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Present state and future prospects for groundwater ecosystems

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SUMMARY

Ecological and socioeconomic aspects of subterranean hydrosystems have changed during the past 40–50 years. The major environmental pressures (mainly anthropogenic ones) impact the quantity and quality of groundwater resources and the state of subsurface ecosystems, and it is expected that the environmental pressures on groundwater will continue, at least until 2025, unless new environmental policies change this state of affairs. The world demographic increase and the general rise of water demand constitute one of the major environmental pressures on groundwater ecosystems especially in less developed countries in Africa, Asia and South America. Specific human activities leading to the depletion of groundwater reserves include agricultural practices, landscape alteration, urbanization demand for domestic and public drinking water, various industrial activities such as thermoelectric production and mining, and the rise of tourism in coastal areas. Climate change is contributing to the water crisis too, especially in areas with arid climate and/or in some humid monsoonal countries. The overload of aquifers with pollutants derived from agriculture (fertilizers and pesticides), from industry (release of hydrocarbon chemicals, especially spills), from waste and industrial waters, from domestic and industrial landfills, from the infiltration of pollutants from surface and from the intrusion of saline water affect groundwater quality. The dangerous increase in contaminated subsurface sites with chemicals and microbial pathogens brings with it health risks to humans. Changes of redox condition in groundwater zones, changes of biological diversity, vegetation changes with modification of agriculture practices and impacts at the biosphere scale, such as the increase in the concentration of nitrous oxides in the atmosphere, all impact groundwater ecosystems. Groundwater ecosystems must be better investigated and understood. Economic, social and ecological lines of thinking have to be combined in order to achieve meaningful policies for the sustainable development of groundwater reserves and for the protection of subsurface ecosystems. Practical measures and ideas for the development of policies up to the 2025 time-horizon should improve the sustainable usage of the world's groundwater resources.

Keywords: groundwater ecosystems, environmental management, ecological sustainability, groundwater depletion, groundwater pollution, groundwater protection, biological diversity

INTRODUCTION

> 'If nature in the twenty-first century will be a nature that we make, then the guide to action is our knowledge of living systems and our willingness to observe them for what they are, our commitment to conserve natural areas, to recognize the limits of our actions, and to understand the roles of metaphor and myths in our perceptions of our surroundings' (Daniel Botkin 1990).

Groundwater (GW) plays a pivotal role in human life and development. In the past it has offered insurance against drought, a vital factor for human survival. Thought once to be an inexhaustible resource for human needs, a belief reflected in many myths, the availability of GW is now critical in many parts of the world. It has become more and more difficult to supply human needs with sufficient quantities of safe and clean water of acceptable quality (see Gleick 1993*a*, 1996; Postel 1998, 2000; World Water Council 2000).

GW is not only important in supporting human welfare, it is also the basis of life for diverse organisms existing below the earth's surface. The complex relationships between the water and the subsurface organisms generate dynamic ecological systems, which are the topic of the rather young field of GW ecology (Gibert 1992).

Quantitative and qualitative aspects of GW were, until recently, mainly studied by hydrologists and hydrochemists, ecologists being less involved in understanding the present or indicating the future status of GW resources. However, during the last 10–15 years, GW problems were analysed increasingly within an integrated hydrological and ecological framework (Nachtnebel & Kovar 1991; Gibert *et al.* 1994*a*,

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1997; Stanford & Gonser 1998; Griebler *et al.* 2001). In the 21st century, a solution for the water crisis we face in many parts of the world today is to incorporate healthy ecological alternatives in the strategic plans dealing with GW policies.

This review addresses the ecological and socioeconomic aspects of GW systems in four modules:

(1) A general presentation of the structure and function of GW systems and their status under non-impacted environmental conditions.

(2) An overview of important driving forces, resulting from the direct or indirect impacts of human activities, which now determine major environmental changes in the GW supply to meet human needs. The approach we use considers actual trends and well-documented case studies that are likely to be relevant to the time-horizon of 2025, despite the fact that the magnitude of their impacts may change.

