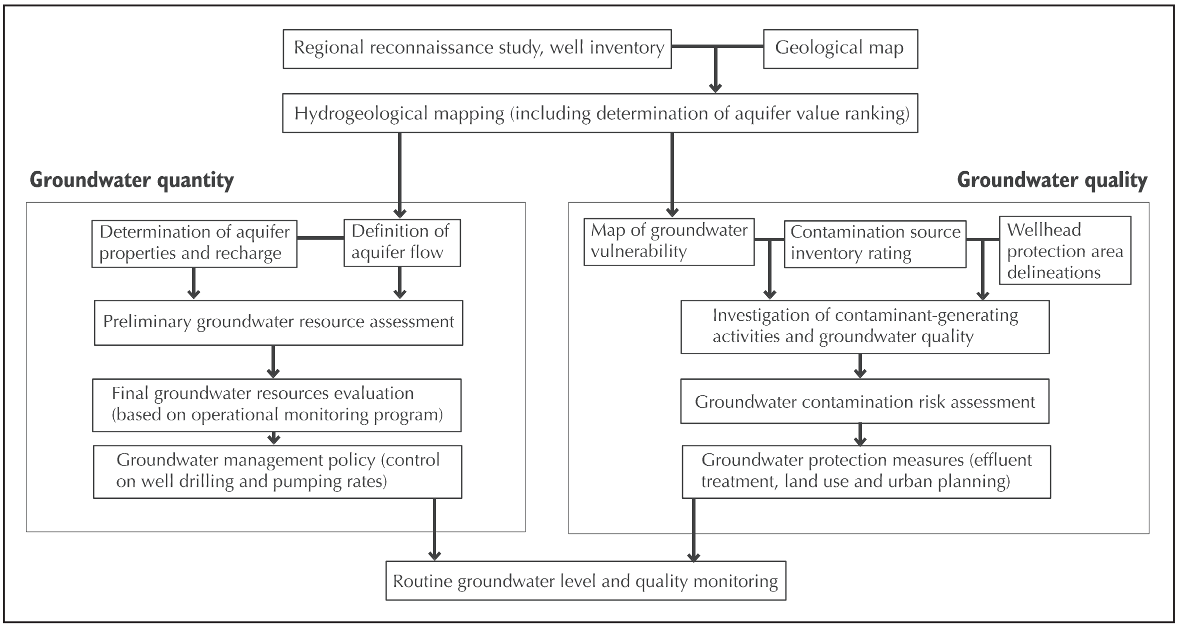
1) prevention of waste generation;
2) recycling and reuse of waste products;
3) processing of waste: reduction of volume (dewatering, incineration, etc) and decontamination of hazardous waste;
4) isolated storage of waste.

This sequence is difficult to apply to diffuse contamination. Moreover, because of its interregional character and its interrelation with land use practice, diffuse contamination is much more difficult to regulate. However, for diffuse contamination, 'prevention' can be translated into development of less harmful products and production methods. In agriculture, for example, less persistent, more degradable pesticides could be developed and applied, while restrictions on the use of fertilisers and pesticides could lead to both cost reduction and environmental benefits.

Groundwater protection requires a number of restrictions on land use and human activities. Integrated land use planning is most appropriate to solve conflicts between land use and groundwater protection, as it takes, from the beginning, all relevant aspects into consideration (Purnell and Thomas, 1987; Vrba and Aldwell, 1991). Integrated land use planning, groundwater protection, and soil and groundwater remediation are only possible after a thorough inventory of potential contamination sources and the assessment of vulnerability and of the value of groundwater resources have been carried out. A monitoring system is necessary to evaluate the interaction of land use practices and groundwater quality. The relationship among various elements and activities of groundwater evaluation and protection program is shown in Fig. 7.1.

The protection of soil and groundwater in urban areas is most difficult in the case of unconfined aquifers. Installation and maintenance of a sewerage system and the safe disposal of hazardous waste are preventive measures. In the case of a confined aquifer, the breaching of confining layers must be prohibited. Generally speaking, in urban areas an area-planning approach is used: the functions of urbanisation and groundwater abstraction for public water supply are separated in such a way that they do not interfere too much.

FIGURE 7.1 Overall scheme of groundwater resource evaluation, management, and protection (*Adapted from:* Foster and Hirata, 1988)



The contamination source inventory is a valuable planning and management tool for prioritising threats to drinking water supplies and for developing adequate management alternatives to deal with the contamination sources according to set priorities. It allows planners and managers to design appropriate controls and to determine the area(s) in which the controls should be applied first, or most.

Although it cannot be completely eliminated, groundwater contamination can be minimised or corrected. There are basically two approaches in dealing with groundwater contamination problems: to handle contamination after it has occurred or to prevent new occurrences (Zaporozec and Miller, 2000). A successful groundwater protection policy must include a combination of three basic alternatives: prevention, remediation by natural attenuation, and remediation technology.

7.2 Protection strategies and decision-support methods

7.2.1 Selecting groundwater protection strategies

Results of the contamination source inventory can be used for developing groundwater protection strategies. The ultimate purpose of the inventory is to protect the sources of water supply, or the groundwater in general, against contaminating substances that have been, or might be, released by the identified contamination sources.

Strategies for groundwater protection may range from careful, complete protection to 'controlled degradation' of groundwater quality, and even to complete dedication of an aquifer or its portion to treat and/or store wastewater. In general, groundwater protection strategies and alternatives can be grouped into three broad categories: natural protection, corrective actions, and preventive actions (Table 7.1).

Selecting a groundwater protection strategy involves making choices (Born et al., 1987). There is no formula available to guarantee making the right choice and a good course of action. The variability in groundwater systems, perceptions of groundwater problems, social and political traditions, and management and financial capabilities suggest that most likely different countries will select different groundwater protection strategies. What might be a good choice in one area, would be completely inappropriate for another. Therefore, the following strategies are intended only as examples of how the planners and managers may address one of the most important aspects of a groundwater protection program: control of contamination sources.

TABLE 7.1 Groundwater protection alternatives (*Source:* Zaporozec, 1998)

Natural protection	*Corrective actions*
Remediation by natural attenuation	Source removal/isolation
(Vulnerability assessment)	Source/contaminant containment
Preventive actions	Physical encapsulation
	Vitrification
	Vertical barriers
Contamination source inventory	Interceptor trenches
Source control/elimination	Hydraulic containment/barriers
Land use controls	Permeable reactive barriers
Design/operation requirements	Cleanup and treatment
Well construction regulations	Pump-and-treat system
Well protection zones	In-situ bioremediation
Laws, regulations, enforcement	Bioventing/air sparging
Inspection and training	Soil vapour extraction
Voluntary management practices	Steam injection
Waste reduction (recycling, reuse)	Soil flushing
Public education	(Site characterisation)
(Monitoring)	

The completed contamination source inventory will probably have answered some concerns the officials, planners, and managers might have had, such as (Born et al., 1987):

- What are the sources of potential contamination problems?
- Which contamination sources pose the greatest threat to groundwater resources and should be given priority in a groundwater protection program?
- Are there areas where contamination already exists or is likely to exist?

The control strategy for each source needs to be based on the type of the source and its potential magnitude of impact. Point sources (e.g. landfills, sewage effluents, leaking underground tanks) can be controlled with well-understood engineering methods. Non-point (diffuse) sources can be controlled by a combination of measures ranging from education to land use planning to actual prohibition of activities resulting in the release of hazardous contaminants, such as pesticide use. Accidents and illegal dumping are a third source of contamination that requires control. Their unpredictability makes it difficult to deal with them. Advance planning can provide for regular inspection and monitoring of sensitive areas, and for emergency spill response plans. Not all contamination sources pose the same threat to groundwater resources. The threat depends upon the size of the population potentially 'at health risk', the toxicity of particular contaminants, and the geographical extent of the area or aquifer that is, or most likely will be, affected by contamination.

To select the scope of management initiatives is the first choice planners and managers must make (Born et al., 1987): Should a groundwater protection program be aimed at all contamination sources at once or should it address them gradually, selecting the most critical first? Many programs probably will have a modest beginning and will focus on contamination sources that have received the highest priority. This choice may reflect limited technical and financial resources or the lack of an immediate need for a more comprehensive program. In contrast, a more comprehensive effort may be essential when the nature of groundwater contamination demands action on a number of fronts; for example, concentrated multiple urban and rural sources.

The second choice relates to the groundwater protection path that is to be followed. To determine to what degree will the groundwater protection program be remedial versus preventive in nature is among the first decisions to be made when selecting groundwater protection strategies. The discovery of groundwater contamination is often the event that triggers citizen concerns and demands for immediate action (Born et al., 1987). In responding, the planners and managers must weigh the costs and effectiveness of addressing the momentary crisis against preventing groundwater contamination problems in the first place. The high costs and limited efficiency of remedial technologies underscores the value of preventive approaches. A well-publicised contamination source inventory conducted in the area will increase public awareness of the value of the local groundwater resource and its problems and potential solutions. Consequently, the public may be more receptive to accept the focus of the groundwater protection program on prevention.

Another choice to be made is between dealing with contamination sources generally, wherever they occur, and focusing on controlling specific areas. The first choice will require substantial technical and financial resources. The second choice would involve addressing the sources in naturally vulnerable areas, critical groundwater recharge areas, or recharge areas of public water supplies.

And finally, the element of time needs to be considered when selecting a groundwater protection strategy. Actions that are short-term in nature, in terms of time to implement them and in duration of their effects, need to be defined. What actions should be integrated as short-term first steps within a long-term program needs to be determined. In addition, long-term actions that can be identified, but implemented in stages over many years need to be addressed (Born et al., 1987).

7.2.2 Decision-support methods

Decision-making with respect to groundwater protection strategies and management alternatives proves to be a complicated affair because various conflicting social interests are involved. A clear analysis of socioeconomical, technical, and environmental aspects of groundwater protection could support planners and decision-makers in their choices. Systems analysis as a tool for presenting strategies and management alternatives is now a common practice. Systems analysis clarifies the interactions between the socioeconomic and environmental subsystems and their elements. By formulating cause-effect relations, consequences of different management alternatives can be evaluated and risk assessments drawn up.

The decision procedure as such, being a political action, is sometimes still rather vague and difficult to understand. Yet, there are various techniques that may help planners to present as clear as possible objectives, alternatives, and decision criteria used. Politicians, in turn, can change and reformulate objectives and criteria according to their principles, which makes their policy more clear to the general public.

If all the consequences of contamination could be expressed in one unit such as US$, decision-making would – in principle – be simple. However, just because environmental deterioration cannot easily be evaluated in economic terms, groundwater contamination has been neglected until recently. Decision-making should be based on different criteria, which may be non-commensurable. Various multiple-criteria decision-support methods have been developed for this purpose, such as the scaling method for priorities proposed by Thomas Saaty (1977). Because of its simplicity and flexibility, Saaty's method has proved to be very useful and acceptable to politicians, at least for a sensitivity analysis of different criteria. The Saaty scaling method is easily extended to hierarchical structures.

7.3 Prevention of groundwater contamination

7.3.1 Preventive actions

Given the importance of groundwater as a source of drinking water for so many communities and individuals and the cost and difficulty of cleaning up contaminated water, the best way to guarantee continued supplies of clean groundwater is to prevent contamination. Contamination of groundwater is not normally easily noticed and the detection of the source of contamination may present difficulty, particularly, for example, where the nature of the underground strata permits contaminating substances to travel considerable distances. Even when the source of contamination has been traced and removed, it may be that the residual contamination of an aquifer will continue to pose problems. Once groundwater has been contaminated, it may take many years after the source of contamination has been eliminated for natural processes to remove the contaminants from the aquifer.

Therefore, a major effort should be directed toward preventing contamination from occurring. The cost of groundwater protection through prevention is generally much smaller than the cost of remediating the groundwater after contamination is found (Zaporozec and Miller, 2000). Prevention of groundwater contamination involves, in the first place, the control or elimination of contamination sources. Table 7.2 shows examples of legal and voluntary measures that can be taken for contamination prevention and for control of individual contamination sources.

Although monitoring (para. 7.5), by itself, is not a method for protecting groundwater quality, it should always be a part of any prevention program to monitor whether the preventive measures are working and contamination has not occurred.

TABLE 7.2 Examples of methods for control of potential sources of groundwater contamination (*Source:* Foster et al., 1993; Zaporozec and Miller, 2000)

Source	*Control method*
Fertilisers and pesticides	Nutrient and pesticide management to meet crop needs. Control of rate and timing of application. Integrated pest management. Banning use of selected pesticides. Regulation of disposal of used containers. Training, guidelines, and education.
Animal waste	Animal waste storage ordinances. Voluntary best management practices for farmers how to manage barnyard and feedlot runoff. Education. Technical assistance.
Irrigation	Improvement of irrigation efficiency by proper scheduling. Education.
Solid waste disposal sites	Regulation of siting, construction, operation, and closure of sites. Lining the bottom with impermeable material (clay) or plastic. Leachate collection and treatment. Impermeable cover. Prohibition of hazardous wastes. Waste reduction. Monitoring.
Septic systems	Regulation of siting and installation. Mandatory periodic inspection. Licensing of site evaluators, installers, and inspectors. Education.
Wastewater lagoons	Site selection requirements. Design and maintenance standards. Impermeable lining of the bottom. Mandatory training of operators.
Underground storage tanks and pipes	Mandatory periodic inspection and pressure testing for leaks. Monitoring.
Aboveground storage tanks	Installation of containment structures under and around the tanks. Periodic inspection for leaks. Education.
Hazardous waste storage and transport	‘Paper trace’ of hazardous materials. Design and operation standards for storage facilities. Mandatory inspection of transportation equipment. Licensing of operators. Heavy fines for spills. Emergency spill response plan. Reuse and reduction of hazardous materials. Education.
Mining waste	Design and operation standards. Monitoring.
Injection wells	Careful investigation of geology and hydrogeology. Strict design, construction, and operation standards. Monitoring.
Water wells	Regulation of siting, construction, and abandonment of wells. Licensing of well drillers. Well protection zones. Education.

7.3.2 Regulatory options

The development of regulations plays an essential role in preventing and/or minimising the effect of groundwater contamination. The necessity to regulate soil and groundwater contamination by law within the general framework of environmental protection has become common option, especially in the more industrialised countries. The central idea is that sustainable use of soil and groundwater for different purposes such as agriculture and drinking water is guaranteed.

A wide variety of regulatory mechanisms can be used to prevent contamination from occurring. They include, for example, permits, standards, the regulation of individual contamination sources, and legal constraints on or licensing of particular activities. One of the most powerful regulatory tools are land use controls that enable local governments address important aspects of contamination prevention that are not adequately covered by national or state regulations (Zaporozec and Miller, 2000). Table 7.3 presents a summary of the regulatory options that can be implemented to prevent or minimise groundwater contamination.

7.3.3 Legislation

However, regulations, which are scattered among a number of legal texts, seldom form a closed system. A general soil and groundwater protection act is then needed to fill the gaps and to reconcile different regulations.

Such a general act could include:

- basic quality standards, which should guarantee a sustainable use of soil and groundwater for various purposes such as dwelling, agriculture, and abstraction of drinking water;
- directives for isolation of local potential contamination sources such as waste sites, fuel tanks, and septic tanks, according to principles of isolation, control, and monitoring (ICM);
- restrictions in land use to safeguard basic quality standards, such as equilibrium fertilisation;
- criteria for soil remediation, based on quality standards and the actual risks to which man and ecosystems are being subjected and the risk of spread of the contaminant;
- delineation of special protection zones with respect to, for example, drinking water abstractions or nature reserves;
- provisions for financial compensation to land users in protection areas;
- a program of inspection and testing of groundwater quality, and standard methods for sampling and analysis.

Legislation often takes a long time. This holds especially for environmental legislation because contaminating processes are complicated and many interests are involved. Environmental deterioration is a long-term process and so is the abatement of contamination. Water legislation is strongly influenced by the legal system of any particular country. To be effective, water legislation should be the result of a socially accepted water policy. Regulations only work when they are accepted by the public and when they can be enforced by regulatory personnel. Enforcement of regulations and standards is perhaps the most difficult task of regulatory agencies (Zaporozec and Miller, 2000). Two alternative approaches can be used to encourage regulatory compliance: penalties (fines, taxes, loss of licenses) and incentives (tax credits, compensation, grants).

7.3.4 Non-regulatory options

Non-regulatory options, such as voluntary management practices, waste reduction through recycling, better 'housekeeping' practices, emergency spill response plans, and public education and information are equally important to effective prevention efforts and can commonly supplement regulatory programs (Zaporozec and Miller, 2000). Examples of some voluntary actions that can help control contamination sources are included in Table 7.2.

TABLE 7.3 Regulatory options for control of some contamination sources

	Regulatory option					
Source	*Land use controls*	*Use restrictions*	*Permits*	*Design/operation requirements*	*Inspection and training*	*Guidelines/ standards*
Pesticide use		•			•	•
Animal waste storage			•	•		•
Solid waste disposal	•		•	•	•	
Septic systems	•		•	•	•	•
Storage tanks	•		•	•	•	
Mine tailings	•			•		
Injection wells		•	•	•	•	
Spills				•	•	•
Well construction and abandonment			•	•	•	

7.3.5 Protection of drinking water

In addition to the protection provided to the groundwater, drinking-water supplies may need individual protection. This can be done by establishing water-well construction and abandonment regulations (Born et al., 1987) and by delineating protection zones around the water supply sources. Ideally, the protection zone should include the entire catchment contributing water to the source. Such protection zone would be complex and relatively large, placing severe economic burden on a community. In practice, the catchment area is divided into two or three subzones, and the most severe restrictions are applied only close to the source (Zaporozec and Miller, 2000).

Groundwater is a preferred source for drinking water because it is usually free of pathogenic germs. In order to prevent contamination by pathogens, various countries started to protect their sources of drinking-water supplies by the delineation of a safety zone, the 'bacteriological zone', around groundwater sources of drinking water. In Europe, this bacteriological zone is based on a groundwater travel (residence) time of 50–60 days between the perimeter of the zone to the well, which is the time thought to be necessary to eliminate bacterial contamination (Matthes et al., 1985).

