

# **1. General Introduction**



## CHAPTER 1

# *General Introduction: The Need to Protect Groundwater*

PHILIPPE QUEVAUVILLER

European Commission, DG Environment (BU9 3/142), Rue de la Loi 200, BE-1049 Brussels, Belgium

### **1.1 Introduction**

Groundwater constitutes the largest reservoir of freshwater in the world, accounting for over 97% of all freshwater available on earth (excluding glaciers and ice caps). The remaining 3% is composed mainly of surface water (lakes, rivers, wetlands) and soil moisture. Until recently, focus on groundwater mainly concerned its use as drinking water (*e.g.* about 75% of European Union (EU) inhabitants depend on groundwater for their water supply). Groundwater is also an important resource for industry (*e.g.* cooling waters) and agriculture (irrigation). It has, however, become increasingly obvious that groundwater should not only be viewed as a drinking water reservoir, but also as a critical aquatic ecosystem.<sup>1</sup> In this respect, groundwater represents an important link of the hydrological cycle for the maintenance of wetlands and river flows, acting as a buffer through dry periods. In other words, it provides the base flow (*i.e.* the water which feeds rivers all year round) for surface water systems, many of which are used for water supply and recreation. In many rivers, indeed, more than 50% of the annual flow is derived from groundwater. In low-flow periods in summer, more than 90% of the flow in some rivers may come from groundwater. Hence, deterioration of groundwater quality may directly affect other related aquatic and terrestrial ecosystems.

Since groundwater moves slowly through the subsurface, the impact of anthropogenic activities may last for a relatively long time, which means that pollution that occurred some decades ago—whether from agriculture, industry or other human activities—may still be threatening groundwater quality today and, in some cases, will continue to do so for several generations to come. The legacy of the past is clearly visible at large-scale contaminated sites, *e.g.* industrial sites or harbour areas, where it is simply not possible, with

state-of-the-art technology and a proportionate use of public and/or private money, to clean up the regional contamination encountered at these locations.<sup>2</sup> In addition, the experience of remediation of the past 20 years has shown that the measures taken have in most cases not been able to completely remove all contaminants and that pollutant sources, even if partially removed, continue to emit for long periods of time (*i.e.* several generations).<sup>3,4</sup> Therefore, an important focus should be on preventing pollution in the first place.

Secondly, since surface water systems receive a continuous discharge of inflowing groundwater, a deteriorated groundwater quality will ultimately be reflected in the quality of surface waters. In other words, the effect of human activity on groundwater quality will eventually also impact on the quality of associated aquatic ecosystems and directly dependent terrestrial ecosystems if so-called natural attenuation reactions such as biodegradation in the subsurface are not sufficient to contain the contaminants.

Finally, groundwater is a “hidden resource” which is quantitatively much more significant than surface water and for which pollution prevention and quality monitoring and restoration are even more difficult than for surface waters, which is mostly due to its inaccessibility. This “hidden” character makes it difficult adequately to locate and quantitatively appreciate pollution impacts, resulting in a lack of awareness and/or evidence regarding the extent of risks and pressures. Recent reports, however, show that pollution from domestic, agricultural and industrial sources is, despite the progress in some fields, still a major concern, either directly through discharges (effluents) or indirectly from the spreading of nitrogen fertilisers and pesticides or through leaching from old landfills or industrial sites (*e.g.* chlorinated hydrocarbons, heavy metals). For example, around one-third of groundwater bodies in Europe currently exceed the nitrate guideline values.<sup>5</sup> While point sources have caused most of the pollution identified to date, there is evidence that diffuse sources are having an increasing impact on groundwater.

This chapter develops the elements discussed above as a general introduction to this book, which further elaborates issues related to groundwater policy, protection and remediation throughout the different chapters.

## 1.2 The Scientific Background

### 1.2.1 The Hydrogeological Cycle

It is estimated that roughly 22% of freshwater is stored underground, representing some 8 million km<sup>3</sup> of 37 million km<sup>3</sup> of freshwater found on the planet. Excluding water from polar ice, groundwater constitutes some 97% of all the freshwater that is potentially available for human use on or beneath the earth's surface. The remainder is stored in lakes, rivers and swamps.<sup>6</sup> Groundwater recharge is essentially ensured by rain that infiltrates through the soil into underlying layers; this recharge is occasionally augmented by streams and rivers that lose water to underground strata. Once underground,

groundwater flows at rates which range from more than 10 metres per day to as little as 1 metre per year until it reaches an outlet, *e.g.* a spring or seepages at the ground surface (which actually keep rivers flowing during dry periods).