(3) Several cases of ecological impacts determined by environmental pressures are discussed, which changed structural and/or functional components of ecosystems.

(4) We present possible responses to the water crisis with which the expanding world population is confronted. We discuss ecological and socioeconomical options proposed as efficient tools for development and/or maintenance of sustainable GW systems. To achieve this latter goal, we emphasize the necessity of combining socioeconomic arguments with ecological strategies based on a solid scientific basis. Our paper follows the DPSIR framework (Driving forces, Pressures, State of Impact and Response), developed for environmental problems in the European Community (EEA [European Environment Agency] 1999; Notenboom 2001). This conceptual model encapsulates the idea that ecosystems, especially those impacted by human activities, change their structure and functions, leading to a diminution of ecosystem goods and services that they can offer to the biosphere.

The present contribution is the result of cooperation between a GW ecologist (DLD), a GW microbiologist (CG), a geochemist with expertise in water management and environmental protection (AG) and an ecologist with expertise in ecotoxicology and environmental protection (JN). We hope to show the positive contribution that ecologists are able to offer within a domain that for a long period of time remained the speciality of hydrologists and water managers.

GROUNDWATER ECOSYSTEMS: STRUCTURE AND FUNCTION

What is groundwater?

GW is an important component of the global hydrological cycle. Atmospheric water reaching the Earth surface infiltrates below the ground, crosses the soil layer, in some cases only partly filling the inner voids (it builds an unsaturated layer), continues to flow underground through fissured or large voids of consolidated rocks or through porous clastic (unconsolidated) sediments forming an underground water-saturated layer, and finally exfiltrates either at the surface of the Earth or into the marine domain (Fig. 1).

Hydrologists and/or hydrogeologists traditionally define GW as the subsurface water contained in the zone of saturation that can move freely (Pfannkuch 1969). However, more recently, microbiologists (Madsen & Ghiorse 1993) have defined GW as all the subsurface water existing below the upper A and B pedological layers, that is the water in the deeper parts of the unsaturated layer of sediments and in the zone of saturation. GW ecologists consider the water existing within the superficial riverbed sediments, in other words the