Because the majority of chemical contaminants are not eliminated after a residence time in groundwater of 50–60 days, an 'outer' or 'chemical' protection zone of several years of residence time was established, for example two or ten years. The aim of this safety zone was to have enough time for carrying out an emergency spill response plan in case the recharge area outside this outer protection zone becomes contaminated. Within the outer protection zone, activities with respect to transport and storage of dangerous substances, waste sites, wastewater treatment, industrial activities, intensive agriculture, cattle breeding, and excavations are restricted or forbidden. The outer protection zone, however, showed some shortcomings (Matthes et al., 1985):

- It is not flexible and hard to change if, for example, new technical information becomes available.
- It does not protect all of the groundwater resources and thus reserves for future exploitations may not be adequately protected.
- It may become unacceptably large in karstic or fractured rock terranes.

A regional protection policy, based on the vulnerability of the recharge area as a whole and the assessment of the contamination threats, could lead to a more optimal and realistic protection system.

Meanwhile, it became known that pathogenic bacteria and viruses can survive underground for many months. Their elimination is much more a process of dispersion, retardation, and filtering (see Chapter 2, para. 2.3), for which a minimum distance of 50–100 m is necessary in fine sediments, and of 500–1,000 m in coarse porous media (Pekdeger et al., 1985). In karstic and fractured rocks, these distances of elimination are still greater. This means that besides a regional protection policy, a primary (bacterial) protection zone around drinking-water wells with a minimum radius of 100–1,000 m is essential to prevent health risks. The safety of such a zone must be guaranteed by law and by property rights of the water company that is responsible for the quality of drinking water. To summarise, groundwater protection zones are only local and ad hoc measures, necessary as long as there is no general protection policy.

7.4 Remediation of contaminated groundwater

Coping with groundwater contamination after it has occurred generates technical and management problems. Remediation of contaminated groundwater can be accomplished either by natural processes or by various remedial technologies.

Clearly, remediation by natural processes (natural attenuation) is a viable option that should be always considered, especially if the difficulty, high costs, and time demands of remedial technologies are taken into account (Zaporozec, 1998). Some sites may be effectively remediated by natural attenuation processes, but others will still need the application of remedial technologies.

Many remedial technologies have been developed during the last two decades to help clean the contaminated groundwater. Most of them are time-consuming and very expensive, and their successful application has not been completely proven. They fall into three broad categories: 1) source removal, isolation, or containment; 2) withdrawal and treatment of contaminated groundwater (pump-and-treat system); and 3) treatment of groundwater in situ (Zaporozec, 1998). Some of these methods are described in the following paragraphs.

Application of different techniques will depend, of course, on the hydrogeological situation of the site and the type of contaminants (Herbert and Kovar, 1998). Therefore, site characterisation (para. 4.4.2) is a first, very important step in site remediation because it will determine the type of remedial technologies and the costs associated with them.

In all cases, groundwater monitoring and the sampling of gases and waters from the soil and the unsaturated zone are critical to the evaluation of the effectiveness of the cleanup technologies being used.

7.4.1 Natural attenuation and semi-passive methods

In favourable natural conditions, natural purification processes (see Chapter 2) can help attenuate contaminated water entering the subsurface and reduce contamination to an acceptable level. A vulnerability assessment should be performed to determine the suitability of the surface and subsurface environment for natural attenuation (Vrba and Zaporozec, 1994). Reliance on natural attenuation is not a do-nothing or a walk-away solution. Remediation by natural attenuation (RNA) generally requires considerable investigation and monitoring (Brady et al., 1998). Besides on physical and chemical processes, use of RNA will depend on the results of site characterisation (para. 4.4.2), assessment of the site's potential risks, and evaluation of potential effectiveness with respect to other remedial methods. The main advantage of RNA is that it does not move contaminants from one place to another (like most remedial measures), but it results in real reductions in contaminant mass.

Natural attenuation is sometimes the only alternative, for example, to abate widespread contamination of groundwater by organic compounds such as mineral oils. The process consists of dilution of solutes by dispersion and retardation and of microbial degradation of organic substances. Biodegradation is most effective in aerobic (containing free oxygen) and suboxic (containing nitrate or sulfate) environments. Mineral oils will not break down in reduced environments.

Enhanced natural attenuation is a semi-passive method, which aims at intercepting a contaminated groundwater-flow zone (a plume) with help of the ditches filled with reactive materials. Examples are bioscreens where microbial activity is stimulated.

In a reducing environment, sulfate-reducing bacteria may precipitate sulfides of heavy metals from sulfate solutions. This opens the possibility to intercept such solutions coming from mine tailings. Methods working with barriers, filled with bivalent iron, to dechlorinate solvents in a reducing environment are in development.

7.4.2 Source removal, isolation, and containment

Soil and groundwater remediation can be accomplished, for example, by removal of the contaminated soil in order to prevent contamination from reaching groundwater. The soil is then treated at a special site. Sometimes industrial areas are so heavily contaminated that isolation instead of remediation is the only possibility. Isolation can take place by chemical immobilisation (e.g. with chalk or cement), by barriers (membranes, clay sheets, sheet piles, or slurry walls), or by hydraulic containment (interceptor trenches or hydraulic barriers). Physical containment includes encapsulation of a source or vitrification (fusion of soil and waste into a glassy monolith) (Zaporozec, 1998).

7.4.3 Pump-and-treat systems

The most widely used approach to groundwater remediation is extraction of the contaminated water and its treatment at the surface, referred to as the *pump-and-treat technology* (NRC, 1994). Contaminated groundwater is captured by a well or a group of wells and brought to the surface treatment facility. Water can be recirculated after the aboveground treatment and conditioning. This technology, however, is limited in its effectiveness for contaminant removal. Therefore, it is often used in the first stage of cleanup operations, primarily to remove the largest portion of the contaminant mass. These systems work in sufficiently permeable aquifers with low adsorption capacities. For some substances, such as dense non-aqueous phase liquids (DNAPLs), there are long tailing effects due to slow desorption of contaminants like oil or tar products. To mobilise and volatilise the DNAPLs, steam injection may be helpful. Addition of compatible surfactants may also be useful.

7.4.4 Active in-situ remediation

With the limitations of pump-and-treat in mind, more appropriate in-situ technologies were developed (Zaporozec, 1998). Among these are soil vapour extraction, biodegradation, bioventing, air sparging, and electrochemical concentration. Soil vapour extraction is used to remove volatile organic compounds from the unsaturated zone by suction wells. It can be combined with bioventing, a delivery of oxygen to the soil. In-situ biodegradation uses microorganisms to convert contaminants to less harmful forms. This method has the added benefit that the contaminated soil and groundwater do not need to be disturbed. Biodegradation is enhanced by supplying electron acceptors (oxygen and nitrate) to stimulate bacterial growth and break down organic compounds. Air sparging, a process similar to bioventing, is used to deliver air below the water table.

Again, these systems only work if the soil and the aquifer are sufficiently permeable and do not clog during oxidation, for example, with iron hydroxides. Further, the partitioning of the contaminant between soil particles, water, and air should be favourable, which means that the aquifer must have a low adsorption capacity for the contaminants.

In electrochemical concentration, contaminating ions can be transported by an electric field, which is induced by electrodes installed underground. By electrolysis, the cations (e.g. heavy metals) will move to the cathode, while their water mantles are carried with them; this is called *electro-osmosis*. The metal ions, collected at the cathode, have to be constantly removed by a circulating fluid in the cathode box. The same holds for the anode with respect to anions. Acidification will enhance the performance. Iron objects underground disturb the electric field and lower the efficiency of this process.

7.5 Monitoring

Groundwater monitoring is one of the important methods supporting the strategy and policy of groundwater protection. Because no preventive control system or remedial technology is

100 percent effective or complete, groundwater quality must be monitored at key points. In general terms, monitoring is the continuous, standardised measurement and observation of the environment (UNESCO/WHO, 1978). In terms of groundwater protection, monitoring is an important device to detect groundwater contamination and to provide an advanced warning of contaminated groundwater approaching important sources of water supply. In addition, groundwater quality monitoring can help define the extent of groundwater contamination and control the quality of drinking water.

According to Vrba and Sobíšek (1998), groundwater quality monitoring 'has the following objectives:

- to collect, process and analyse background data on water quality and quantity as a baseline for evaluating the current state and for anticipating the changes and trends of the hydrogeological system, and
- to provide information for the planning, management, and decision-making about groundwater resource development, protection, and conservation and for the implementation of legislative and control measures and regulations.'

The goals of any proposed groundwater monitoring program should be clearly stated and understood before decisions are made on the types and numbers of wells needed and their locations and depths, constituents of interest, and water sampling procedures. The placement and number of wells will depend on the results of contamination source inventory, complexity of hydrogeological setting, and degree of temporal and spatial detail needed to meet the goals of monitoring program (Barcelona et al., 1987).

Groundwater quality monitoring is a technically and financially demanding process. Therefore, the benefits and information derived from the monitoring should always be compared with the cost of obtaining this information (Vrba and Sobíšek, 1988).

Groundwater monitoring programs can operate at the international, national, provincial/state/regional, or local (site-specific) level. The type and density of monitoring stations for these four categories and sampling frequency and requirements were described by Meybeck (1985) within the framework of the Global Environmental Monitoring System (GEMS), and are included in Table 7.4.

Table 7.4 Categories of groundwater monitoring stations operating in groundwater quality monitoring programs (*Source:* Meybeck, 1985)

Monitoring program	*Category and importance of monitoring station*			*Station density*	*Sampling frequency*	*Variables analysed*	*Characteristics of monitoring station*
	Baseline	*Trend*	*Impact*				
International	D	C	LS	VL	L	B + O -	Baseline station: natural background groundwater quality.
National	D	C	LS	L	L	B + O -	Trend station: trends in groundwater quality due to natural processes and human impacts.
Provincial/ State	C	D	LS	M	M	B + O +	
Local	LS	LS	D	H	H	O +	Impact station: changes of groundwater quality due to various human impacts.

Station significance: D - Dominant, C - Complementary, LS - Low significance.
Station density: H - High: several m^2 to 10; M - Medium: 10 to 100; L - Low: 100 to 1,000; VL -Very low: 1,000 and (in km^2) more
Sampling frequency: H - High: more than 12 times a year, M - Medium: 2 to 12 times a year, L - Low: 1 to 4 times a year.
Variables analysed: B - Basic: physical, chemical, and biological variables included into the drinking-water standards. O - Optional: heavy metals, organochlorine compounds, oil hydrocarbons, and other variables depending on monitoring program objectives.
\+ Regular analysis.
\- Occasional analysis.

Each purpose for groundwater quality monitoring must satisfy somewhat different requirements, and may require different strategies for well location, design, and construction. Four basic types of monitoring in relation to groundwater protection can be distinguished (Barcelona et al., 1987):

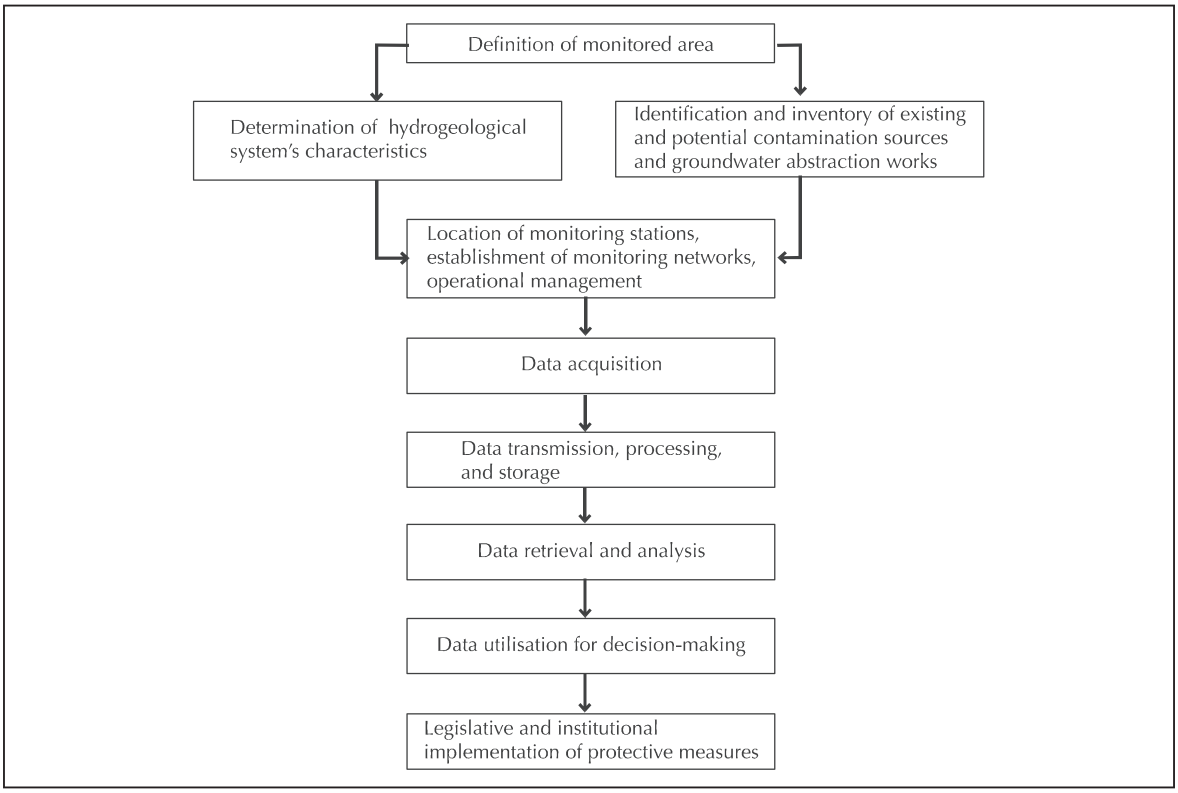
1) *Ambient trend monitoring:* measurements of groundwater quality to establish an overall picture of temporal and spatial trends within a groundwater basin or region. Existing public and private wells are used to the maximum extent possible.
2) *Source monitoring:* measurements of effluent quality for contamination sources that may affect groundwater, usually done for regulatory purposes. Monitoring wells are located and designed to detect the movement of contaminants from a given source or activity (early warning or offensive detection monitoring).
3) *Case preparation monitoring:* carefully documented measurements within a given area to gather evidence for legal proceedings or enforcement actions of past, existing, or anticipated groundwater contamination situations. Requires a level of detail similar to source monitoring.
4) *Research monitoring:* investigations on groundwater quality and contamination occurrence and movement. Requires a sophisticated level of detail to expand the understanding of complex mechanisms of groundwater movement and solute transport.

In the design of groundwater quality monitoring program four basic factors must be considered (Vrba and Sobíšek, 1988):

1) monitoring objectives;
2) extent of the area to be monitored;
3) duration of monitoring;
4) potential impacts on the groundwater system and their effects.

Design of a groundwater quality monitoring program should be flexible and continuously adjusted in response to the movement of a contamination plume or to the effects of groundwater remediation efforts. The elements of a groundwater quality monitoring system are shown in Fig. 7.2.

FIGURE 7.2 Simplified scheme of development of a monitoring system (*Source:* Vrba and Sobíšek, 1988)



For details on monitoring objectives and strategies, well design, and water quality sampling the reader is referred to the report on IHP-V Project 3.2 *Monitoring strategies for detecting groundwater quality problem*s (Vrba, 2002).

8 Case studies

Inventories of contamination sources widely vary in terms of their purpose and scope. To demonstrate this variety, a few examples from various regions of the world are included in this chapter. They may provide a better picture of why and how various nations approach the inventory.

The presented case studies describe the inventories of anthropogenic sources of contamination at a local level (case studies 8.4 and 8.6 from Nicaragua and the United States, respectively); at a regional level (case studies 8.2 Brasil and 8.5 South Africa); or at a national level (Italian case study 8.3). However, many inventories are carried out also for the purpose of determining the extent of natural contamination sources. A prime example is the case study from Bangladesh (8.1), which was set up to evaluate the causes and origin of poisoning of drinking-water supplies by naturally-occurring arsenic.

The goal of the local inventory of contamination sources in the Managua area, Nicaragua, was to characterise contamination sources and quantify the potential contamination load to the groundwater for groundwater protection purposes in an urban, suburban, and rural area with rapid, partly spontaneous urban growth. The local inventory of contamination sources in south-eastern Wisconsin, USA – a mix of urban, suburban, and rural land with local concentrations of industries – is an example of an inventory conducted with limited financial and manpower resources, which resulted in a qualitative assessment of the nature of predetermined sources and of the extent of potential contamination problems within the framework of a long-term, regional water quality plan.

The case study evaluating the contamination threat to aquifers in the state of São Paulo, Brasil, is an example of a regional inventory of contamination sources in an area of intense industrial and agricultural activity. In this case, screening of contamination sources was necessary to prioritise the activities according to their groundwater contamination risk. Disposal of waste is of great concern in South Africa. An example of the evaluation of the suitability of land for a regional waste disposal site in the Western Cape Province demonstrates the methodology for site selection. Even though this case study does not discuss contamination inventory per se, it outlines a process for identifying suitable areas for an important potentially contaminating activity.

Inventory of contamination sources at the national level is represented by the study of the contamination of drinking-water supplies in Italy and its causes. The inventory was conducted within the territory of individual municipalities, and the contamination sources were classified into seven categories: industrial, urban, agricultural, stock breeding, waste disposal, seawater intrusion, and naturally-occurring substances.

8.1 Arsenic contamination in groundwater in Bangladesh

Jan Nonner

8.1.1 Problem definition

In Bangladesh, the contamination of shallow groundwater with arsenic has reached critical levels. The Government of Bangladesh became first aware of the problem in 1993, and ever since, reports on illnesses and poisoning by drinking of arsenic-containing groundwater have been increasing. By 1997, the affected areas comprised the western and southwestern part of the country, and alarming reports were also received from the Sylhet area in the northeastern part of Bangladesh.