The time scales at which groundwater flows hence considerably vary, depending on hydrogeological conditions. It may take years to decades for water to move through the soil to reach the water table, the level at which the ground is fully saturated, where it may remain underground for tens or even thousands of years before reappearing at the surface.<sup>6</sup> Geological settings may also trap groundwater from both its source and its outlets. Finally, climate change may also lead to groundwater losses by depriving aquifers from recharge as it appears in a number of regions which turned into deserts.

The level of available geological and hydrogeological information varies from area to area, and this has an effect on the protection schemes to be developed.<sup>7</sup> Where the information is adequate, a comprehensive scheme, based on hydrogeological concepts, is achievable. However, as mentioned below, aquifers are rarely homogeneous and their geological variability conditions the nature of groundwater flowing through their respective lithologies and structures, which makes it difficult to establish large-scale conceptual hydrogeological models.

## 1.2.2 Waters in Aquifers

The nature of aquifers, consisting either of unconsolidated materials such as sand or gravel or consolidated rock such as sandstone, has a considerable influence on groundwater flows and hence on pollution pathways (see Section 1.4.3). On the one hand, unconsolidated materials, such as sands, can store up to 30% of their volume as water. On the other hand, consolidated materials may also store large volumes of water, depending upon their porosity, but groundwater flow is usually very slow owing to the small size of the pores. In some types of rocks, the capillary attraction between the groundwater and the pore surface does not allow water to be released and hence to flow. However, consolidated materials may also store water in fractures in the rock, which although they usually represent less than 1% of the total volume can be enlarged by dissolution in rocks such as limestones. Enlarged fractures enable the aquifer both to store large volumes of water and permit high groundwater flows,<sup>7</sup> which has an impact on pollution spreading (see Chapter 5.5).

Aquifers are usually bounded above by an unsaturated zone, which contains both air and water, and below by an impermeable bed constituted, for example, of clay or rock. The boundary between the unsaturated and saturated zones (water table) is found at different depths depending on the hydrogeological and climatic settings, *e.g.* as much as 100 m below the surface in arid areas and close to the surface in humid areas. Some aquifers are, however, bounded entirely by impermeable layers and contain groundwater under pressure (which enables water abstraction by artesian wells).

### 1.2.3 Groundwater Flows

With aquifer characteristics in mind (in particular the type of materials containing the water), it is possible to better approximate groundwater flows. Groundwater moves through aquifers as a result of differences in pressure or elevation of the water table within the aquifer. The groundwater flow may be slowed down by various obstructions while moving from the point of recharge to its exit from the aquifer. In some cases, impermeable rock formations (known as aquicludes) such as shale stop completely the water flow, while other geological strata (known as aquitards), such as clay lenses embedded with sand, may slow down the groundwater flow.

The groundwater flow rate depends on the permeability and porosity of the aquifer, and on the pressure gradient. As an example, highly permeable aquifers such as limestones respond rapidly to changes in recharge and abstraction rates, and groundwater levels in such areas may fluctuate by as much as 10 m a year and may change by up to 50 m a year.<sup>7</sup>

The greatest variations in groundwater flow patterns occur where changes in rock types, *e.g.* limestone overlying sediments and a hard crystalline rock, induce discontinuities in flow and may bring groundwater flow to the surface on the junction between the two rock types. Variations in groundwater flow may also occur within an unconsolidated alluvial aquifer, *e.g.* great lateral variations occur in the mix of gravel, sand and clay making up the aquifer matrix. In larger-scale alluvial aquifers, layers of sand or gravel-rich sediment interbedded with clay-rich layers induce lateral flow following the more permeable sand- and gravel-rich zones.

Needless to say that groundwater flow rates are very small in comparison to those of surface water. In this respect, some groundwater from deep alluvial basins is likely to be thousands or even hundreds of thousands of years old. The slow movement of groundwater largely contributes to its purity since contaminants become highly attenuated during the usually long groundwater flowing pathway to the surface. Groundwater may also become enriched with elements that are naturally present in rocks. Furthermore, saltwater intrusion may occur near coastlines, in particular where the water table is lowered due to abstraction, and this is likely to be accentuated by rising sea levels due to climate change.

### 1.2.4 Groundwater Quality

Most groundwater originates from water that has permeated first the soil and then the rock below it. The soil removes many impurities and the rock through which the water then flows, perhaps for thousand of years, filters and purifies the water even further.<sup>7</sup> It therefore usually reappears at the earth surface free of pathogenic micro-organisms. This is the reason for an increasing exploitation of groundwater resources (see Section 3.1).