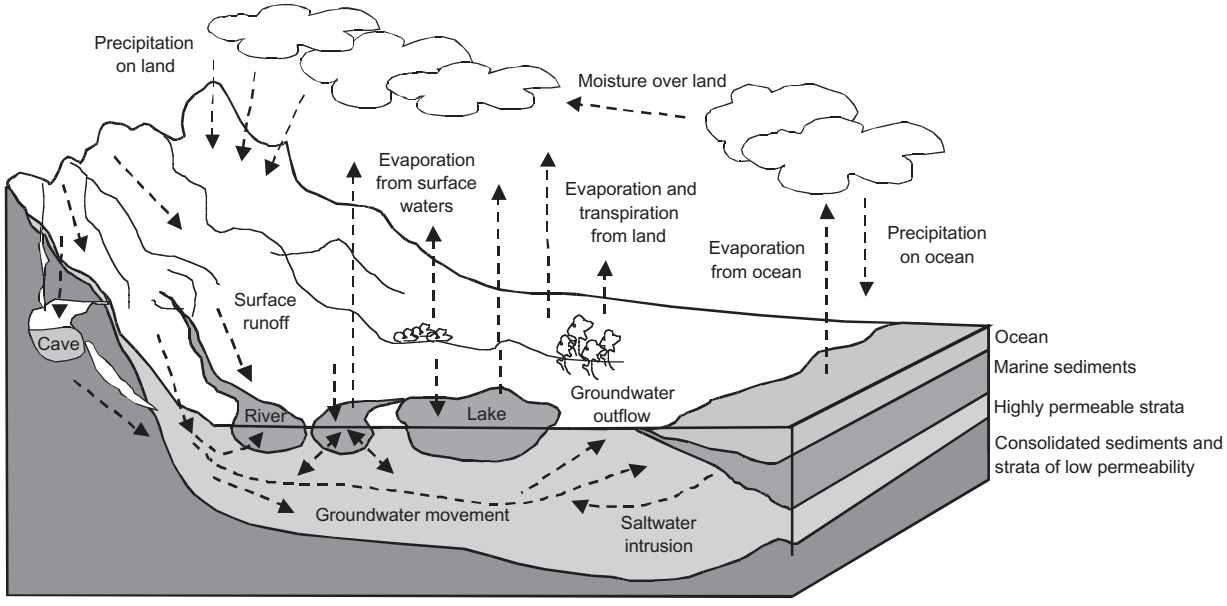


Figure 1 The hydrological cycle.

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Table 1 Distribution of water on the Earth's surface (from Shiklomanov 1993; UNEP 2002).

Major stocks of water	*Volume (10^3 km^3)*	*% Total water*	*% Fresh water*
Salt water			
Oceans	1 338 000	96.54	
Saline/brackish water	12 870	0.93	
Salt water lakes	85	0.006	
Inland waters			
Glaciers	24 064	1.74	68.5
Permafrost ice	300	0.022	0.86
Fresh groundwater	10 530	0.76	30.06
Freshwater lakes	91	0.007	0.26
Marshes, wetlands	11.5	0.001	0.03
Rivers	2.12	0.002	0.006
Soil moisture	16.5	0.001	0.05
Atmospheric water	12.9	0.001	0.04
Living organisms	1.12	0.0010	0.003
Total water	1 386 000	100	
Total fresh water	35 029		100

hyporheic habitat (Orghidan 1959), as also belonging to the GW domain (Rouch & Danielopol 1997). Note that when geochemists discuss aspects of GW pollution they also integrate the unsaturated zone of aquifers (Barcelona *et al*. 1988).

Even if it represents a minor fraction of the total hydrosphere, the volume of fresh GW builds an extensive subsurface aquatic domain forming 30% of the world's total freshwater reserves (Table 1); surface waters, such as lakes, marshes, wetlands and rivers, comprise less than 1% (Shiklomanov 1993; UNEP [United Nations Environment Programme] 2002).

Groundwater ecosystems

Subterranean aquatic ecosystems are open systems through which energy flows and matter is processed in various ways. Such systems are built from three major blocks, namely (1) the geologic substratum, (2) GW itself, and (3) living organisms, each playing a distinct role (Figs. 2 and 3).

The subsurface substratum (groundwater habitats)

The geologic substratum can be either consolidated rocks through which water sometimes carves large solution channels and flows very rapidly (for example, geological karstified formations), or clastic loosely packed sediments (like sand, gravel and pebbles) through which water moves much more slowly (Fig. 2). Permeable sediments play the same role in the subsurface as open reservoirs on the surface. Water can be stored or further transmitted to other sediment layers. Hydrologists are especially interested in the water-storage capacity of permeable geological formations and their