8.1.2 Hydrogeological setting

More than 75 percent of the Bangladesh area is made up of deltaic, alluvial, and marshy deposits (Fig. 8.1.1). Residual deposits associated with old land surfaces (II) and areas of consolidated sedimentary rock (I) are located in the isolated central and northwestern parts of the country, and in the east, respectively. The deltaic (IV) and alluvial (III) deposits contain numerous layers of sand with occasional gravel, which form good aquifers that are exploited on a large scale by municipalities and smaller communities. Groundwater, which is pumped from these deposits using deep and shallow wells, contains arsenic that is, supposedly, derived from the arsenic-containing mineral-rich sediments deposited in the area by the rivers. The Ganges River appears to be one of the main sources of these sediments. The arsenic contained in the mineral-rich sediments is therefore of natural origin, but there has been speculation that it may have been released into groundwater as a result of human interferences in the area including pumping, dewatering, and reservoir construction.

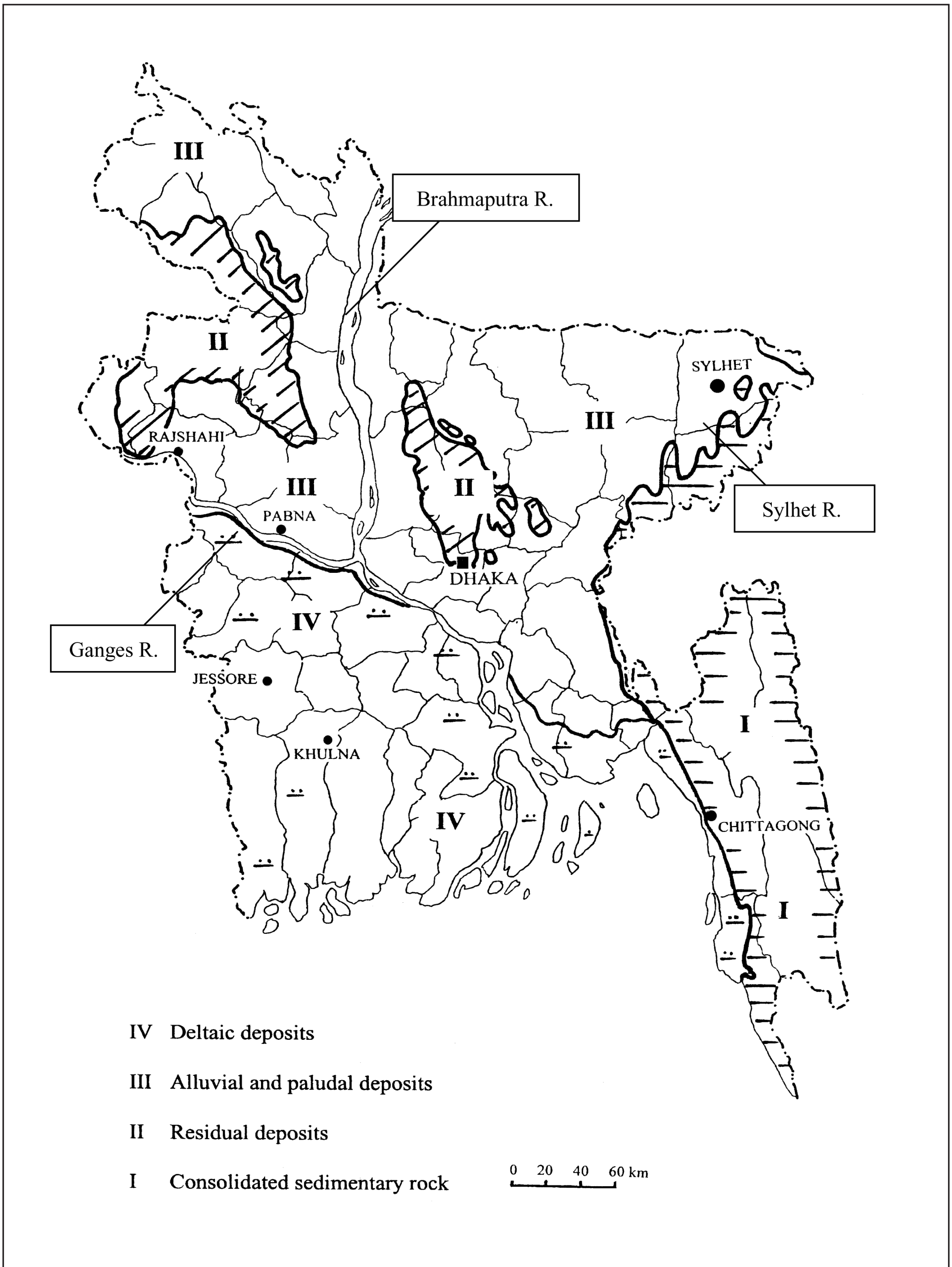
8.1.3 Existing inventory of the arsenic source

The inventory of arsenic-affected areas in Bangladesh has been done on a rather unplanned basis. Water sampling for arsenic has concentrated on wells in communities where a lot of cases of arsenic poisoning caused concern with the local health officers. Understandably, the local and national press has played a role in focusing attention on these communities. The uncoordinated sampling programs have caused the information on arsenic to be only partly available at a large number of organizations including the Department of Public Health Engineering (DPHE), the Universities in Rajshahi and Dhaka, consultancies, and non-governmental organizations (IIIHEE et al., 1997). Some of these organizations have produced maps showing percentages of well samples with elevated arsenic concentrations arranged per district.

8.1.4 A new inventory approach

An additional systematic groundwater sampling program in the affected areas in Bangladesh was carried out in 1998. A total of just over 2,000 shallow and deep wells were sampled on a 'thana' (municipality) basis. Using a suitable geographical grid, 5 to 10 wells per thana were systematically selected, and subsequently visited. The sampling density varied between 30 and 40 km^2 per sample. A protocol describing georeferencing procedures, use of water sample collection forms, bottling techniques, etc was developed and used. Samples collected were primarily analysed by the DPHE for arsenic, iron, and hardness (DPHE, 1997). Cross-checking of sample analyses was carried out by the British Geological Survey in Wallingford, England. The storage and processing of hydrogeological and hydrochemical data including arsenic was done with the help of the Visual Foxpro data base code, which was linked to ArcView for the generation of layers of various parameters. With all data being stored on CD-ROM, the procedures that followed formed a sound basis to present and analyse the results in a professional manner.

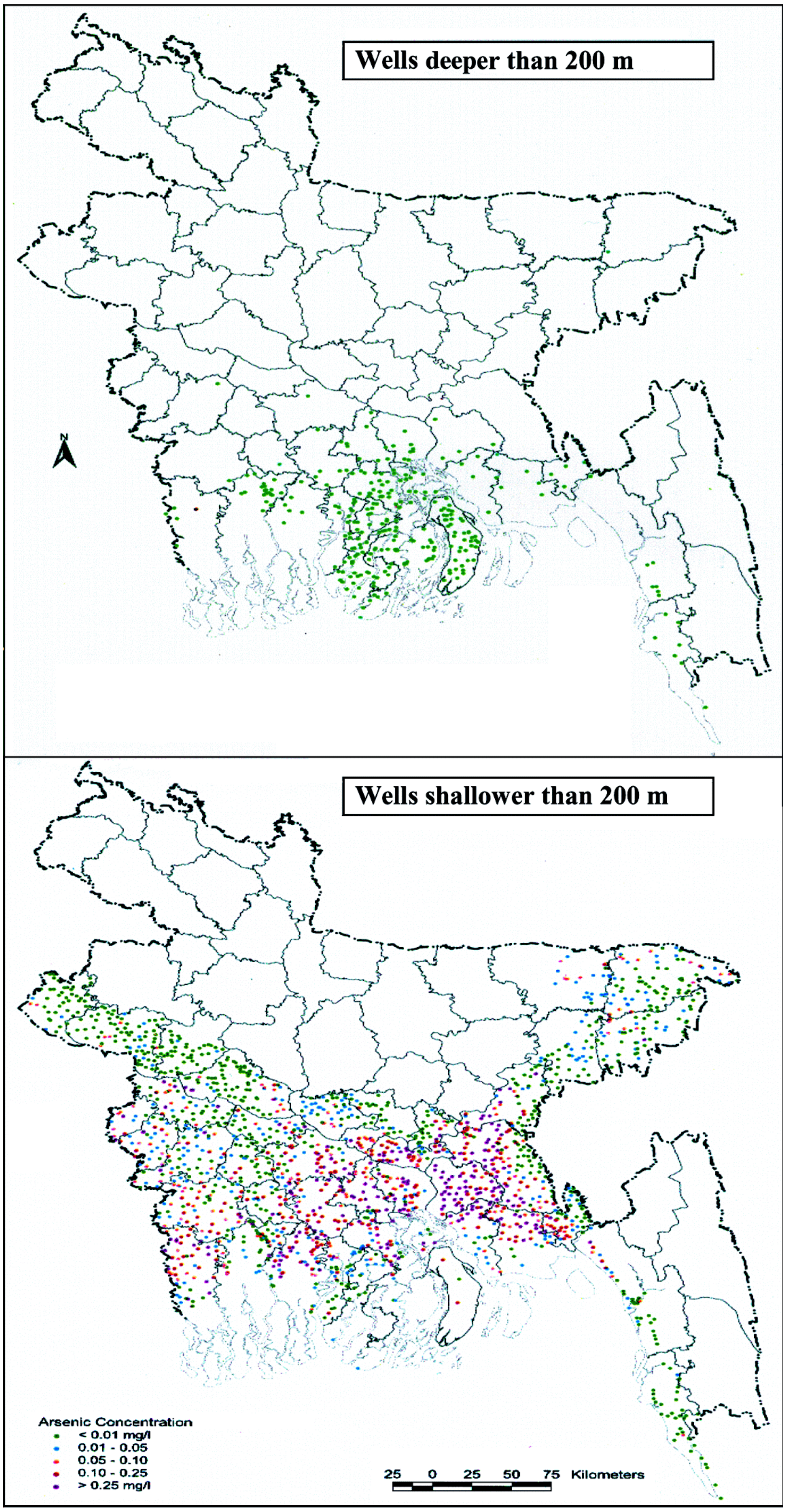
FIGURE 8.1.1 Geological units in Bangladesh (*Source:* British Geological Survey)



8.1.5 Presentation of results

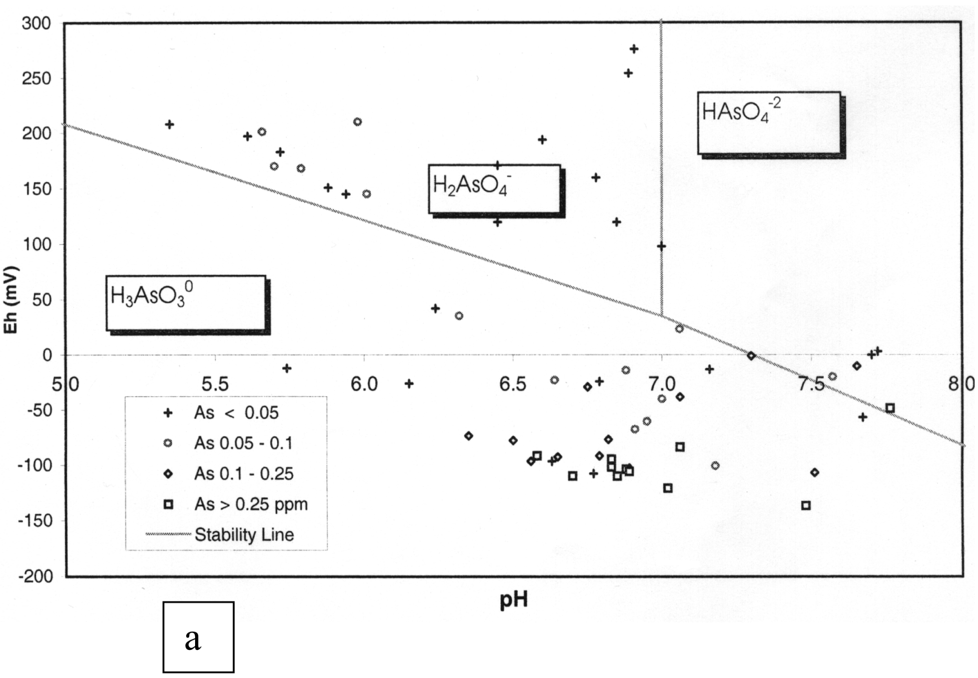
Results of the inventory have been presented as plain text, tables, diagrams, and in particular, maps. Diagrams and maps have been compared with each other to find correlations between the distribution of groundwater rich in arsenic and geological formations, groundwater chemistry, groundwater use, etc. For example, the maps in Fig. 8.1.2 show the comparison between the

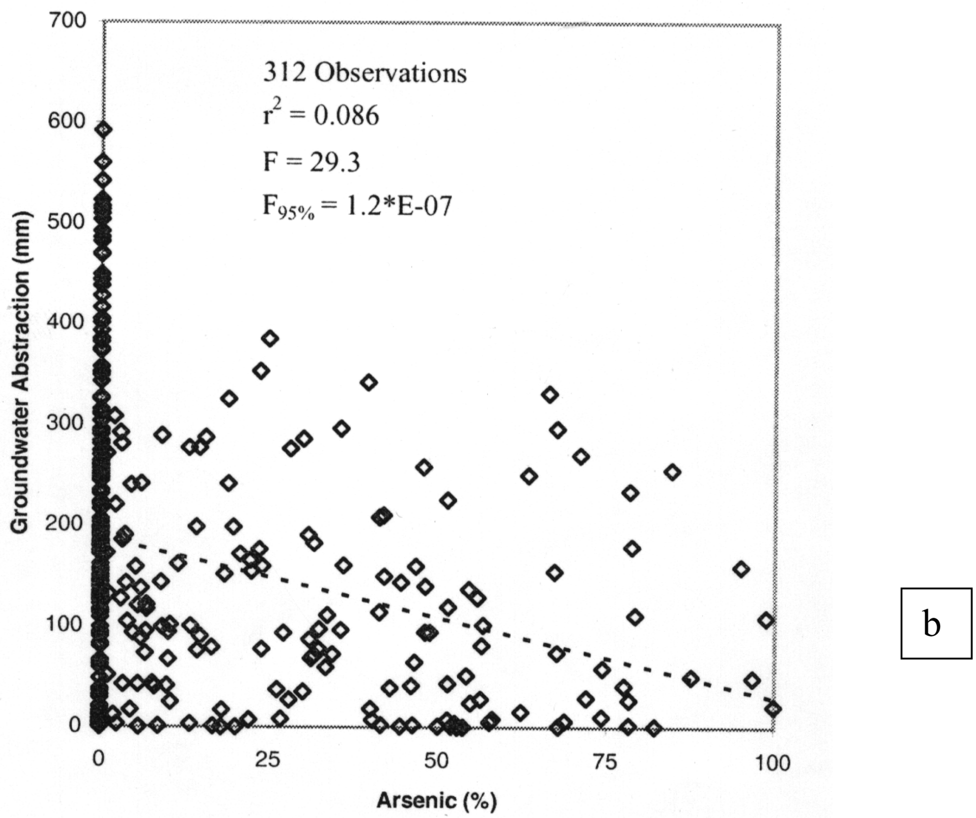
FIGURE 8.1.2 Comparison of arsenic levels in groundwater in the deeper and shallower aquifers (*Source:* British Geological Survey/Mott MacDonald Ltd., 1999)



arsenic concentration in groundwater of the deeper geological formations and the concentration in shallower formations. Overlaying these maps against the map shown in Fig. 8.1.1, arsenic concentrations can also be compared with geological formations outcropping at the land surface. The diagrams shown in Fig. 8.1.3 a) and b) present examples of relationships between arsenic concentrations in groundwater and the redox potential (an essential parameter in groundwater chemistry) and arsenic concentrations and groundwater use, respectively. The map and diagram-comparative approach to compare groundwater contamination-related parameters has led to some essential findings for the Bangladesh case.

FIGURE 8.1.3 Relationships between a) arsenic concentration and redox potential and b) arsenic and gross groundwater abstraction (*Source:* British Geological Survey/Mott MacDonald Ltd., 1999)





8.1.6 Conclusions for the Bangladesh basin

One of the essential conclusions related to the groundwater system in Bangladesh was that the arsenic-rich groundwater is confined to shallow geological formations (especially from 20 to 40 m below the land surface), and in particular, to the recent deltaic and alluvial deposits. Groundwater contaminated with arsenic is also positively correlating with low redox potentials (reducing conditions) (Fig. 8.1.3a), high iron concentrations, and generally low sulfate concentrations. No direct positive relation exists with groundwater use (Fig. 8.1.3b). Based on these comparisons and the results of sediment samples taken at wells in Bangladesh, the origin of the arsenic in groundwater was mainly attributed to the arsenic-containing iron-hydroxide coating on fine sand, which is deposited in the basin by the large Ganges, Brahmaputra, and Sylhet Rivers. Burial of the sediments causing transfer to reducing conditions stimulated the dissolution of the coatings, which released the arsenic into the groundwater.

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8.2 Potential groundwater contamination sources in the state of São Paulo, Brasil

Ricardo Hirata

8.2.1 Study area

São Paulo is one of the most important states in Brasil. It is located in the southern part of the country and has an area of 247,564 km² and a population of 33 million people, which is concentrated mainly in the metropolitan region of the city of São Paulo (50%) and in 7 other regions (15%). The remaining 35 percent of the population are distributed in other 470 municipalities. With a GDP of US$ 330 billion (35% of the country), São Paulo has very complex urban and rural activities that result in the existence of a multitude of potential contaminant loads and many environmental problems.