While groundwater is generally less easily/rapidly polluted than streams and rivers, it often contains high concentrations of dissolved elements from the rock

through which it has passed. Another feature is that when groundwater is polluted, many processes occur during its pathway to the surface; in particular, pollutant loads may be attenuated by adsorption by the rock itself or biochemical transformation into substances that are less harmful than the original compounds. However, severe pollutions may affect groundwater quality over long periods, *i.e.* once pollutants reach the water table, it may take a very long time before they are flushed out from the aquifer. Furthermore, groundwater quality affected by pollution may take a long time to recover since the water within the aquifer moves so slowly. Once polluted, aquifers are difficult—and sometimes even impossible—to clean up. The process can be likened to trying to squeeze out the last traces of soap from a sponge.<sup>7</sup>

As stressed above, the complex nature of groundwater is compounded in the context of pollution and quality problems. Let us repeat that the chemical characteristics of aquifer materials and the way pollutants react with them vary greatly. In some cases, pollutants are “filtered” out mechanically or through adsorption onto particles within the soil or aquifer matrix. In other cases, however, pollutants remain mobile and can rapidly spread throughout an aquifer. The aquifer matrix itself can become contaminated and pockets of pollutants can serve as continuous sources of contamination. For example, small pockets of organic solvents can remain as pollution sources virtually indefinitely because of their low solubility in water. Furthermore, changes in pH or other groundwater characteristics can cause the release of toxic materials, such as fluoride, from natural sources within aquifers. Given the hundreds of thousands of naturally occurring compounds in groundwater and aquifer materials, and the similarly large number of compounds present in waste water released to aquifers, understanding and managing pollution problems is a highly complex task. This illustrates the importance of preventing pollution of groundwater from the start rather than dealing with the consequences (Chapter 5.5).

All the above considerations have an impact on the way groundwater background levels are evaluated and also on the assessment of groundwater quality either related to its use or to its environmental value. These aspects are discussed in various chapters of this book (Chapters 5.1–5.3 and 9.1).

## **1.3 Groundwater Deterioration Risks**

### **1.3.1 Quantitative Aspects**

#### *1.3.1.1 Over-exploitation*

Groundwater is extensively used by humans throughout the world as a drinking water resource, with some countries depending almost entirely on it while others only partly using the groundwater resource for drinking water abstraction. Groundwater supplies are of obvious importance in arid areas but they are also extensively used in humid areas, largely because they provide water that requires little or no treatment and which can be cheaply produced.

In addition, its supplies are not subject to abrupt change as a result of abnormal weather, *i.e.* a dry summer while affecting reservoirs will have little effect on groundwater levels. Finally, groundwater can often be tapped near to where it is needed while surface water must be either developed at the sites of natural dams or reservoirs, or piped at considerable distances to where it will eventually be used.<sup>7</sup> However, groundwater should not be seen as a simple alternative to the use of surface water.

The inadequate control of groundwater abstraction in many parts of the world usually results in some form of over-exploitation, which can lead to either reversible or irreversible damages (this consideration also applies to damages due to pollution, see Section 1.3.3). In the first case, matters can be corrected and only the question of costs is involved. In the second case, costs are also involved but, in addition, sustainability issues arise since future generations are deprived of an important resource.<sup>7</sup>

Many aquifers are being over-exploited in the sense that water is abstracted faster than the average recharge rate. This is particularly problematic in the case of fossil groundwater. The control of the balance of groundwater levels (equilibrium between abstraction and recharge) is, however, difficult to apprehend in that the recharge rate of groundwater resources is not constant and can vary considerably with the rainfall pattern. This means that what may be considered as over-exploitation in one year may be a perfectly acceptable rate of exploitation in another. To complicate matters, in some arid areas major recharge only occurs once a decade or even less frequently.<sup>7</sup> In this circumstance, defining a sustainable abstraction rate is difficult. Adding to this, climate changes impact on the dynamic balances of groundwater resources, and these are not easily predictable.

### 1.3.1.2 *Falling and Rising Water Tables*

Over-abstraction and subsequent fall of the water table may lead to severe damage linked to ground subsidence, which is caused by water draining from the pores in underground strata, causing the rock to compact. Unconsolidated strata, especially clays which have high water content, are particularly susceptible to this phenomenon.

Conversely, circumstances such as over-irrigation of land may lead to rising of the water table, leading to waterlogging of agricultural land which is often associated with salinisation. This is due to two causes: a rising water table that brings saline water into contact with plant roots; and the evaporation of irrigation water by sun, leaving the salt behind. Another occurrence of rising water table is observed in urban areas where urban recharge rates may be higher than natural (pre-natural) ones. This is not so problematic when cities consume large quantities of water (thus balancing the high recharge rates) but it may be so when groundwater is not abstracted any more, which increasingly happens owing to contaminated groundwater beneath the cities. Rising water tables under cities may lead to urban flooding, with associated costs (need to pump water out, *etc.*).