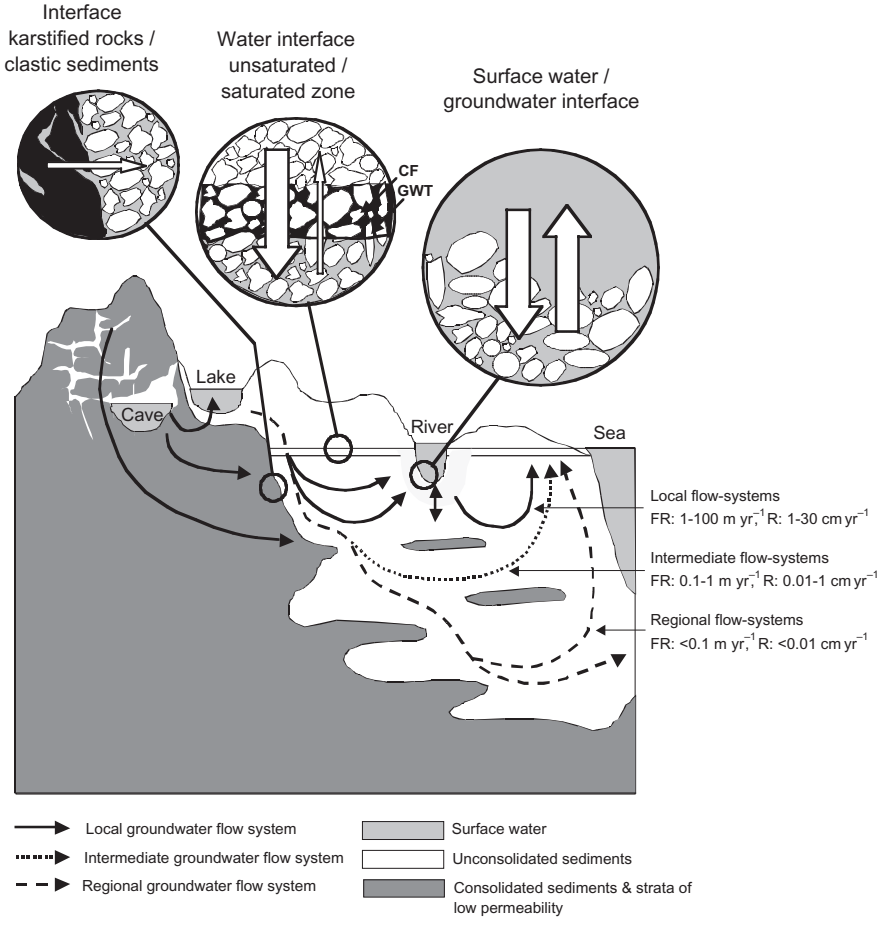


Figure 2 The flow of water carrying energy and matter through the subsurface domain. Circles show various types of interface systems. Arrows indicate the direction and, by their size, the relative importance of the matter and energy flow. GWT = groundwater table, CF = capillary fringe, FR = flow rate, R = recharge (from Lovley & Chapelle 1995).

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potential economic exploitation (Todd 1959). The renewal capacity of the aquifers within a given geological formation or a geographical area is an important criterion for water management decisions.

Groundwater

One of the main functions of the water in the subterranean ecosystem is to transport energy and matter from the surface of the Earth and/or from underground and further distribute them through the subsurface (Fig. 2). During the movement of the water through the subsurface, its chemical properties change due to physical, chemical and biological processes. The transport of water through the subsurface is studied mainly by hydrologists and hydrochemists and is important for the understanding of the ecological dynamics of any GW system.

Groundwater organisms and their diversity

The groundwater domain is inhabited by diverse micro-, meio- and macro-organisms (Fig. 3; Botosaneanu 1986; Wilkens *et al*. 2000; Chapelle 2001). They play an important role in the recycling of organic matter transported by water and in the redistribution of energy and matter, over areas ranging from few millimetres to metres (Ward *et al.* 1998; Simon & Benfield 2001; Boulton *et al*. 2002). Secondary producers dominate GW ecosystems because of lack of light (Gibert *et al*. 1994*b*). Primary producers are represented by chemoauthotrophic micro-organisms, namely Bacteria and Archea (Stevens 1997; Pedersen 2001).

Generally oligotrophy characterizes anthropogenically unaffected GW habitats and plays an important role in shaping the peculiar biotic communities and general function of the GW ecosystems (Gibert *et al*. 1994*b*). In many GW systems, population densities are low, food chains are simple, trophic levels are few and feeding behaviour is unspecialized (Gibert 2001*a*).