Groundwater is a very important source for public and private water supply in the state of São Paulo. Around 70 percent of the municipalities (approximately 35% of the total population of the state) use this resource for totally or partially supplying their needs. Because of this importance, a project was developed, at a regional scale, to provide analysis of the contamination threat to the most important aquifers of the state.

8.2.2 Methodology

The basic concept for identifying critical areas was an adaptation of the method proposed by Foster and Hirata (1988), which states that groundwater contamination risk is the interaction of:

'a) the contaminant load that is, will be, or might be applied on the subsurface environment as a result of human activity; and

b) the aquifer contamination vulnerability that is the result of the natural characteristics of the strata separating the aquifer from the land surface.'

The concept of contamination risk is defined as the probability that groundwater in an aquifer will become contaminated to concentrations above the Brasilian guideline values for drinking-water quality. According to such a scheme, it is possible to have areas of high natural aquifer vulnerability, but virtually no risk of groundwater contamination, when the contaminant load is low or absent and vice versa.

Critical areas, where the adoption of control measures should be prioritised and detailed studies conducted, were defined combining the map of aquifer contamination vulnerability – developed at the scale of 1:500,000, using the GOD methodology (Foster, 1987) – and the contaminant load classification for industrial and agricultural activities, solid waste disposal facilities, and urbanisation with on-site sanitation. This methodology took advantage of using available data, which had already been collected for other purposes. Because of the objectives of this guideline, just the results of contaminant load classification are presented here.

The contaminant load was classified according to its nature in agricultural and industrial activities, as well as solid waste disposal facilities and on-site sanitation. The areas were identified and their potential contaminant load was rated for each selected contaminant-generating activity group as low, moderate, or high. The complexity of human activities and the scale of the project did not allow the application of a unique system to rate the contamination sources. Being a regional analysis, the metropolitan area of the city of São Paulo (which represents 50 percent of the total economic activity of the state) was not included in the project.

All potential contamination sources were plotted on a 1:50,000-scale map. Then the information was transferred to a 1:500,000-scale map to permit interaction with the aquifer natural vulnerability map at the same scale. Three specific maps were produced, one for point sources and two for agricultural activities and on-site sanitation systems. The maps were manually prepared by the overlay technique (Hirata et al., 1991a; b).

To assess the groundwater contamination risk, each activity was analysed in a 3x3 matrix, considering three classes of aquifer natural vulnerability and three classes of contaminant load.

8.2.3 Contaminant load classification

(i) Industrial activities

Basically, the contaminant load classification is focused on the industries that use, produce and/or discharge hazardous substances. Substances involved and their quantities were identified. The final classification of a specific industry was based only on the highest value that is obtained by analysing separately industrial processes, solid waste disposal facilities, and effluent lagoons. The method for rating industrial activities – in the levels high, moderate, and low – is based on the volume of both hazardous substance and effluent, calculated indirectly from the size of the facility. The rating scheme is presented in Figs 5.2a and 5.2b of this guideline.

The state of São Paulo, excluding the metropolitan region of the city of São Paulo, had 24,000 industries in 1991. The Environmental Sanitary Technology Company (CETESB), responsible for environmental monitoring, has kept continuous monitoring of almost 2,000 industrial facilities. This project analysed these controlled facilities and, using screening procedure, identified 526 industrial plants, which were classified in low (218), moderate (132), and high (176) categories of potential contamination risk (Table 8.2.1).

The region that had more elevated concentration of high risk activities was Campinas, where, from 139 industries recorded, 68 showed high and 38 moderate potential load risk. The chemical industry, followed by sugar and alcohol plants using infiltration of their effluents to the soil, along with food and leather tanning, were classified as high potential contaminant load. The region of Ribeirão Preto included an impressive industrial park with a total number of more than 6,000 facilities. The project distinguished as significant for groundwater 135 of them, from which 41 were classified high and 30 moderate potential. The industries of highest contamination potential were sugar and alcohol plants and leather tanning factories (Fig. 8.2.1).

(ii) Agricultural activities

The method for evaluating the agricultural activity was based on Foster and Hirata (1988). Using their method, a very approximate and simplified estimate of the proportion of the applied weight lost by leaching was estimated for all agricultural practices in areas larger than 50 ha. The basic information needed was: type of cultivation practice and its area; production per area (ton/ha/year); type and amount of agrochemical (µg/ha/year) and fertiliser (kg/ha/year) applied in each culture; fraction of organic carbon (foc) present in soils; and the amount of water due to excess of rainfall (mm/year, precipitation – potential evapotranspiration). The Kow (octanol-water partition) and Koc (organic carbon partition) indices were defined for each agrochemical compound. In many cases, the quantity of agrochemicals or fertilisers applied was not available. The values of agrochemical and fertiliser volumes used were based on the recommended quantities by Brasilian technical publications (Hirata et al., 1991a). Some interviews were conducted to check this information.

The results of the agricultural activity survey identified some risk associated with the following agrochemicals: dalapon, atrazine, simazine, alachlor, 2,4-D, metalachlor, metamidofos, trichlorfon, malathion, monocrofos, carbaril, carbofuran, aldicarb, and fosetil. These products were applied on crops of sugar cane, citrus, cotton, soya, beans, and banana. The amounts of fertilisers were identified and analysed. Nitrate concentration anomalies in some private and public wells have been assumed to result from the use of nitrogenous fertilisers, although the magnitude of the problem is unknown.

(iii) Solid waste disposal facilities

Basically, the classification of the potential contamination sources took into account the construction characteristics of the facility (landfill or open dump). Normally in all open dumps and some landfills, the origin of the wastes is unknown, which means they could have received some hazardous materials. For the project, it was considered as an adequate construction standard when the facility had an impermeable base and/or surface, including clay or plastic liners; a surface water drainage system; a leachate drainage collection and treatment; and a control of the origin and control of the origin and volume of solid waste inputs.

Excluding the metropolitan region of the city of São Paulo, there were 521 open dump

TABLE 8.2.1 Groundwater contamination risk from industrial sources in the state of São Paulo

Aquifer contamination vulnerability	*Subsurface contaminant load*					
	*	*Low*	*	*Moderate*	*	*High*
Low	25	Sugar and alcohol	07	Metal processing	03	Textile mills
	02	Chemicals	02	Pulp and paper	02	Rubber products
	05	Textiles mills	03	Textile mills	10	Metal processing
	06	Food and beverages	04	Mechanical engineering	02	Food and beverages
	03	Pulp and paper	07	Food and beverages	16	Chemicals
	03	Mechanical engineering	01	Pharmaceutical	10	Sugar and alcohol
	03	Metal processing	03	Chemical	02	Electric and electronic
	01	Pharmaceutical	01	Electric and electronic	01	Pharmaceutical
	05	Leather tanning	06	Sugar and alcohol	04	Leather tanning
	01	Woodwork	01	Leather tanning	01	Mechanical engineering
	01	Petrol and gas refineries	01	Miscellaneous	01	Miscellaneous
		(III)		(II)		(I)
Moderate	14	Food and beverages	04	Mechanical engineering	01	Pulp and paper
	44	Sugar and alcohol	01	Metal processing	06	Chemicals
	01	Metal processing	15	Food and beverages	12	Sugar and alcohol
	04	Mechanical engineering	03	Leather tanning	01	Electric and electronic
	02	Leather tanning	02	Chemicals	05	Mechanical engineering
	01	Miscellaneous	01	Textile mills	04	Metal processing
			09	Sugar and alcohol	05	Food and beverages
					11	Leather tanning
					02	Petrol and gas refineries
		(III)		(II)		(I)
High	07	Chemicals	03	Chemicals	07	Sugar and alcohol
	08	Food and beverages	04	Pulp and paper	02	Mechanical engineering
	01	Pulp and paper	01	Textile mills	08	Chemicals
	04	Metal processing	03	Metal processing	03	Metal processing
	01	Rubber products	02	Mechanical engineering	01	Plastic products
	05	Mechanical engineering	01	Electric and electronic	01	Pulp and paper
	12	Sugar and alcohol	02	Sugar and alcohol	11	Leather tanning
	02	Textile mills	01	Food and beverages	01	Textile mills
	01	Petrol and gas refineries	01	Petrol and gas refineries	01	Miscellaneous
		(II)		(I)		(I)

* Number of potential contamination sources for each activity.

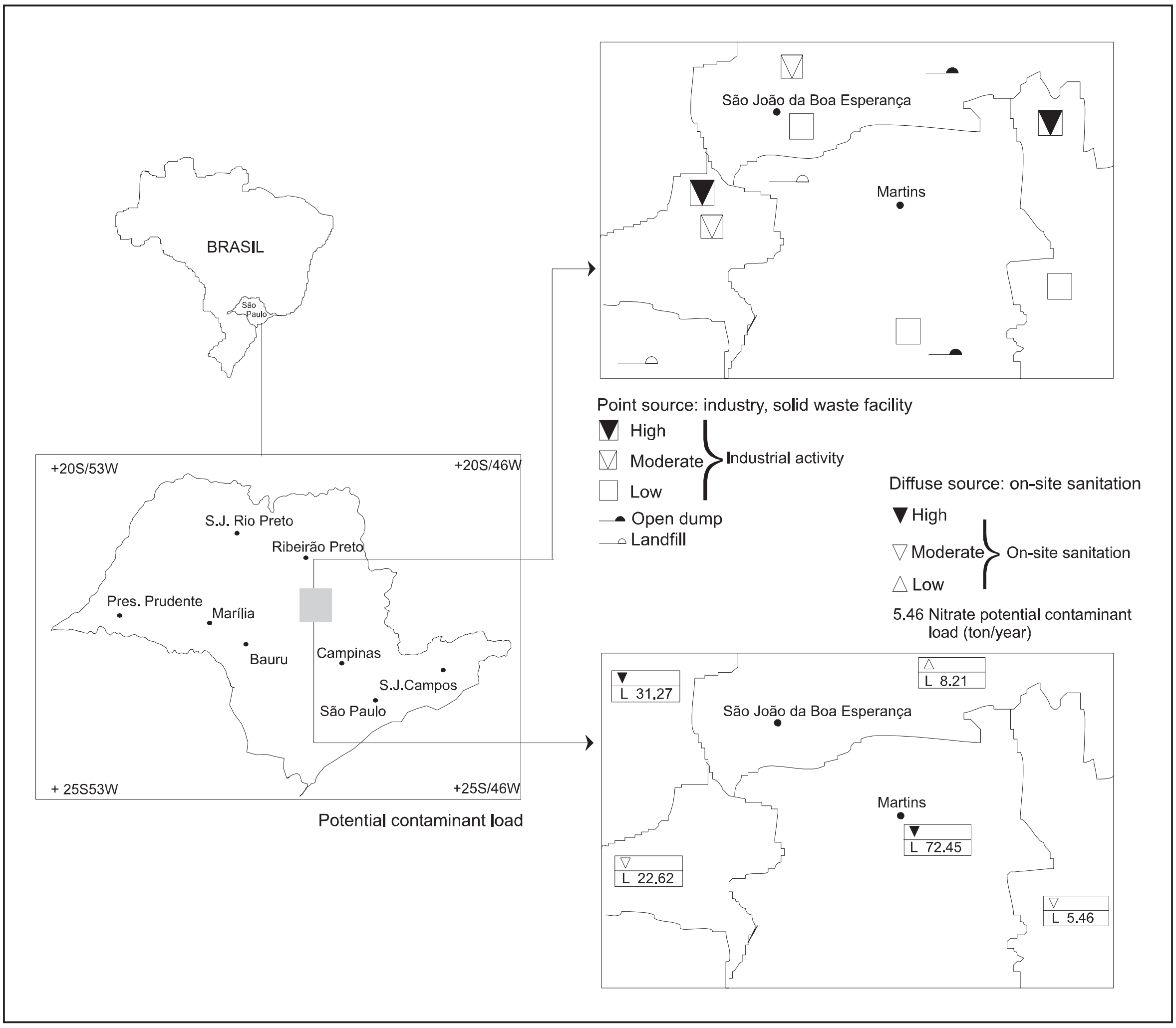
I, II, III High, moderate, and low groundwater contamination risk.

facilities and 39 landfills in the state of São Paulo in 1992. The total volume of waste was 3,380 ton/day, generated by a population of 7.5 million people. For the project, 79 municipalities were studied in more detail. The criterion for this selection was based on the facility location in areas of higher vulnerability and/or the size of municipalities (more than 50,000 people.) All facilities were plotted on 1:50,000- and 1:500,000-scale maps.

(iv) On-site sanitation

The most serious groundwater contamination problems from on-site sanitation systems are nearly always associated with high density and spatial distribution of latrines or septic systems. These sources were evaluated for each municipality, analysing how many people were not served by an adequate sewage system. The potential amount of nitrogen input into the aquifer was computed for each municipality taking into account that each person can generate 4 kg/year of potential nitrate (Foster and Hirata, 1988). All cities were analysed and the potential contaminant levels were attributed according to statistical distribution of values. The São Paulo Statistical Data System Foundation (SEADE) has studied the population who have houses connected to public sewage systems. The information is annually collected directly from the public and private sanitary companies. Based on the total number of buildings and the served population, it is

FIGURE 8.2.1 Detail of contaminant load map and highest groundwater contamination risk areas in the state of São Paulo



possible to evaluate the relative amount of nitrogen load moving into the aquifer from on-site sanitation systems, which include, among other, septic systems and dry and wet latrines.

As to the sanitation condition, the state of São Paulo presents satisfactory service. The project analysed 567 municipalities and just 8.8 percent and 10 percent had high (>50 ton/year of potential nitrate) and moderate (50–20 ton/year) indexes, respectively. The region that most utilised on-site sanitation systems was Campinas, followed by Sorocaba, because of its high population concentration and its rapidly growing urbanisation. For these regions, these higher index areas were associated with slums, which use on-site sanitation systems and shallow wells for water, normally contaminated by nitrogen, bacteria, and viruses.

8.2.4 Conclusions

The regional approach methodology described above is regarded as the first step in the evaluation of groundwater contamination risk assessment, and is intended to prioritise areas, but not to substitute for systematic field inspection and monitoring. Therefore, this method is useful in areas of intense activity, as in the case of the state of São Paulo, or when a screening procedure is necessary to identify areas or activities that present higher groundwater contamination risk.

In the case of subsurface contaminant load, it is not necessarily the largest and the most sophisticated facilities that generate the largest subsurface contaminant load and the highest groundwater contamination risk. This is because their chemical handling and effluent disposal practices are more carefully controlled and monitored. Equal or greater concern is associated with small services, industries, and activities, because they are widely disseminated, often use considerable quantities of potentially toxic groundwater contaminants, and their effluent disposal practices may not be subject to strict control. A regional approach has difficulty in identifying these activities.

Finally, it is realised that the potential contamination source analysis plays a more important role in the groundwater contamination risk assessment than aquifer contamination vulnerability. The reason for this is that groundwater contamination is much more controlled by the type and volume of a contaminant, and associated to its mode of disposition and its hydraulic load, than by the characteristics of the unsaturated zone or the aquitard. Actually, assessment and mapping of aquifer vulnerability has a very restricted meaning associated with very mobile and persistent contaminants in the long term.

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8.3 Inventory of contamination of water supply sources in Italy

This inventory is presented as an interesting example of a national survey of the contamination of drinking-water supplies and its causes. The survey was conducted on the recommendation of the Italian Department of Civil Protection (DPC) by the National Group for Prevention of Hydrogeological Hazards (GNDCI), under the direction of Dr. Giuseppe Giuliano, Water Research Institute of the National Research Council (IRSA-CNR), during 1989–90 and 1995–96 (Giuliano et al., 1998).

A special inventory form was designed to characterise each contamination source and its territorial, temporal, physical, institutional, and economic aspects. A data base was developed to store and process the collected data and information. The data set included 674 contamination cases affecting 594 drinking-water sources on the territory of 834 municipalities. Regional distribution of contamination sources and the origin of the sources is shown on Fig. 8.3.1. The sources were plotted on a map at the scale 1:1,200,000 as point sources and diffuse sources. For convenience, the areas of diffuse contamination were shown on the map as the actual municipal territories.

The main causes of contamination were related to industrial effluent discharges and waste injection wells, leakage from municipal sewers and septic systems, and agricultural activities (fertiliser application and animal feedlots) (Table 8.3.1). Also important was the contamination caused by uncontrolled resource development and overpumping in coastal areas (seawater intrusion). In the areas that have been populated and developed for a very long time or in the areas where human activities are very intensive, the groundwater was frequently affected by more than one contamination source.