### 1.3.1.3 Saltwater Intrusion

Under natural conditions, coastal aquifers discharge freshwater into the sea. However, in case of (over)abstraction of groundwater in areas that are close to the coastline, this process may be reversed, leading to salt water moving inland and polluting the aquifer<sup>†</sup>. Examples of such occurrences can be found in many places of the world.<sup>7</sup> The problem may be severe on islands where the freshwater aquifer is only a few metres thick (*e.g.* composed of highly permeable sediments) and surrounded by salt water; in this specific case, aquifer abstraction has to be particularly well managed.

## 1.3.2 Links to Associated Ecosystems

### 1.3.2.1 Links to Associated Aquatic Ecosystems

In many areas, it is groundwater that makes the use of surface water sources possible during dry seasons. Groundwater provides the base flow to many of the world's rivers, and this flow continues throughout the year, regardless of weather conditions. Many rivers would dry up in hot and dry summers if they would not be fed by groundwater. This is particularly important in both humid and arid regions where precipitation is highly variable. Between precipitation events, groundwater and return flows from agricultural, domestic and other users are the primary source of flows in rivers. Since return flows generally have higher pollution loads than groundwater flow, the groundwater contribution is important to both the quantity and quality of dry-season flow in surface watercourses. An evaluation of quantitative aspects of groundwater–surface interactions is described in Chapter 9.3 of this book.

Productivity in coastal ecosystems is also highly dependent on the balance between freshwater inflows from surface water, groundwater discharge and saline ocean water. Disruption of this balance through diminution of groundwater contributions to base flow could have major effects on the coastal environment.

### 1.3.2.2 Links to Dependent Terrestrial Ecosystems

Wetlands are some of the most productive and biologically diverse inland ecosystems. In many if not most cases, water availability in wetlands depends on high groundwater levels. Consequently, the fall of the water table may have a direct impact on wetlands as the land is drying out. In this respect, a number of the world's major wetland areas, which are sensitive ecosystems supporting a large number of plant and animal species, are now under threat due to over-abstraction. In addition, groundwater pollution also represents a major threat not only to the habitat of many rare species but also in affecting the purifying role of the wetlands with respect to inland lakes.

---

<sup>†</sup>Note that the term “pollution” is appropriate when saltwater intrusion is indeed due to over-abstraction, *i.e.* due to human activity.

Besides wetlands, groundwater levels and quality directly influence surface vegetation communities. Phreatophytes, plants that derive a major portion of their water needs from saturated soils, can be the dominant vegetative species in ecosystems where groundwater levels are shallow. They often form critical wildlife habitat and may serve as important sources of food and timber. This vegetation also uses substantial amounts of water. Removing these species can reduce evapotranspiration and hence the demand on groundwater resources, which may cause levels to rise and thereby lead to waterlogging and other environmental problems.

### 1.3.3 Groundwater Pollution

#### 1.3.3.1 Introduction

Once polluted, groundwater is extremely difficult to clean up owing to its inaccessibility, its huge volume and its slow flow rates. The three major pollution threats, namely urbanisation, industrial activities and agriculture, are discussed in the following paragraphs. Let us distinguish here pollution impacts related to either human uses or the environment. In the first instance, pollutants found in groundwater are listed according to their toxic impacts on drinking water quality according to, for example, WHO drinking water quality guidelines or EU legislation (Drinking Water Directive). Pollutants may also be distinguished according to their ecotoxicological impacts, *i.e.* substances which are detrimental to the environment such as those pollutants listed in the EU Water Framework Directive (see Chapter 3.1). This distinction is important in that the “pollution impact” should be assessed differently whether it is related to a particular use of the water resource or to an impact on the aquatic or terrestrial environment. As noted in Section 2.4, groundwater may contain high concentrations of chemical substances that are present naturally (due to interactions of the groundwater with the soil or surrounding rocks) and which as such does not correspond to a pollution (*i.e.* due to human activities) but which may hamper the use of the groundwater for drinking water abstraction; this does not mean, however, that the groundwater is of “bad environmental quality”. These two aspects of groundwater quality and related needs for protection against pollution are further discussed in the policy context in Chapters 3.1 and 3.2. Furthermore, issues of natural attenuation, risk assessment at contaminated sites (including megasites), remediation and prevention are extensively described in Chapters 5.4, 5.6, 5.7, 7.1–7.3).