Diverse groups of micro-organisms inhabit the subsurface aquatic domain, i.e. Bacteria, Archaea, Protozoa and fungi. The prokaryotic Bacteria and Archaea have been found throughout the subsurface to depths of several thousand metres where the elevated temperature limits life (Ghiorse 1997). While only a few of the micro-organisms (0.01 to 10%) are found suspended in the pore water, most of the living microorganisms are associated with the sediment surfaces, forming microcolonies and biofilms (Griebler *et al.* 2002). The biomass of GW-dwelling prokaryotes in the unconsolidated subsurface domain accounts for about 6–40% of the earth's total microbial biomass; this is a minimum estimate, based on unconsolidated sediments representing only 20% of the terrestrial subsurface, yet these sediments may be much more extensive (Whitman *et al*. 1998). By way of contrast, superficial soil habitats account for less than 10% and open waters for less than 1% of the Earth's total microbial biomass. Eucaryota, namely protozoans (flagellates, amoebae and ciliates) and fungi, seem restricted in their distribution to GW habitats located close to the vadose (unsaturated) zone, to the soil or to the bottom sediments of surface waters

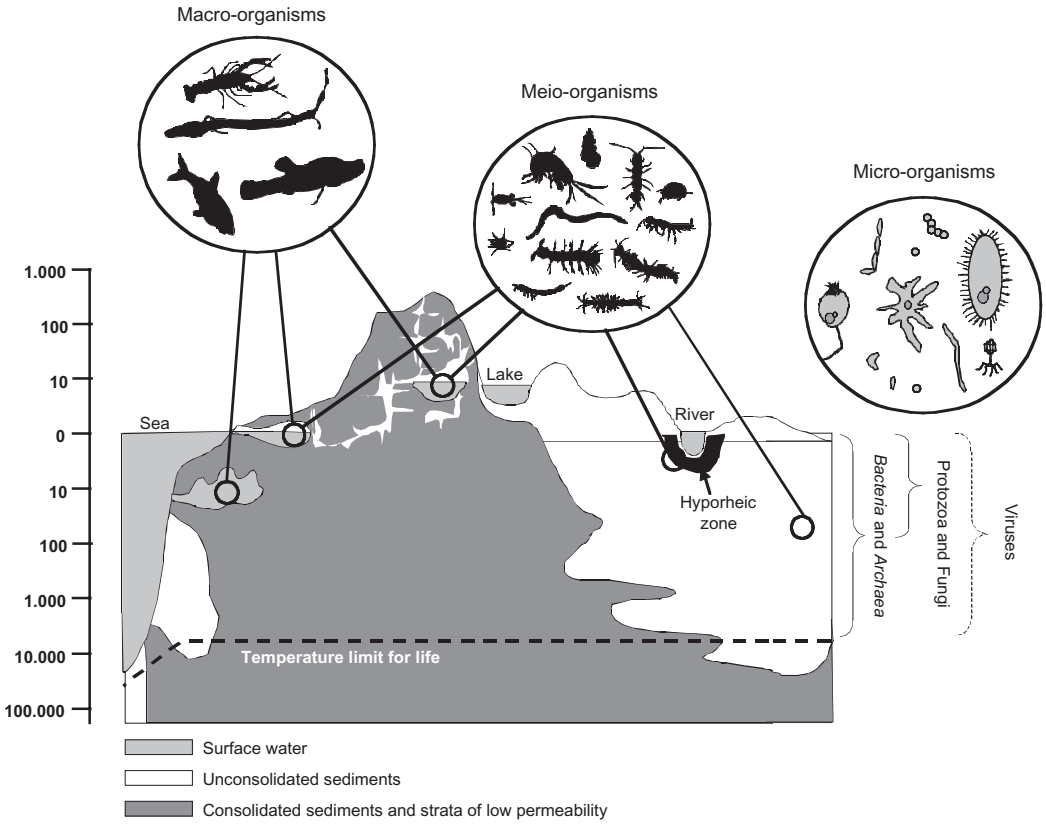


Figure 3 Major types of groundwater organisms within the subsurface environment. Macro-organisms (body size >2–5 mm), like crayfishes, fishes and amphibians, live in cave water; meio-organisms (body size 0.02–2 mm) are mainly small crustaceans and worms; micro-organisms (body size <0.02 mm).