Table 8.3.1 The most frequent contamination sources and contaminants (*Source:* Giuliano et al., 1998)

Contamination sources	*Number of cases*	*Contaminants*	*Number of cases*
Industrial effluent discharges	118	Bacteria	249
Leaking sewers and septic systems	108	Anions	207
Liquid waste disposal	93	Chlorinated solvents	105
Application of fertilisers	89	Heavy metals	62
Animal feedlots	88	Cations	50
Waste injection wells	61	Pesticides	45
Uncontrolled resource development	53	Other organic compounds	41
Overpumping in coastal areas	43		

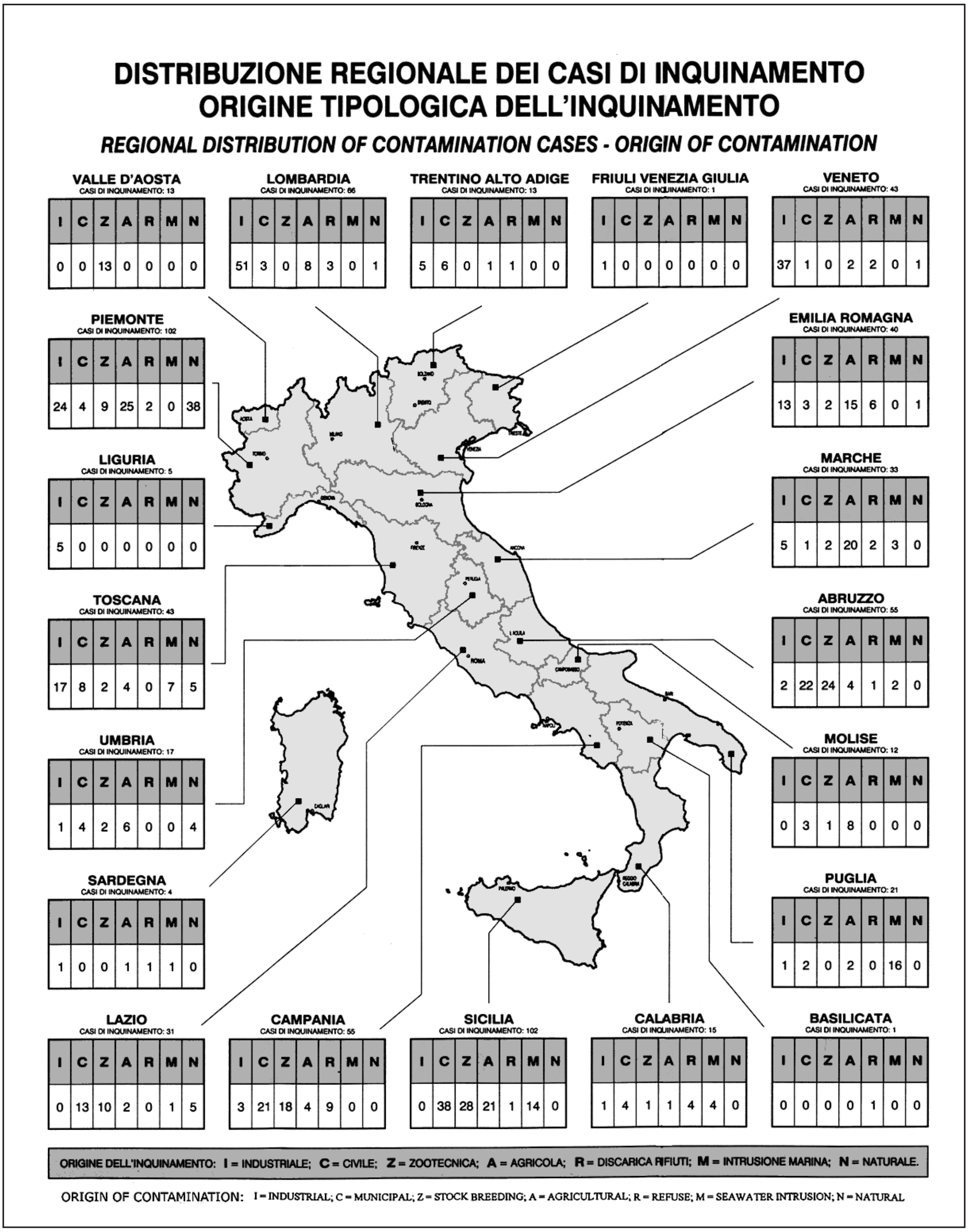
The most frequently detected contaminants were bacteria, inorganic substances (particularly anions such as nitrate and chloride; for cations, the most frequent were sodium and magnesium), chlorinated solvents, heavy metals, pesticides, and other non-degradable organic compounds.

Most of the contaminated water supply sources were in the shallow water-table aquifers (less than 50 m), single wells of a low to medium yield (up to 50 l/s), serving municipalities of a relatively small size (up to 5,000 people). The most frequently affected aquifers were the alluvial aquifers in the northern and central Italy plains and the karstic or fissured aquifers in southern Italy. In most cases, the aquifers had no surface protective layers.

One of the most contaminated areas is the Po River valley and Veneto-Friuli plain in northern Italy, which has one of the highest concentrations of industrial and agricultural activities in Europe. Disposal of industrial waste, largely uncontrolled in the past, and heavy use of agricultural chemicals were the primary causes of groundwater contamination there (Fig. 8.3.2). The most frequent contaminants were chlorinated solvents and heavy metals of industrial origin and nitrates and pesticides related to agriculture and cattle breeding.

Since most of the affected water supply sources were of small to medium size, they were managed locally. Technical and financial resources for contamination control and remediation usually were limited. In about one third of the inventoried cases, especially those related to

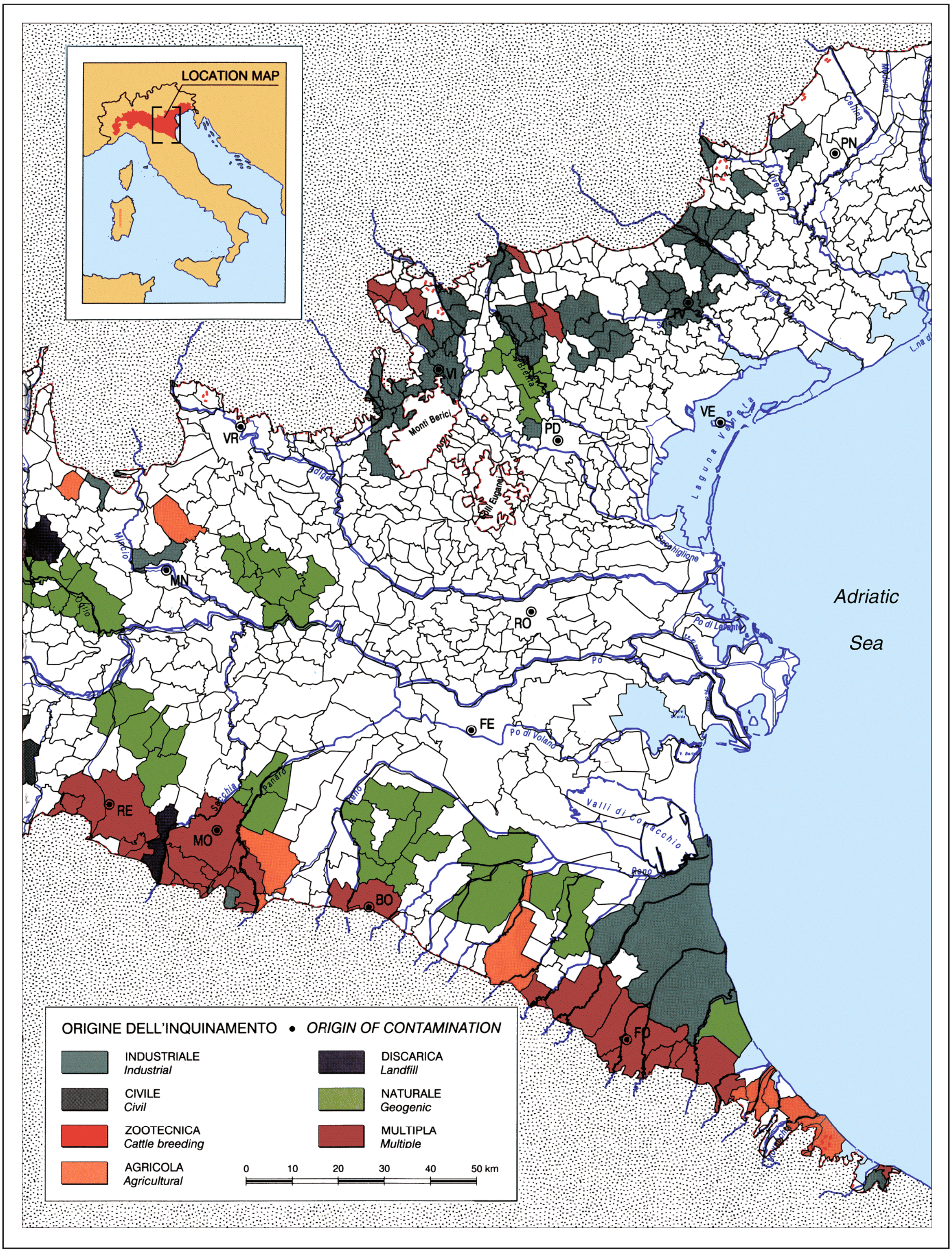
FIGURE 8.3.1 Regional distribution of contamination cases in Italy: origin of contamination
(*Source:* Giuliano et al., 1998)



contamination by bacteria or inorganics, no control measures were implemented. In other cases, contamination control was directed primarily toward the water supply sources, and only occasionally toward the contamination sources. The primary means was the treatment of contaminated water. However, many studies are under way to design monitoring programs and to recommend the administrative and technical measures needed for protecting the water supply sources.

Excerpted by Alexander Zaporozec

FIGURE 8.3.2 Part of the map 'Contamination in the lower Po River valley at the municipal level'
(*Source:* Giuliano et al., 1998)



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8.4 Groundwater contamination source inventory in the Managua area, Nicaragua

P.-O. Johansson, C. Scharp, T. Alveteg and A. Choza

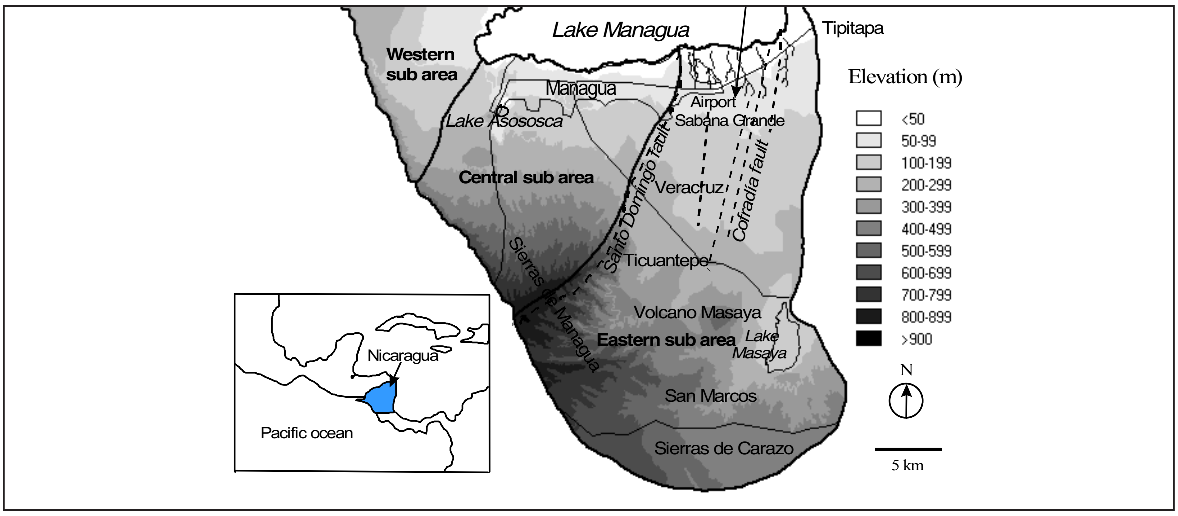
8.4.1 Introduction

A framework for groundwater protection was developed and tested for the Managua groundwater system, Nicaragua. The proposed framework for groundwater protection consists of the assessment of three basic components: groundwater vulnerability, potential contamination load, and relative protection value. The framework is meant to be used as a screening tool and for prioritisation of detailed studies, and should essentially be based on readily available data. The presentation is here limited to the groundwater contamination source inventory and a combined evaluation with the vulnerability assessment. For details on the assessments of vulnerability and protection value see Johansson et al. (1999) and Scharp et al. (1998).

8.4.2 Potential threats to groundwater

The Managua groundwater system is located south of Lake Managua, Nicaragua (Fig. 8.4.1). The area is approximately 900 km². Groundwater is the sole source for public water supply and there are no immediate realistic alternative sources. The rocks of the aquifer are of volcanic origin with a complex stratigraphy composed of semi-consolidated pyroclastic deposits and pyroclastic flows with interbedded lava flows and fossil soils. The underlying formation is composed of tuffaceous sandstone and siltstone with fossil soils, and is regarded as impermeable. The saturated thickness varies between 100 and 400 m and the transmissivities in tested wells varied between 1 and 10,000 m²/d, though most wells had values of 10 to 1,000 m²/d. The aquifer is in most parts considered to be unconfined, though perched water tables can be found locally (JICA/INAA, 1993). The average groundwater recharge is estimated at 270 mm/year (JICA/INAA, 1993), but with a considerable spatial variation.

FIGURE 8.4.1 The Managua groundwater system with its subdivision into three subareas



The population of the study area has increased from less than 0.5 million to approximately 1.5 million between 1971 and 1995. Approximately 85 percent of the population lives in the Managua urban and suburban area. The population growth has lead to housing shortages and spontaneous settlements. Approximately 300,000 people live in gradually legalised or still illegal settlements. In urban Managua approximately 70 percent of the dwellings have house connections for water supply, and another 20 percent have stand posts. Flush toilets are available in 55 percent of the houses, and the rest rely on latrines or lack any facility (JICA/INAA,1993).

More than 80 percent of Nicaragua's industry is located in the study area. Among these are textile, food processing, chemical, metal processing, and pharmaceutical industries. About two thirds of the total number of industries are light industries and some 90 percent are small companies with less than four employees. Besides being the main industrial zone of the country, the study area is an important agricultural zone for producing cash crops. The most important crops are corn, beans, sorghum, pineapple, horticultural products, and to a lesser extent, coffee. From the 1950s to the 1980s cotton was a major crop, especially in the eastern subarea of the watershed. During this period large amounts of pesticides were used.

8.4.3 Methodology

(i) Contamination source characterisation

The identification of potential contamination sources was based on existing information available from various authorities, maps, and satellite images. All sources were field checked, although commonly only doubtful sources need to be checked in the field. The identification was followed by a screening procedure that narrowed the number of potential sources (para. 8.4.4). The screening was an organizational procedure where the sources were divided into five major categories: 1) industrial, 2) urban, 3) agricultural, 4) landfills, and 5) other (petrol stations, oxidation ponds, cemeteries, etc). These categories were further subdivided into groups depending on the type of activity carried out. The subdivision was based on considerations of a) type of activity, b) handling and storage of chemicals, c) handling of wastes and effluents, and d) area affected by disposals. Each group was assigned high, moderate, or low priority or no priority, according to the relative amount of time to be spent on the evaluation of that particular group of sources.

The contamination sources that were given high, moderate, or low priority in the screening were then characterised to assess their potential contamination load to the groundwater using a modified method developed by Foster and Hirata (1988). Five characteristics of the contaminant source were considered as being of major importance to assess the potential contamination load: 1) contaminant class, 2) relative concentration, 3) mode of disposition, 4) duration of load, and 5) potential for remediation.

Ratings between 0.0 and 1.0 were set for each of the five assessed characteristics. The final score was assigned by summing up the ratings and dividing by five. For each source, the contaminant assigned the highest total score was chosen to represent that particular source. The final scores were classified as low, moderate, or high potential contamination load for scores of <0.6, 0.6–0.8, and >0.8, respectively.

(ii) Combined evaluation of contamination sources and vulnerability

The potential contamination load map was superimposed upon the vulnerability map to evaluate the existing contamination liability by use of a 3x3 matrix indicating low, moderate, or high contamination liability to the groundwater (Fig. 8.4.2). The contamination liability matrix is skewed in a way that gives higher weight to the potential contamination load than to the vulnerability for moderate and high potential contamination loads in low vulnerability areas. A precautionary approach is appropriate here, considering the uncertainty in the vulnerability assessment and the impact of mobile, persistent contaminants.

8.4.4 Results of contamination source characterisation

In the screening procedure, 21 of the 103 identified point sources were given no priority and were not included in the characterisation. The no priority sources were very small domestic waste dumps and textile manufactures without washing of fabric. The only example of an activity given an increased priority after field checking was a landfill with disposal of liquid wastes. All of the diffuse sources were included in the characterisation procedure. The study indicated that most of the contamination sources with high potential contamination load were concentrated in the eastern subarea: 1) Zona Franca located close to the international airport; 2) factories north of Ticuantepe along the Masaya highway; 3) the town of Tipitapa, and 4) the city of Masaya (Fig. 8.4.3).