#### 1.3.3.2 Urbanisation and Related Discharges

Urbanisation introduces many changes to the aquifers that lie under cities. Natural recharge mechanisms are modified or replaced and new ones are introduced. Leakages and seepages from mains water and sanitation systems become an important part of the hydrological cycle in the urban environment. In this respect, many sub-city aquifers are polluted with human wastes,

particularly where there is insufficient connection to mains sewerage. In Europe, the situation has improved with the implementation of the Urban Wastewater Treatment Directive, but in many developing countries, septic tanks, cesspits and latrines are still common in major cities. Septic tanks, when properly operated, produce an effluent of acceptable quality in areas of low population density. In practice, they are, however, often overloaded and operate inefficiently. Effluent is often discharged directly into inland waterways, whence pollutants find their way into the underlying aquifer.<sup>7</sup> This pollution leads to increasing occurrence of pathogens in groundwater (in particular helminths, protozoa, bacteria and viruses), which may have a direct impact on the bacteriological quality of water abstracted for human consumption (in particular when drinking water is provided by shallow private boreholes with insufficient sanitary controls). Domestic effluents are also responsible for increasing nitrate concentrations in groundwater.

It should be noted, however, that while sewage and urban wastewater is generally regarded as a major source of pollution, it is also considered as a large and important resource, *i.e.* in many arid areas, it is used with minimal, if any, treatment to irrigate crops, including some intended for direct human consumption.<sup>7</sup> The water used also supplies crops with essential elements such as nitrogen and phosphate which would otherwise have to be added as artificial fertiliser. This re-use is often debated as regard to its safety, and many experts consider that a better use for urban wastewater is probably to recharge the aquifer from which it came. During the recharge process, the water is considerably purified. If it is required for irrigation, it can then be abstracted either from irrigation wells or from streams whose flows has been increased by the recharge. Letting sewage water stand in shallow surface ponds and filter down through the soil and the aquifer below can be an effective means of treatment. The more slowly this is done, and the more that the surface ponds are rested between treatments, the more complete will be the treatment. Allowing ponds to dry out regularly leads to a breakdown of nitrates in the sewage, with the release of harmless nitrogen gas. With careful control, nitrogen concentration in the recharge water can be reduced to below  $5 \text{ mg L}^{-1}$ . At the same time, most bacteria and protozoa are eliminated, and levels of organic compounds and phosphates are greatly reduced. This infiltration treatment, although it uses land areas, presents the advantage of providing a cheap underground storage system from which water can be pumped for non-potable uses.<sup>7</sup>

Solid waste disposals represent another source of major urban groundwater pollution. The worst risks occur where uncontrolled tipping, as opposed to controlled sanitary landfill, is practised, and where hazardous industrial wastes, including drums of liquid effluents, are disposed of at inappropriate sites which are selected on the basis of their proximity to where the waste is generated rather than their suitability as landfill sites. Often no record is kept of the nature and quantity of wastes disposed of at a given site and abandoned sites represent a potential hazard to groundwater for decades. To make matters worse, disposal is often on low ground where the water table is high and direct contamination of shallow groundwater likely.<sup>7</sup>

### 1.3.3.3 Industry

Nearly all industries produce liquid effluents, which according to legislation have to be properly treated before they are allowed to be discharged to a water course. There are, however, still many illegal discharges (in particular from small industries producing paper and textiles, processing leather, metals and other materials and repairing vehicles, as well as small service industries such as metal workshops, dry cleaners, photo processors, *etc.*), *e.g.* of acids, oils, fuels and solvents which have a direct impact on water courses, particularly canals, or disposed into the ground and finding their ways to groundwater.

Chlorinated solvents are particularly insidious pollutants because of their persistency, toxicity and the way they travel in aquifers. In this respect, many groundwater supplies are contaminated by such substances, a common cause of which is leaking storage tanks. Unfortunately, cleaning up a polluted aquifer—usually by removing contaminated soil and continuous pumping of the aquifer—is extremely difficult, very costly and takes a great deal of time.<sup>7</sup> Industrial effluents also often contain high levels of metals such as iron, zinc, chromium and cadmium, many of which are highly toxic, even carcinogenic.

A specific industrial pollution is related to mining and petroleum extraction. Quarrying and open-case mining, for example, remove the protective layer above an aquifer, leaving it more vulnerable to pollution. Deep mines or oil fields may produce fluids that are disposed of at the surface and may therefore pollute shallow aquifers, and pollutants from spoil heaps may leach into groundwater. Finally, rising water levels in abandoned mines produce acid mine drainage with subsequent mobilisation of oxidised metal ores, leading to increasing concentrations of sulfate, iron, manganese and other metals, which can cause serious groundwater pollution.

Details on risk assessment of industrial pollution can be found in Chapters 5.6 and 7.1.

### 1.3.3.4 Agriculture

Agriculture is responsible for one of the main pollution groundwater threats. The main source arises from the intensive use of nitrogen-rich fertilisers and of pesticides, a problem that has spread from the industrialised countries to developing ones. The high levels of nitrate and, in some areas, pesticides in groundwater are clearly linked to agricultural activities. This pollution is generally worse where the soil is very permeable, allowing agricultural chemicals to be quickly washed down to underlying aquifers. However, not all nitrates in groundwater are due to agriculture, as we have seen that much of it also originates from untreated sewage. Monitoring techniques can hardly distinguish between the different agricultural and sewage nitrates (besides isotopic measurements). The leaching of nitrate from fields not only leads to pollution but is also a serious source of waste: nitrate that percolates down into aquifers has done nothing to stimulate plant growth. Other components of fertilisers, including potassium and chloride, also find their way from fields to aquifers.

Regarding pesticides and herbicides, substances currently in use are designed to be toxic and, sometimes, persistent. There is no doubt that pesticides are leached through the soil and carried down to underlying aquifers (see Chapter 9.2). In some circumstances, soils can adsorb or immobilise a large fraction of such agricultural chemicals. Many pesticides and herbicides, however, break down slowly under aquifer conditions and, as a result can persist over long time periods. In any case, groundwater pollution data are generally scarce, and the extent of pollution in Europe is hence not accurately known.

Further considerations on diffuse groundwater impacts from agricultural land use are discussed in Chapters 7.3 and 8.2.

## **1.4 Groundwater Risk Assessment: Implications for Policy**

### **1.4.1 Groundwater Protection Needs**

Public and policy-maker perceptions of groundwater represent an important root cause of emerging problems.<sup>8</sup> In many cases, regardless of the degree of formal education individuals have had, perceptions of groundwater resource dynamics are partial at best. Groundwater is often viewed, for example, as an inexhaustible resource, cleaned by the filtering action of aquifers and held, as in a “bowl” or “lake”, or “underground river”. These perceptions do not reflect reality, and often result in use patterns that cause unanticipated problems. Most misunderstandings relate to the scale of aquifer systems, the distribution of groundwater within them and the timescales on which groundwater systems function (see Chapter 5.5).

Groundwater protection relies on two closely interlinked components:<sup>7</sup> (i) land surface protection, based on hydrogeological concepts and information particularly regarding aquifers and vulnerability; and (ii) groundwater protection responses for potentially polluting activities, giving guidelines on the acceptability of the activities, investigation requirements and, where appropriate, the likely planning or licensing controls. Groundwater protection schemes enable authorities to take account of (i) the potential risks to groundwater resources and sources; and (ii) geological and hydrogeological factors, when considering the control and location of potentially polluting activities.<sup>7</sup>

Although groundwater is one of the world’s key natural resources, it is still not sufficiently well protected and poorly controlled. In many instances, the extent of groundwater pollution still remains to be evaluated or even detected, given the slow rates of groundwater movement and the volume of storage involved. In 1996, UNEP indicated that what we know of pollution levels in aquifers may only be the tip of an underground iceberg,<sup>6</sup> which consideration is still valid ten years later. There is, in any case, no doubt that this important resource needs to be better protected from both over-exploitation and pollution. This is the aim of the developing groundwater legislation which is described in Chapter 3.1.

### 1.4.2 Assessment, Prevention and Control

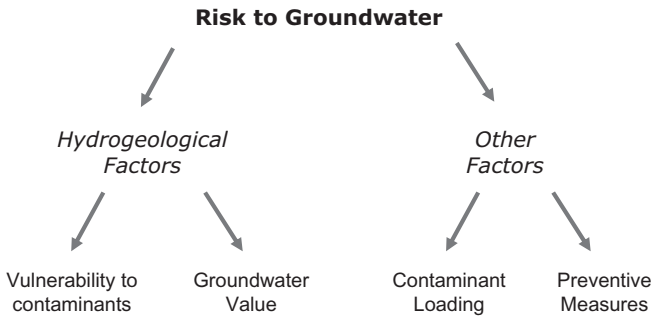
Assessment and appropriate controls of major threats are highly necessary particularly in areas subject to irreversible side effects such as saltwater intrusion and land subsidence (in the case of over-abstraction), but also in the case of high aquifer vulnerability, taking into account pollutant loads (in the case of pollution). Vulnerability assessments and controls require a number of legal and administrative steps, examples of which are described in the light of the EU Water Framework Directive and associated Groundwater Directive (see Chapter 3.1). In the case of pollution, there is a need to distinguish between point sources of pollution, such as landfills and specific industrial discharges, and diffuse sources of pollution linked to agricultural activities and to a lesser extent atmospheric deposition. Efforts should be made to reduce pollution from pollution sources, paying particular attention to practices in areas where aquifers are highly vulnerable. This means that land-use planning regulations have to be enforced in the most sensitive areas. This also concerns of course agricultural practices (see Chapter 8.2).