FIGURE 8.4.2 Principles for combining groundwater vulnerability and the characterisation of contamination sources and assigning a low, moderate, or high contamination liability to groundwater

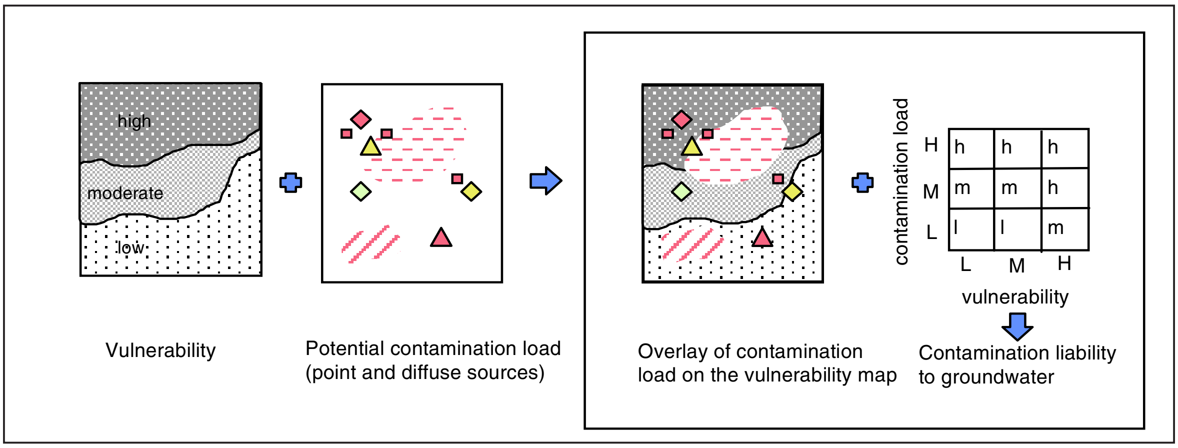
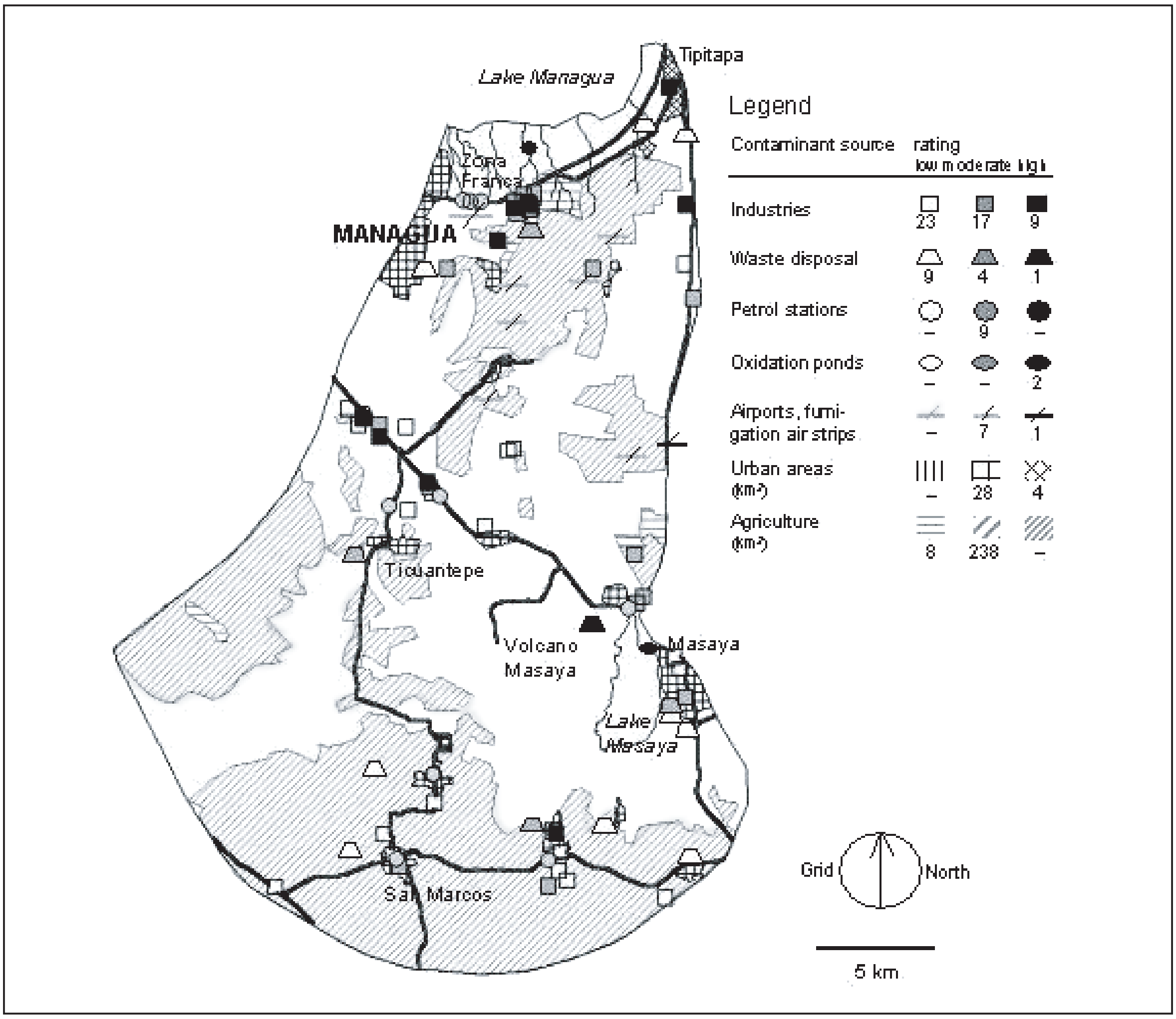


FIGURE 8.4.3 Location and classification of contamination sources in the eastern subarea (the number of classified point sources and the areal extent of diffuse sources in km^2, together with their respective rating of low, moderate, or high, are indicated in the legend)



The Zona Franca comprises a variety of activities ranging from tanneries to metal workshops to textile manufactures. Not all sources received a high rating. However, the concentration of potentially contaminating activities, including the airport, merits special attention. Among the factories along the Masaya highway, the method gave high ratings to the chemical plants producing paint and chlorinated disinfection agents. The town of Tipitapa has several urban settlements without sewage systems. In the city of Masaya most sources received a low to moderate rating with exception of the oxidation pond originally designed for approximately half the amount of sewage water it receives today. In addition to this, several factories that do not treat their effluents are connected to the pond. The waste disposal site west of Lake Masaya receives liquid industrial waste and was, therefore, assessed as a site of high potential contamination load.

The agricultural areas were mostly assessed as being of moderate potential contamination load. The north central part of the area, where cotton was formerly grown, was given a moderate rating. During the 30 years of cotton cultivation many pesticides of the so called 'dirty dozen', such as toxaphene and DDT, were utilised intensively. There are several air strips in the area, which were used for storage, loading, and aerial spraying during the period of cotton cultivation. All except one are out of service today. However, the former handling and storage of pesticides on these sites merits special attention.

The distribution of contamination liability of the classified point sources is presented in Fig. 8.4.4a. In all, 54 features were classified as having a high to moderate contamination liability to groundwater. In these cases, protection measures need to be considered and more detailed studies carried out to protect the groundwater from becoming contaminated. Among the sources that have been classified as having a high to moderate groundwater contamination liability, the protection value map was used to indicate the priority for actions. Using that procedure, 15 features were given highest priority for initiating detailed studies and/or protective measures.

The distribution of the liability to groundwater contamination from diffuse sources (agricultural land and urban areas) is given in Fig. 8.4.4b. Approximately 270 km^2 were classified as high or moderate in contamination liability to groundwater. However, out of these, only 34 km^2 were evaluated as having high contamination liability. The large majority of the areas are agricultural lands that resulted in a moderate contamination liability.

FIGURE 8.4.4 Matrices for evaluation of contamination liability to groundwater (outcome of classification of sources is indicated in parentheses after each class: a) number of sources, b) area in km^2)

a) Point sources

Potential contamination load \ Vulnerability	*Low*	*Moderate*	*High*
High	High (0)	High (10)	High (3)
Moderate	Moderate (3)	Moderate (26)	High (8)
Low	Low (6)	Low (22)	Moderate (4)

b) Diffuse sources (km^2)

Potential contamination load \ Vulnerability	*Low*	*Moderate*	*High*
High	High (0)	High (10)	High (3)
Moderate	Moderate (3)	Moderate (26)	High (8)
Low	Low (6)	Low (22)	Moderate (4)

8.4.5 Discussion and conclusions

The characterisation of contamination sources is perhaps the most difficult and time-consuming part of the work, considering the large number of contamination sources and types of contaminants involved. To avoid misinterpretation, it is important to stress that the developed method is qualitative and should be used as a planning and screening tool and that it cannot replace site-specific, detailed investigations. A major uncertainty arose in the evaluation of former cotton fields exposed to excessive application of persistent and non-degradable pesticides. These areas were, according to the method, classified as being of moderate potential contamination load. Nevertheless, these areas must be considered with care in future land use, detailed studies on residual pesticide concentrations in the unsaturated zone must be carried out, and transport to wells closely monitored.

The results from the superimposition of the potential contamination load on the vulnerability map indicated that not very many of the contamination sources with high potential contamination load were located in highly vulnerable areas. For the moment, the most problematic area is in the north, close to Lake Managua, where there are shrinking and swelling clays and the groundwater level is close to the land surface. Examples of activities causing high potential contamination load in this area are residential areas without sanitation facilities (high nitrate leaching and microbiological contamination), industries in the Zona Franca, and an oxidation pond.

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8.5 Identifying potential areas in the Western Cape Province, South Africa, suitable for developing a regional waste disposal site

Julian Conrad and Gideon Tredoux

8.5.1 Introduction

As the pressure on our scarce water and land resources grows, increasing sophistication in resource protection and management becomes necessary. Although South Africa is not as fortunate as other countries with regard to regional groundwater resources, it does have local resources, which if properly managed on a sustainable basis, could play a major role in meeting the country water requirements. Thus, in this arid country, which receives well below the world average rainfall, protection of groundwater resources is a crucial concern. Of the many and varied activities that can cause contamination of groundwater resources, disposal of waste is of critical concern in South Africa. There are many waste sites that do not meet minimum standards and there are many that have a limited life span. The concept of waste transport by rail, which is termed *waste-by-rail*, is well embraced and proven overseas. South Africa has an extensive rail network and for this reason South Africa's major rail transporter has embarked on a strategy that will lead toward the advancement of the waste-by-rail concept.

A project was carried out to identify areas suitable for a regional landfill site within the Western Cape Province. The study was essentially a 'desk top' study, using available data and a numerical processing approach to determine suitable areas for waste disposal. The processing was carried out using a Geographical Information System (GIS). The GIS is ideal for preliminary site-suitability studies because it efficiently stores, retrieves, analyses, and displays information according to user-defined specifications. Thus, once a GIS data base is developed, it can provide an efficient and cost-effective means of analysing different options and potential site attributes. However, GIS can be limited by a lack of available, accurate, or up-to-date data. Many data sets had to be obtained, and uniformly georeferenced for this project prior to the commencement of the analysis.

The numerical processing was carried out using the Unix-based GIS, ArcInfo. The analysis was limited to an extent by the availability of data and also by the level of accuracy of the data sets. However, in terms of this pre-feasibility study, this did not hamper the project in any way. The results obtained from the analysis were presented on a composite map, which showed the input data sets, the ranked data sets, the final result, and a few of the criteria that will need to be considered in the future phases. The analysis and results can also be viewed in a more dynamic manner, using desktop Windows-based GIS software.

8.5.2 Objective

The primary objective of this project was to identify broad areas in the Western Cape Province that are potentially suitable for the development of a waste disposal site. The selection of such areas was to be based on a set of predetermined selection criteria, namely:

- groundwater potential (or the lack thereof),
- aquifer vulnerability,
- maximum distance of 50 km from existing railway lines,
- agricultural potential of land, and
- land use and/or population density.

Only existing information was used in the investigation and the data had a maximum resolution scale of 1:250,000.

8.5.3 Siting procedures

Siting a landfill requires a substantial evaluation process in order to identify the most suitable location, that is, a location that meets the requirements of government regulations and minimises economic, environmental, health, and social costs. Evaluation processes or methodologies are structured to make the most use of available information and to ensure that the results obtained are reproducible so that outcomes can be validated and defended.

Hopkins (1977) evaluated and compared, quite extensively, general methods for generating land suitability maps. He defined eight methods: gestalt, ordinal combination, linear combination, non-linear combination, factor combination, cluster analysis, rules of combination, and hierarchical combination. Because of the complementary characteristics of several of the methods, application of more than one method was recommended in carrying out land suitability analysis.

The DRASTIC (Aller et al., 1987) and LeGrand methods (Canter et al., 1987) are examples of site evaluation procedures that focus on a single domain. They can be used to evaluate groundwater contamination potential from proposed landfill (Noble, 1992). Examples of more general procedures include interaction matrices (Camp Dresser & McKee Inc, 1984) and the weighted rankings method, which are impact assessment techniques used to evaluate the various impacts of proposed landfills. These procedures result in an impact rating, which is interpreted as the relative suitability of each potential landfill site (Siddiqui et al., 1996).

With the growth in the availability of digitised data, several methods of site selection have become available. Examples of these methods are the methods of intrinsic suitability used by the Minnesota Pollution Control Authority (Noble, 1992) and the George Noble's method (Noble, 1992). However, these methods use GIS capabilities only for screening out unsuitable areas. There are factors that still need to be considered that are not exclusion factors. These factors can best be evaluated by means of a rating and weighting procedure.

Once potential areas have been identified, they can be evaluated and classified according to the analytic hierarchy process (AHP) or a similar process. Since its introduction in the late 1970s, AHP has been applied in a wide variety of practical settings to model complex decision problems. Its ability to rank and assess decision alternatives quantitatively has led to many applications in many diverse areas (Siddiqui et al., 1996). The AHP is becoming popular in decision-making studies where competing objectives are involved. Although the objective of this project was to highlight potentially suitable areas, AHP ranking of those areas was not carried out.

8.5.4 Methodology

With the knowledge base developed by reviewing the literature (e.g. Al-Bakri et al., 1988; Andreottola et al., 1989; Ball, 1994; Frantzis, 1993; Gebhardt and Jankowski, 1986; Minor and Jacobs, 1994; Siddiqui et al., 1996), and also from experience in other site selection projects, a group of four specialists derived the optimum methodology for this project. The group included a hydrogeochemist, an environmentalist (with expertise in the field of waste site selection), a mathematical modeller, and a GIS specialist. From their sessions, the criteria required for the project were determined, and then reduced to those data sets according to availability.

After determining the relevant data sets, it was decided that two components would form the basis of the methodology. The first would be to exclude all the areas that would almost certainly not be acceptable for a waste disposal site and the second would be to rank and weight the non-exclusionary areas. In addition, a few of the factors that will be important in the next phase, i.e. the ground-truthing and more detailed investigation phase of waste site location, have been identified.

(i) Exclusionary criteria

These criteria and the relevant exclusion distances were obtained, as far as was possible, from the guidelines of the Department of Water Affairs and Forestry's Waste Management Series (1994). Where explicit information was not available from DWA&F's document, the information was derived from overseas guidelines, as well as local expert opinion.

Exclusionary criteria included structural geology (faults), topographic slopes, rivers, lakes, large dams, coastlines, major roads, rail lines, population density, proximity to residential areas, airfields, power lines, mountainous areas, indigenous forests, and conservation areas. Exclusionary criteria that were not considered in the analysis included: the location of public water supply surface water intakes, public water supply wells, sole source aquifers, the 50-year flood levels, areas contributing to large dams, agricultural potential, land use, location of archaeological/historically important sites, areas with mineral rights, servitudes, atmospheric factors (e.g. areas with very high wind velocities), and visibility impacts (e.g. scenic areas that are visible from major roads and railways). In addition, economic, social, and political factors were not taken into account in this project.

The reasons for not including these data were that the data were either not available in a usable digital format or not of sufficient accuracy or not relevant for this pre-feasibility study. These criteria will, therefore, have to be considered in a further phase, once closer identification of potential sites is reached.

(ii) Non-exclusionary criteria

After the exclusionary areas were identified, the remaining areas were rated according to suitability. The four criteria for which data could be obtained and that were seen as important were: geology (lithology), depth to groundwater, soil texture, and soil depth. Each of these categories was rated from 1 to 9 (the lower the number, the more favourable the site), and then a weighted equation developed for the final result. The DRASTIC approach (Aller et al., 1987) was used as a guideline to determine rating and weighting values. The final results from the equation were then divided equally into five classes of suitability. The numerical approach taken in the rating was that the lower the score, the more suitable the area for a waste disposal site.

(iii) Weighting equation

The equation used for obtaining the final scores of non-exclusionary areas is as follows:

$$\text{Score} = 5 (G * GW) + (ST * SD)$$

where: G = geology, GW = depth to groundwater, ST = soil texture, and SD = soil depth.

The scores resulting from this rating and weighting were then divided linearly into five categories, with the lowest score representing the most suitable area and the highest score the least suitable.

The following assumptions were made in determining the above equation:

- leachate and gas management will be implemented;
- soil possibly will be removed during construction;
- the waste site has a 50- to 100-year life span;
- the site has an extent of approximately 4 km^2.

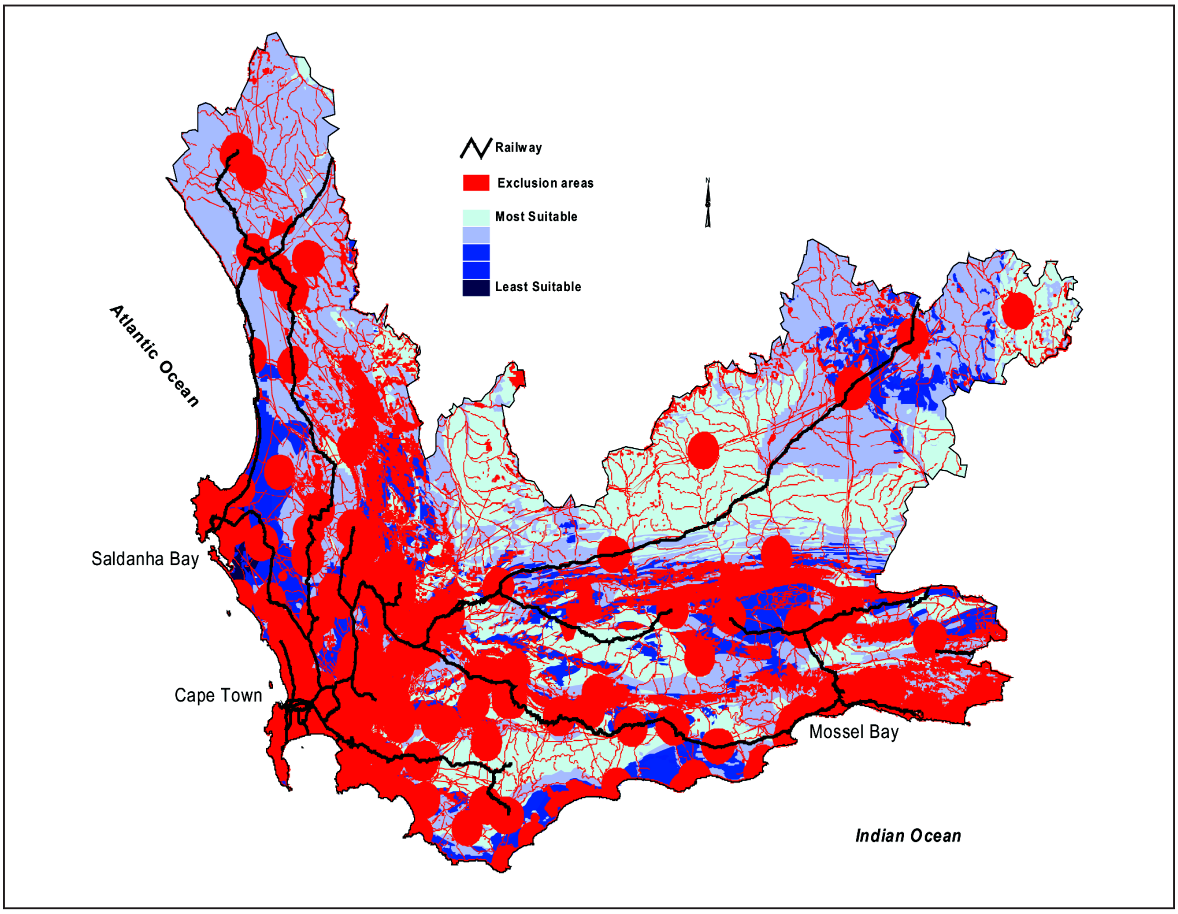
8.5.5 Results and conclusions

Results for the project can be viewed on Fig. 8.5.1. The results obtained clearly show the exclusionary areas. The 10-km buffer zones around cities and towns are clearly evident. Where possible, the actual shape of the town was used in the buffering. However, this factor needs further work to determine the growth potential for the city/town in the next 50 to 100 years. It may well be more or less than the arbitrary 10 km chosen in this analysis. Landfill odour, dust, and other factors will ultimately determine the acceptable distance from any residential area. It is interesting to note that with a 50-km buffer around the railway lines, there is virtually complete coverage of the Western Cape Province.

This pre-feasibility study provides a clear graphic representation of areas potentially suitable for the development of a regional waste disposal site for the Western Cape Province (Fig. 8.5.1). The result obtained is subject to various assumptions and area suitability may change when a different set of assumptions are made. Should this become necessary, the GIS overlay technique used is flexible enough to allow rapid re-evaluation of area suitability. 'What-if' scenarios can quickly be established (e.g. changing the acceptable distance from rail links to 30 km instead of 50 km).

Not all factors impacting on waste disposal site selection could be included in this analysis. Aspects such as the existence of archaeological sites, site accessibility, land potential, cost, etc, have to be considered in any detailed site selection procedure. The study has subsequently been extended to cover other provinces in South Africa and a national study is also underway.

Figure 8.5.1 Areas in the Western Cape Province potentially suitable for a regional waste disposal site



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8.6 Regional inventory of groundwater contamination sources in southeastern Wisconsin, USA

Alexander Zaporozec

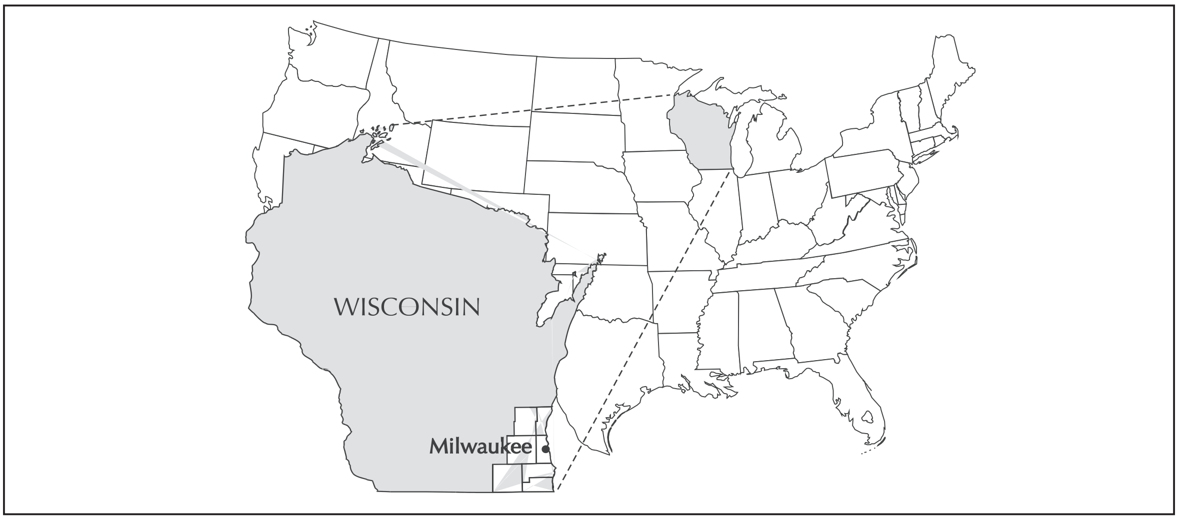
8.6.1 Regional setting

The Southeastern Wisconsin region is comprised of seven counties, including Milwaukee County, which is one of the major metropolitan areas in the United States (Fig. 8.6.1). The region has a total area of 6,965 km^2, or about 5 percent of the total area of the state of Wisconsin. Southeastern Wisconsin contained in 1996 about 37 percent of the state population, and is one of the most rapidly growing regions of Wisconsin.

The geological setting of the region is a thick wedge of Paleozoic sedimentary rocks (sandstones and dolomites) that overlie Precambrian crystalline basement rocks. The upper part of the Paleozoic sedimentary sequence is overlain unconformably by Pleistocene deposits ranging from 0 to 125 m in thickness and consisting of sand and gravel or sandy, clayey silt dating from the late Wisconsin glaciation. A water-table aquifer is contained within these unconsolidated sediments and in the upper bedrock. The lower part of the Paleozoic bedrock, consisting of permeable sandstones and dolomites, forms an important artesian aquifer that supplies most of municipal and industrial wells in the region.

Groundwater is an important element in the continued development of the region. Therefore, the Southeastern Wisconsin Regional Planning Commission (SEWRPC) undertook in 1993 a 4-year study, in cooperation with the Wisconsin Geological and Natural History Survey (WGNHS), to inventory and evaluate the groundwater resources and their potential for attenuation of contaminants (SEWRPC, 2001). An important part of the study was the inventory of groundwater contamination sources.

FIGURE 8.6.1 Location of south-eastern Wisconsin in the United States



8.6.2 Approach to inventory

For the purposes of the inventory, potential contamination sources in southeastern Wisconsin were listed in three categories according to their location (Table 8.6.1):

1) sources originating on the land surface;
2) sources originating below the land surface and above the water table;
3) sources originating below the land surface and below the water table.

No attempt was made to inventory all the possible sources listed in Table 8.6.1. The Commission

TABLE 8.6.1 Human activities that may create groundwater quality problems in southeastern Wisconsin

Originating on the land surface	*Originating below the land surface*
	Above the water table
Above-ground storage tanks	
Accidental **spills**	Animal waste storage facilities
Agricultural activities: **animal feedlots** **fertiliser and pesticide storage, mixing, and loading** fertiliser and pesticide application irrigation return flow silage and crop residue piles	Landfills Leakage: underground storage tanks underground pipelines sewers
	Septic systems
Dumps	Surface wastewater impoundments
Highway deicing	Sumps, dry wells
Liquid waste spreading or spraying (**sludge**, septage, sewage, **wastewater**, whey)	Waste disposal in dry excavations
Salvage yards	*Below the water table*
Stockpiles (chemicals, **salt**)	Groundwater development: improperly abandoned wells and holes improper well construction overpumping
Infiltration of contaminated surface water or precipitation	
	Drainage or disposal wells
	Waste disposal in wet excavations

selected ten categories of contamination sources that may have the greatest impact on the groundwater quality in the region (indicated in bold in Table 8.6.1). The primary emphasis of the inventory was on the clusters of on-site septic systems, landfills (including active, abandoned, and those containing hazardous materials), leaking underground storage tanks, spills of hazardous materials, and abandoned wells. Lesser priority received the remaining five contamination sources: sludge and wastewater land application sites, bulk fertiliser and pesticide storage facilities, major farm animal operations (100,000 animal units or more), stockpiles of salt for highway deicing, and salvage yards.

Inventory of the cases of existing contamination was not part of the study. However, information on contamination was obtained at least qualitatively. The Wisconsin Department of Natural Resources (DNR) requires that all water wells in the areas of known contamination have special well casings. This special well-casing requirement program was created under Wisconsin Administrative Code NR 112 to provide additional protection of drinking water in areas where aquifers have been contaminated. Reported special well-casing areas indicated where contamination had been detected. The most often found contaminants were volatile organic chemicals (VOCs) and bacteria. Other contaminants included petroleum products, nitrate, landfill leachate, and detergents.

Due to limited financial and personnel resources, the contamination source inventory was in its entirety an office study. Potential contamination sources were located from the state and local agency files; no identification was done in the field. Most of the data were obtained from the Wisconsin DNR, which is the primary agency responsible for regulating and protecting groundwater resources in the state and is currently completing the inventory of all major sources of contamination under its jurisdiction. The remaining data were located in the files of the Wisconsin Department of Transportation (underground leaking tanks and salt storage), Wisconsin Department of Agriculture (agrochemicals and animal farms), SEWRPC (on-site septic systems and land use), and WGNHS (water well reports).

The southeastern Wisconsin region is a good example of how the type and quality of data on contamination sources may vary between the urban areas and non-urban areas (Table 8.6.2). The eastern and central parts of the region are predominantly urban, with large population centres along Lake Michigan: Milwaukee, Racine, and Kenosha. The western part remains predominantly rural with isolated urban centres.

TABLE 8.6.2 Difference in type, distribution, and quality of data between urban and non-urban settings (*Source:* Eaton and Zaporozec, 1997)

Data characteristics	*Urban setting*	*Rural/suburban setting*
Type of data	Industry-related: tanks, spills Salt storage Salvage yards	Land application of wastewater Subdivisions with on-site septicsystems
Distribution of data	Locally abundant Concentrated at specific sites Wide distribution at low densities	Regionally abundant
Quality of data	High precision and detail Very time specific Subject to local, often unknown influences	Generalised Representative over long time span

8.6.3 Inventory results and data presentation

No attempt was made to rank quantitatively the various potential contamination sources in the region. The evaluation represents only an informed judgement on the nature and extent of potential contamination sources and on potential problems.

Results of the contamination source inventory indicated that the greatest potential problems are the large numbers of leaking underground storage tanks (majority of them in urban areas) and spills of hazardous materials (mostly concentrated along highways and within urban areas near storage tanks). Also thousands of abandoned domestic wells are expected to be within areas now served by municipal water systems. Individual on-site septic systems were not inventoried. Instead, the contamination source inventory focused on areas of clustered systems (more than 32 housing units per section)*, which number 120 in the region and present a greater threat than the individual units. A large number of inactive landfills were found near urban centres, and also scattered throughout the region. Thirteen percent of those contain some amount of hazardous materials.

More than 48 km^2 were approved for land application of wastewater and sludge in rural areas of southeastern Wisconsin, almost half of them being tracts of land smaller than 0.2 km^2. There were 30 bulk agricultural chemical storage and loading facilities scattered throughout the

* Most of the land in the United States is divided into legal tracts, based on the U.S. Public Land Survey System adopted by Congress in 1785. The basic unit is called a township (6 miles x 6 miles), which consists of 36 sections, each approximately 1 square mile (or 2.59 km^2) in area.

region, most of them well-operated and controlled. Major animal farm operations are not common in southeastern Wisconsin; there were only six farms with more than 100,000 animal units. Although there are relatively large numbers of salt storage facilities and salvage yards in the region, they represent only a minor threat to groundwater. Most of the salt piles are covered to prevent infiltration of rainwater; and salvage yards are well-operated and handle only non-hazardous materials.

The most difficult part of the inventory was the identification of abandoned wells. In the years before there were municipal water supply systems, people in the cities were dependent entirely upon domestic wells for household water. As the public water systems were built and their areas expanded, these domestic wells were often abandoned without being properly closed and sealed. Their locations were often long forgotten, and buildings, parking lots, or roads may have been built over the top of these open wells. These forgotten wells represent a great threat to groundwater quality because they can serve as direct conduits for transmission of contaminants from the land surface to an aquifer and can permit contaminated water to migrate freely from one aquifer to another. This is particularly critical for southeastern Wisconsin, where the open intervals of most wells include several different aquifer units.

Most of these old wells are located in Milwaukee County (Fig. 8.6.1). Although the first public water system in the city of Milwaukee was built already in 1873, it was not until 1963 when most of Milwaukee County was converted to municipal water supply. Given the financial and time constraints of the study, it was not possible to locate the abandoned domestic wells in the field. As a substitute, which would enable to at least estimate the extent of the problem, the gradual expansion of the area served by the municipal water system was mapped and records inspected of wells drilled since 1936 (when the law providing for the registration of well drillers and mandatory submission of well reports was enacted in Wisconsin). The densities of well records per section were then plotted, which provided a reasonable estimate of improperly abandoned wells (up to 8,000) and information on where such wells are most likely to be found.

All identified contamination sources were summarised in tables and plotted on county maps at the scale 1:48,000. Most of the contamination sources were presented on maps as points. For the numerous sources (tanks, spills, and abandoned wells), the data were presented in densities per section. Sites for the land application of wastewater and sludge (diffuse contamination) were shown in acres of approved land.

8.6.4 Implications for regional groundwater quality planning

The primary goal of the project was the regional assessment of groundwater resources in southeastern Wisconsin and their potential for contamination. Results and recommendations of the project were incorporated as a groundwater management component for a long-term regional water quality management and protection plan of the region.

Maps of potential contamination sources can be used in conjunction with groundwater vulnerability or other maps for successful land use and water quality planning. One of such products is a map of potential problem areas, which was compiled by superimposing maps of potentially contaminating sources over the naturally vulnerable areas and critical recharge areas of deep aquifers, which are very important sources of many municipal and industrial water supplies in southeastern Wisconsin. Final analysis of the places that may cause potential groundwater quality problems showed that, at the present, the inventoried contamination sources do not present a significant threat to groundwater quality in most cases. There are only a few landfills, a couple of agricultural chemical storage facilities, and one major farm operation that are located in naturally vulnerable areas. It was recommended that construction, operational, and maintenance procedures at these sources be examined to determine if the potential threat to groundwater quality exists and if control measures are needed.

However, most of the areas in which contamination of shallow aquifers may have already occurred (as indicated by the results of special well-casing requirement program) are located in the most vulnerable areas of the region. Immediate remedial actions and the identification of additional suspected contamination areas were strongly recommended.

The delineation of the potential problem areas was not intended to suggest that these were the only areas where potential groundwater quality problems may occur. All inventoried contamination sources have to be considered as having a potential to contaminate groundwater. The map of potential problem areas was intended only as a planning tool to prioritise the potential problems and to indicate which areas should be addressed first in a regional water quality management plan.

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Appendix A

Glossary

The glossary includes technical terms used in this guideline to help readers understand their meaning because different terms have different meaning to different people. The following definitions were compiled from numerous sources and simplified to present their general meaning as utilised in this publication. More specific definitions can be found in Fetter (1994), Pfannkuch (1990), UNESCO (1992), and U.S. Geological Survey (1989).

Adsorption	The attraction and adhesion of ions and molecules in solution to surfaces of solids with which they are in contact. Synonym: sorption. Reverse process: desorption.
Advection	A physical process by which solutes/contaminants are transported by the bulk motion of flowing groundwater.
Aquifer	A rock unit that potentially yields groundwater to wells in exploitable quantities. Related terms: confined/unconfined aquifer, groundwater system. Compare: aquitard.
Aquifer sensitivity	The intrinsic susceptibility of an aquifer to contamination solely related to the hydrogeological characteristics of an aquifer and the overlying soil and geological materials. Related terms: susceptibility, vulnerability.
Aquitard	A low-permeability rock unit. Compare: aquifer.
Artesian aquifer	See confined aquifer.
Artesian well	A well in which the water level stands above the top of an aquifer but not necessarily above the land surface.
Attenuation capacity	The intrinsic ability of earth materials and an aquifer to absorb, dilute, or retard contamination by complex physical, chemical, and biological processes in the soil-rock-groundwater system. Related term: contamination potential.
Bedrock	The consolidated (solid) rock that underlies soils and other unconsolidated deposits.
Brine	Saline water that has a concentration of total dissolved solids much above that of sea water, conventionally above 100,000 mg/l.

Casing	See well casing.
Complexation	Combination of cations with molecules or anions containing free pairs of electrones.
Concentration	The relative content of a dissolved component in water.
Confined aquifer	An aquifer bounded above and below by beds of distinctly lower permeability than that of aquifer itself. Synonym: artesian aquifer (obsolete term). Compare: unconfined aquifer.
Connate water	Interstitial water that has been out of contact with the atmosphere for an appreciable part of a geological period. Compare: fossil water.
Contaminant	A naturally-occurring or human-produced substance that renders water unfit for a given use.
Contamination	Introduction into water of any undesirable substance not normally present in water (e.g. microorganisms, chemicals, waste, or sewage), which renders the water unfit for its intended use. Compare: pollution. Related terms: contaminant, contamination plume, contamination potential, contamination source.
Contamination plume	The spreading of a contaminant in the direction of groundwater flow from point of origin to the point where contaminant concentration falls below the objectionable limits. The outer boundaries are in some cases difficult to detect. Related terms: contaminant, contamination.
Contamination potential	Susceptibility of groundwater to contamination from a specific contamination source or by a specific contaminant. Synonym: degree of hazard (risk). Related terms: attenuation capacity, contamination.
Contamination source	Natural substance/process or human activity/facility that has caused or has a potential to cause contamination of groundwater. Related terms: contamination; diffuse, line, and point sources.
Degassing	A process of removing gas or gaseous decay products from groundwater.
Desorption	See adsorption.
Diffuse source of contamination	A source of contamination that does not emanate from a discernible confined, or discrete conveyance (e.g. leading of agrochemicals). Synonym: non-point source. Compare: line source, point source.
Discharge	The volume of water flowing through an aquifer past a specific point in a given period of time. Compare: recharge.