A key step in assessing pollution risks is based on the analysis of the groundwater vulnerability (ease with which groundwater may be contaminated by human activities). It depends on the time of travel of infiltrating water (and contaminants), the relative amount of contaminants and the contaminant attenuation capacity of the geological materials through which the water and contaminants infiltrate (see further discussion in Chapters 5.4 and 9.2). As all groundwater is hydrologically connected to the land surface, it is the effectiveness of this connection that determines the relative vulnerability to contamination. Groundwater that readily and quickly receives water (and contaminants) from the land surface is considered to be more vulnerable than groundwater that receives water (and contaminants) more slowly and in lesser quantities. The travel time, attenuation capacity and quantity of contaminants are a function of the following natural geological and hydrogeological attributes of any area: (i) the subsoils that overlie the groundwater; (ii) the type of recharge, whether point or diffuse; and (iii) the thickness of the unsaturated zone through which the contaminant moves. In general, little attenuation of contamination occurs in bedrocks via fissures, and high attenuation will be possible in subsoils (sands, gravels, glacial tills (or boulder clays), peat, alluvial silts and clays). Groundwater is most at risk where the subsoils are absent or thin and, in areas of karstic limestone, where surface streams sink underground at swallow holes.

Vulnerability may be mapped according to the elements in Table 1.1. Establishing such maps is an important part for deciding upon a groundwater protection scheme and an essential element in the decision-making on the location of potentially polluting activities.<sup>7</sup> Firstly, the vulnerability rating for an area indicates, and is a measure of, the likelihood of contamination. Secondly, the vulnerability map helps to ensure that a groundwater protection scheme is not unnecessarily restrictive on human economic activity. Thirdly, the vulnerability maps help in the choice of preventive measures and enable developments, which have a significant potential to contaminate, to be located

**Table 1.1** Vulnerability mapping guidelines (adapted from Ref. 7).

Vulnerability rating	Hydrogeological conditions				
	Subsoil permeability (type) and thickness			Unsaturated zone	Kast features
	High permeability (sand/gravel)	Moderate permeability (e.g. sandy subsoil)	Low permeability (e.g. clayey subsoil, clay, peat)		
Extreme	0–3 m	0–3 m	0–3 m	0–3 m	–
High	> 3 m	3–10 m	3–5 m	> 3 m	N/A
Moderate	N/A	> 10 m	5–10 m	N/A	N/A
Low	N/A	N/A	> 10 m	N/A	N/A



**Figure 1.1** Factors under consideration for groundwater risk assessment.

in areas of lower vulnerability. This assessment strongly relies on proper characterisation of groundwater settings and related risks, an issue that is discussed in Chapter 5.1.

In this respect, the risk depends on (i) the hazard afforded by a potentially polluting activity, (ii) the vulnerability of groundwater to contamination, and (iii) the potential consequences of a contamination event. The hazard depends on the potential contaminant loading. The natural vulnerability of the groundwater dictates the likelihood of contamination if a contamination event occurs. The consequences to the target depends on the value of the groundwater, which is normally indicated by the aquifer category (regionally important, locally important or poor) and the proximity to an important groundwater abstraction source (e.g. a public supply well). The risk assessment encompasses geological and hydrogeological factors and factors that relate to the potentially polluting activity. This is illustrated in Figure 1.1.

In the light of the above, prevention of groundwater contamination is of critical importance and must be a key aim for the following reasons:<sup>7</sup>

- Once groundwater contamination occurs, the consequences last far longer than surface water contamination (months, years and sometimes

decades) because groundwater moves slowly through the soil and unsaturated zone of the aquifer. Remediation is frequently not practical or is very expensive. Also, it is both impractical and a poor environmental strategy to provide comprehensive treatment to remove certain pollutants, such as pesticides and other trace organics. It is therefore preferable to prevent or reduce the risk of groundwater contamination than to deal with its consequences.

- Groundwater is an important resource used for drinking water, industry and agriculture, and should be protected for present and future usage.
- Groundwater provides the base flow (*i.e.* the water which feeds rivers year-round, and upon which flood flows are superimposed) to surface water systems, many of which are used for water supply and recreational purposes.