Dispersion	A mixing process in flowing groundwater causing a solute/ contaminant to spread out due to the nature of the porous medium, gradually occupying an ever increasing space, and declining in concentration.
Dissolution	A chemical process by which mineral and rock material passes into solution. Compare: solution.
Evapotranspiration	Combination of evaporation (the process by which water passes from the liquid to the vapour state) and transpiration (the process by which plants give off water vapour through their leaves).
Fissure	See fracture.
Fossil water	Entrapped residual water in a sediment from the time of deposition. Compare: connate water.
Fracture	A general term for any break in a rock due to mechanical failure by stress; includes cracks, joints (fissures), and faults.
Fracture trace	The surface representation of a fracture zone (e.g. a characteristic line of vegetation or linear soil-moisture pattern). Related term: lineament
Groundwater	Subsurface water in the saturated zone below the water table. Related terms: groundwater flow, groundwater system.
Groundwater flow	Pattern of groundwater movement in the saturated zone from the point of recharge to the point of discharge. Related terms: groundwater, groundwater system.
Groundwater system	An interconnected body of aquifers, usually of regional extent, which acts and can be studied as an unit. Related terms: aquifer, groundwater, groundwater flow.
Hydraulic conductivity	A measure of the ability of a porous medium to transmit a fluid. Compare: permeability.
Hydrolysis	A chemical decomposition reaction involving the elements of water.
Infiltration	Passage of water from the land surface into and through the upper soil layers. Compare: percolation.
Ion	An atom or group of atoms that carries a positive (cation) or negative (anion) electric charge as a result of having lost or gained one or more electrons.
Ion exchange	A process by which an ion in a mineral lattice is replaced by another ion that was present in aqueous solution.
Leachate	Liquid produced by water percolating through a porous or soluble material, such as refuse in a landfill; can contain dissolved and suspended solids in high concentrations.

Lineament	A natural linear topographic feature of regional extent (longer than 1,500 m) that is believed to reflect crustal structure (such as fault line). Related term: fracture trace.
Line source of contamination	Linear source that can spread contamination over larger distances, e.g. a leaking pipeline or contaminated stream. Compare: diffuse source, point source.
Metadata	A system used to describe the origins of and to track the changes to geospatial data ('data about data').
Non-point source of contamination	See diffuse source.
Nutrients	Compounds of nitrogen, phosphorus, and other elements essential for life and plant growth.
Oxidation-reduction	Chemical reaction in which a participating element loses electrons (oxidation) or gains electrons (reduction).
Paludal	Pertaining to a marsh.
Percolation	The flow of water through an unsaturated porous material. Compare: infiltration.
Permeability	The ability of a porous medium to transmit a fluid. Compare: hydraulic conductivity, porosity.
Piezometric surface	See potentiometric surface.
Plume	See contamination plume.
Point source of contamination	Any single, well-defined, distinct source of contamination (e.g. a landfill, waste injection well, leaking underground tank). Compare: diffuse source, line source.
Pollution	Addition of pollutant to water, which restrains the use of water. Compare: contaminant, contamination.
Porosity	The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment. Compare: permeability. Related terms: primary porosity, secondary porosity.
Porosity, primary	The porosity that was present when a rock or sediment formed.
Porosity, secondary	The porosity that developed after a rock or sediment formed, through processes such as fracturing, solution, or weathering.
Potentiometric surface	An imaginary surface that represents the level to which water will rise in tightly cased wells. The water table is the potentiometric surface of an unconfined aquifer. Synonym: piezometric surface (no longer used; in older literature limited to the static level of water in a confined aquifer). Compare: water table.

Precipitate	To separate from solution by chemical or physical change. Related term: precipitation.
Precipitation	The process of forming a precipitate. Also: Water that falls to the land from the atmosphere in form of rain, snow, sleet, or hail. Related term: precipitate.
Recharge	The addition of water to an aquifer. Compare: discharge.
Retardation	A general term for the many, principally chemical, processes that act to remove the contaminants in groundwater, or slow down their travel.
Saturated zone	The subsurface zone in which all interconnected openings are filled with water under pressure greater than atmospheric. Synonym: zone of saturation, phreatic zone (obsolete term). Compare: unsaturated zone.
Septage	Liquid and sludge pumped out from a septic tank at regular intervals.
Slug test	An aquifer test performed either by pouring a small instantaneous charge of water into a well or lowering a slug (solid piece of metal) below the water table.
Soil	The upper 1 to 1.5 m of unconsolidated material. Contains living matter and supports plants. Related term: unsaturated zone.
Solute	The substance present in a solution; the dissolved inorganic or organic constituent. Related term: solution.
Solution	A process by which a solid (or liquid or gaseous) substance is mixed with water. A liquid containing a dissolved substance. Compare: dissolution. Related term: solute.
Sorption	See adsorption.
Spring	Localised natural discharge of groundwater at the land.
Susceptibility of groundwater to contamination	Lack of ability of groundwater to resist the impact of contamination on the quality of groundwater. Compare: aquifer sensitivity, contamination potential, vulnerability.
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.
Unconfined aquifer	An aquifer with the water table forming a free upper surface. Synonym: water-table aquifer. Compare: confined aquifer.
Unconsolidated deposits	Loose material overlying bedrock. Includes: soil; glacial, stream, or windblown deposits; weathered bedrock; and organic deposits.

Unsaturated zone	The zone between the land surface and the water table that contains both water and air. Consists of the soil water zone, the intermediate vadose zone, and capillary zone. Synonym: zone of aeration, Compare: vadose zone, saturated zone. Related term: soil.
Vadose zone	See unsaturated zone.
Vulnerability of groundwater	An intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts. Compare: aquifer sensitivity, susceptibility.
Water table	The imaginary, upper surface of the unconfined aquifer along which the pressure is about atmospheric. Synonym: phreatic surface (obsolete term). Compare: potentiometric surface.
Well	Shaft or hole, sunk, dug, or drilled into the earth to extract water. Related term: well field.
Well casing	A solid piece of pipe, typically steel or PVC plastic, used to prevent the sides of the borehole from caving and to prevent unwanted fluids from entering the borehole. Related term: well screen.
Well field	A tract of land containing a number of wells. Related term: well.
Well log	A record of the lithology of the rock and soil encountered in a borehole from the surface to the bottom.
Well screen	A tubular device with either slots, holes, gauze, or continuous-wire wrap; used at the end of a well casing, which enables the water to enter the well and which keeps sediment from entering the well. Related term: well casing.
Zone of aeration	See unsaturated zone.

Appendix B

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Appendix C Model legend

In an effort to standardise the symbology to be used on groundwater contamination inventory or risk maps, the tables following below show the proposed symbols and principles of their cartographic representation. The standardisation of a map legend will assist in the development of a common language and understanding with regard to groundwater contamination inventory and groundwater contamination risk maps.

The symbols proposed here are not an exhaustive collection, so changes and additions to the symbol set are welcome and can be submitted to the UNESCO IHP office in Paris (1 rue Miollis, 75015 Paris, France). The symbols will be made available for downloading from the Web (http://www.unesco.org/water), as a Word document.

C.1 Cartographic representation

Decisions on the cartographic representation, mainly the legend, the map scale, and a suitable topographic base map must be made in the preparatory phase of a groundwater contamination inventory (see paras. 4.1.3, 6.1.1, and 6.1.2). The legend should give maximum information and assist in the interpretation of the map, whilst still maintaining clarity. To be of maximum value, the legend used must be clear, concise, and complete (Vrba and Zaporozec, 1994). The user must not be required to guess what the symbols and/or colours on the map indicate. The colours used must be carefully chosen to permit legibility (par. 6.1.3*(ix)*). Experience has shown that distinctly different and less intense colours are generally more effective than confusingly similar shades or bright colours. It is important to print a sample of the map first and adjust the shades and brightness as needed. Cartographers are well trained in colour composition and should always be asked for advice, to avoid poorly composed maps being presented.

Results of a groundwater contamination inventory are presented on maps in the form of points, lines, and areas. Point symbols of a varying form, size, orientation, filling, and colour (Struckmeier and Margat, 1995) show, for example, the location of a well, its size, and its yield or the location of a buried storage tank or of another point source of contamination and its status. Line symbols are used for linear features such as pipelines, streams, and boundaries. Areal characteristics, such as diffuse sources of contamination, extents of contaminated areas, or source protection zones, are illustrated by colours and ornaments (patterns). Symbols, colours, and ornaments (patterns) should be based on recommended international standards (Struckmeier and Margat, 1995; Vrba and Zaporozec, 1994) as far as possible.

C.2 Groundwater contamination inventory map

When designing a groundwater contamination inventory map, it is useful to categorise the presented information into primary and secondary classes.

C.2.1 Primary information

The primary information presented on a groundwater contamination inventory map are the contamination sources and the ambient groundwater quality conditions, including the spread of existing contamination of groundwater. Symbols in the proposed legend have been adapted from the symbology developed by IAH for groundwater vulnerability maps (Vrba and Zaporozec, 1994) and for hydrogeological maps (Struckmeier and Margat, 1995). The proposed symbols for potentially contaminating activities, i.e. agricultural, municipal, mining, industrial, and other, are included in Table C.1. Generally, they are shown in red or black. The ambient groundwater quality conditions, such as the area of contaminated groundwater or seawater intrusion are listed in Table C.2, and usually are shown in colours or patterns.

In addition, contamination inventory maps should also include the objects that may be affected by contamination spreading from the existing and potential sources of contamination, which may need protection against such contamination. These objects include all water supply sources and related features. Also shown should be protection measures already in effect (e.g. source protection zones) or other important features, such as significant recharge areas. Recommended symbols are included in Table C.3, and are shown on a map in violet.

C.2.2 Secondary information

The secondary information includes topographic features and major hydrological features. This information should be included as a base map upon which the primary information is shown.

A suitable topographic base forms the background of the contamination inventory map. Background topographic features (roads, railroads, settlements, streams, etc) serve as orientation features for the map user. For these, a standard set of topographic symbols should be used. Topographic information is shown in a grey tone.

Hydrological information cannot be shown in a great detail on the contamination inventory map. It should include only selected features that are relevant to the goals and objectives of the inventory. Too much detail would reduce legibility of a map. If there is a need for more hydrological information, it can be included as one of the supporting maps (para. 6.2) alongside the main groundwater contamination inventory map.

The major hydrological features, both groundwater and surface water, recommended for the inclusion on a contamination inventory map are listed in Table C.4. Groundwater features (for example, springs, cones of depression, or direction of groundwater flow) are shown on a map in violet. Surface water features (character of streams, stream/groundwater relationship, etc.) are shown in blue.

C.2.3 Sample map

An example of the groundwater contamination inventory map with the proposed legend is included in Chapter 6, para. 6.1.5 (Fig. 6.3).

C.3 Groundwater contamination risk map

The compilation and construction of a groundwater contamination risk map is described in para. 6.2.4. Information presented on a groundwater contamination risk map is shown again in colours and symbols (para. C.1). The base map for a groundwater contamination risk map should be the same as that for the groundwater contamination inventory map (para. C.2.2).

The basis of a groundwater contamination risk map is a combination of a groundwater vulnerability map (para. 6.2.2) and a groundwater value map (para. 6.2.3). These maps should be constructed using colours recommended in international legends for hydrogeological maps (Struckmeier and Margat, 1995) and for groundwater vulnerability maps (Vrba and Zaporozec, 1994).

Combination of these two maps expresses the degree of protection needed and the associated urgency for the protection of groundwater. The resulting groundwater units are differentiated by areal colours showing the degree of groundwater protection urgency. The greater the urgency, the brighter and more reddish the areal colours. This map is overlain by a contamination inventory map showing the contamination risk rating of contamination sources and contaminated areas.

Symbols showing contamination sources and contaminated areas are recommended in Table C.1 and C.2, respectively.

Contamination risk rating is given by an index (letter or number) indicating the high (HR or 1), moderate (MR or 2), or low (LR or 3) potential contamination risk. Risk of groundwater contamination is a combination of the probability of contamination (combination of groundwater vulnerability and contamination sources) and the consequence of contamination (groundwater value rating). The risk assessment does not consider actual health risks due to the presence of a particular contaminant in groundwater. Rating of contamination sources can be done by any of the methods mentioned in Chapter 5 (paras. 5.3.2 and 5.3.3).

Areal categorisation of the risk is commonly arranged in a traffic-light pattern. Usually, three categories of groundwater contamination risk are shown on the map (Table C.5):

1) High risk (HR) - deep red colour.
2) Moderate risk (MR) - orange colour.
3) Low risk (LR) - light green colour.

An example of the groundwater contamination risk map is included in Chapter 6, para. 6.2.5 (Fig. 6.10).

Map symbols

Table C.1 Potentially contaminating activities (*Source:* Struckmeier and Margat, 1995; Vrba and Zaporozec, 1994)
(Note: Symbols for anthropogenic sources can be shown on map in red or black)

NATURAL SOURCES

- Limit of formations containing minerals with potential for contaminating groundwater (chemical element indicates potential contaminant, e.g. As for arsenic or Rn for radon)

AGRICULTURE

- Barren or untilled area (without use of fertilisers, pesticides, etc)
- Cultivated area with limited use of fertilisers, pesticides, etc
- Cultivated area with frequent and abundant use of fertilisers, pesticides, etc
- Fertiliser or pesticide storage (F or P)
- Animal waste storage facility
- Animal feedlot with indication of number of animals
- Area affected by irrigation return flow
- Flood irrigation area (e.g. rice field)
- Spray irrigation of wastewater, whey, etc
- Silage

FORESTRY

- Severely deforested area

URBAN SOURCES

- Controlled landfill (M = solid waste)
- Uncontrolled or unauthorised landfill (M = solid waste, I = industrial waste)
- Abandoned landfill (M = mixed solid, I = industrial, H = hazardous waste)
- Septic tank, cesspool, or latrine
- Collection point for untreated wastewater
- Urban area or large settlement, no sewerage system
- Urban area or large settlement, with sewerage system
- Municipal wastewater treatment plant (1 = primary, 2 = secondary, 3 = tertiary)
- Salvage and junk yard
- Leaking underground storage tank

Table C.1 (contd.)

MINING	
	Active quarry (P = excavation to piezometric surface)
	Abandoned quarry (P = excavation to piezometric surface)
	Filled quarry (P = excavation to piezometricsurface)
	Mine, pit (arrow indicates presence of a pumping plant)
	Mine tailings
INDUSTRY	
	Controlled landfill (I = mixed industrial, H = hazardous waste)
	Industrial wastewater pond
	Industry with effluent of organic biological waste (S = linked to urban sewerage system)
	Industry with effluent of inorganic waste (S = linked to urban sewerage system)
	Disposal or injection well
	Oil/fuel storage (S = surface, U = underground)
	Chemical storage or stockpile (S = surface, U = underground)
	Pipeline (G = gas, P = petroleum, C = chemical)
	Hazardous or toxic chemical spill, accidental or illegal
	Nuclear power plant
	Slaughterhouse
WATER MISMANAGEMENT	
	Seawater intrusion
	Boundary of saline water in an aquifer (seawater intrusion or inland salinisation)
	Well with faulty construction
	Improperly abandoned well
MISCELLANEOUS	
	Contaminated stream (G = draining groundwater, L = feeding groundwater)
	Highway, motor way, railway
	Airfield
	Military establishment
	Cemetery

TABLE C.2 Ambient groundwater quality conditions (*Source:* Struckmeier and Margat, 1995; Vrba and Zaporozec, 1994)

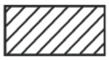
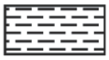
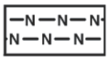
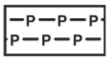
	Area with naturally poor groundwater quality (requires treatment for drinking water)
	Area with salty groundwater (exceeding 1 000 mg/l TDS)
	Area with groundwater contamination beyond national/international limits
	Area with nitrate concentrations exceeding drinking water standards
	Area with groundwater contamination by pesticide
	Area with groundwater contamination by non_biodegradable organic compounds
	Area with groundwater contamination by organic/biological matter
	Area with groundwater contamination by inorganic substances
	Area of underground mining affecting groundwater regime or quality
	Area of open cast mining affecting groundwater regime or quality
— 4 —	Isoline defining concentration of contamination (units must be specified in the legend, e.g. mg/l or Ig/l)

TABLE C.3 Objects of protection (*Source:* Struckmeier and Margat, 1995; Vrba and Zaporozec, 1994)

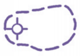
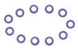
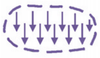
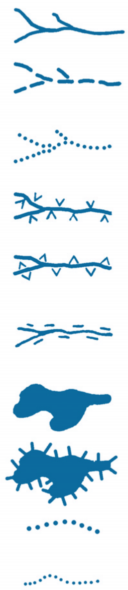
	Well for drinking water supply (L = multilayered aquifer system)
	Well for agricultural or industrial water supply (L = multilayered aquifer system)
	Well field: drinking water supply; agricultural or industrial water supply
	Spring developed for drinking water supply
	Important undeveloped spring
	Thermal (T) or mineral (M) spring
	Underground drainage gallery (e.g. kanat)
	Underground storage for drinking water
	Limit of the cone of depression resulting from groundwater abstraction
	Limit of area of intensive groundwater abstraction
	Groundwater recharge site
	Area of significant groundwater recharge
	Fenced perimeter of groundwater development work
	Source protection zone

TABLE C.4 Major hydrological features (*Source:* Struckmeier and Margat, 1995)

GROUNDWATER

- Contours of the potentiometric surface (with height relative to reference level; broken line where uncertain)
- Direction of groundwater flow
- Groundwater divide
- Limit of area with confined groundwater
- Spring; group of springs
- Groundwater seepage area
- Non-aquifer

SURFACE WATER



- Stream with perennial runoff
- Stream with intermittent runoff
- Dry valley, possibly with episodical runoff (emphemeral stream)
- Stream draining the groundwater system (gaining stream)
- Stream feeding the groundwater system (losing stream)
- Independent stream (no communication with an aquifer)
- Freshwater lake
- Perched lake (no communication with an aquifer)
- Main surface water divide
- Secondary surface water divide

TABLE C.5 Potential groundwater contamination risk

Contamination risk	Colour
HIGH	HR
MODERATE	MR
LOW	LR