### 1.4.3 Monitoring

The assessment and controls of groundwater quantity and quality have to be supported by representative and reliable monitoring data. Groundwater monitoring is largely a national responsibility but, because groundwater does not respect national boundaries, monitoring has to be conceived at national, regional and international levels. This is exactly the principle of the Water Framework Directive (see Chapter 3.1). Improved monitoring systems are needed to provide information not only on groundwater quantity and quality in the light of its use as drinking water resources, but also for the evaluation of its environmental quality in relation to associated aquatic and directly dependent terrestrial ecosystems. In particular, existing monitoring networks hardly provide early warning of pollution, and networks are needed to include monitoring of pollution loads, particularly in vulnerable recharge areas. Recommendations have been given by UNEP in this respect<sup>6</sup> (see Table 1.2).

Groundwater quality monitoring has at least four objectives that need to be carefully distinguished in the design of monitoring systems:

- definition of the extent of groundwater pollution (analysis of pressures and impacts);
- quality control of groundwater used as drinking water (drinking water supply surveillance);
- early discovery of groundwater pollution from a given activity (offensive detection monitoring); and
- provision of advance warning of the arrival of polluted water at important sources of supply (defensive detection monitoring).

Detailed monitoring guidelines in support of policy implementation, more specifically to the EU Water Framework Directive and new Groundwater Directive (see Chapter 3.1), have been developed and are summarised in Chapter 6.1.

**Table 1.2** Key elements in an early warning monitoring strategy (adapted from Ref. 6).

		<i>Aquifer type</i>			<i>Semi-confined</i>
		<i>Unconfined</i>			
		<i>Granular</i>	<i>Thin unsaturated zone</i>	<i>Deep unsaturated zone</i>	
		<i>Fractured</i>			
Travel time from surface to saturated aquifer zone		Hours to weeks	Days to months	Years to decades	Decades +
Pollution risk	Chemical	High	High for mobile compounds	High for mobile and persistent compounds	Moderate for persistent compounds only Very low
	Bacteriological	High	Moderate	Low	
Early warning monitoring required		Monitor at water table	Monitor at water table	(1) Monitor unsaturated zone and (2) at water table	Monitor semi-confining layer and aquifer
Pollution indicators	Domestic wastewater <sup>a</sup> Industrial effluent	Cl, NO <sub>3</sub> , NH <sub>4</sub> , SO <sub>4</sub> , FC	Cl, NO <sub>3</sub> , NH <sub>4</sub> , SO <sub>4</sub> , FC	Cl, NO <sub>3</sub> , NH <sub>4</sub> , SO <sub>4</sub> , FC	Cl, NO <sub>3</sub> , NH <sub>4</sub> , SO <sub>4</sub>
		Chlorinated hydrocarbons, other organic compounds, metals	Metals, range of organic compounds	Persistent organics (metals)	Persistent organics (metals)

<sup>a</sup> FC: faecal coliforms.

## 1.5 Conclusions

Groundwater protection is essential in relation to the intrinsic water resource quality for various uses, and its environmental value. Basic environmental principles include the following:

- *Sustainable development* principles, seeking to ensure that economy and society can develop to their full potential within a well-protected environment, and with responsibility towards present and future generations and the wider international community.
- *Precautionary principle*, requiring that emphasis should be placed on dealing with the causes, rather than the results, of environmental damage and that, where significant evidence of environmental risk exists, appropriate action should be taken even in the absence of conclusive scientific proof of cause.
- *Polluter pays principle*, of which the objective is to allocate correctly the costs of pollution, consumption of energy and environmental resources, and production and disposal of waste to the responsible polluters and consumer, rather than to society at large or future generations, which in turn provides an incentive to reduce pollution and consumption.

## References

1. J. Gibert, in *Groundwater Ecology: A Tool for Management of Water Resources*, ed. C. Griebler, D. L. Danielopol, J. Gibert, H. P. Nachtnebel and J. Notenboom, European Commission, EUR 1987, 2001, p. 413.
2. S. Heidrich, M. Schirmer, H. Weiss, P. Wycisk, J. Grossmann and A. Kaschl, *Toxicology*, in press.
3. P. Grathwohl, *Diffusion in Natural Porous Media, Contaminant Transport, Sorption/Desorption and Dissolution Kinetics*, Kluwer Academic, 1998.
4. G. Teusch, H. Ruegner, D. Zamfirescu, M. Finkel and M. Bittens, *Land Contamin. Reclam.*, 2001, **9**, 1.
5. EEA, *Groundwater Quality and Quantity in Europe*, Environmental Assessment Report 3, Copenhagen, 2000.
6. UNEP, *Groundwater: a threatened resource*, UNEP Environment Library 15, Nairobi, Kenya, 1996.
7. Irish EPA, *Groundwater Protection Schemes*, 1999 (ISBN 1-899702-22-9).
8. J. J. Burke and M. H. Moench, *Groundwater and Society: Resources, Tensions and Opportunities*, United Nations, 2000 (ISBN 92-1-104485-5).