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(Madsen & Ghiorse 1993, Hirsch *et al.* 1992). The subsurface may harbour almost the same biomass or even more than surface ecosystems (Gold 1992).

Additionally, groundwater ecosystems harbour an impressive number of animal species that are known exclusively from subterranean waters (referred to as stygobites), such as the crustacean species belonging to the orders Bathynellacea, Thermosbaenacea, Remipedia, Mictacea, and Spaeleogriphacea (Sket 1999). As an adaptation to energy-poor environments, stygobites typically show life histories involving delayed maturity, greater longevity, smaller clutch size, larger eggs and lower percentages of mature ovigerous females (Gibert *et al.* 1994*b*). The ecological characteristics of subterranean animal assemblages offer in many cases information on the functional state of GW ecosystems and/or on the degree of connectivity, especially between above soil (epigean) and subsoil (hypogean) ecosystems (Malard *et al.* 1997; Boulton 2000).

Many stygobitic species are relicts of animal groups that have disappeared from surface water systems (Humphreys 2000). Such animals deserve protection within well functioning GW systems (Culver & Sket 2000). Shallow GW habitats, especially the hyporheal (the ecotonal zone connecting the surface-running water system to that of the deep subterranean) generally display high species richness, a mixture of surface dwelling and exclusively hypogean (stygobitic) taxa (Rouch & Danielopol 1997).

Groundwater investigations at ecosystem level

GW ecosystems vary in size and structural complexity. Small-scale systems (metres to hundred of metres), like those existing in alluvial sediments along rivers, offer better possibilities to understand their functional properties (Danielopol *et al.* 2000). Karstic systems form large complex ecosystems, sometimes spanning kilometres of galleries and fissures below the Earth (Gibert *et al.* 2000). Large aquifers at the scale of kilometres, encompassing alluvial plains or a whole river sector within a watershed, form regional or basin GW systems, which are particularly important for water management. The aquifer along the Danube River in Lower Austria between Vienna and Hainburg, spanning about 60 km within wetlands of the Danube, is such an example (Danielopol *et al.* 1991). However, the vast transboundary Guarani aquifer in the eastern and south central portions of South America distributed between Argentina, Brazil, Paraguay and Uruguay (an area of *c.* 1.2 million km^2) requires a common institutional and technical framework for integrated basin management (GEF-WB [Global Environmental Facility of the World Bank] 2001).

The subsurface hydrosphere can be characterized globally as a giant groundwater arena where the superficial layers of the Earth are, from an ecosystem point of view, very dynamic, forming a source-sink system where the matter and energy which infiltrate from the surface and accumulate underground will be rapidly processed and further transmitted either to deeper layers or returned to the epigean domain. The water residence time in superficial alluvial aquifers can vary from several days to a few years (Mathess 1982). With the increasing distance from the surface toward the deeper part of the Earth, the ecological dynamics slow gradually, the subterranean domain now behaves like a leaky-sink system where the water moves slowly, the residence time is much increased (Fig. 2), and the matter and energy carried with the water is only partly processed and further redistributed to other segments of the subterranean environment (Lovley & Chapelle 1995). This means that the renewal of the water, carrying with it energy and matter proceeds at low rates and the residence times can reach thousands of years. Finally, within the very deep Earth layers (>2–5 km deep), the ecological dynamics are so slow that we use the term inactive GW (Kotwicki 1991), where energy and matter remain stored for millions of years. The total volume of the deep inactive GW within the Earth's crust is thought to be more than ten times that of the active groundwater layers (Kotwicki 1991).

The key role of microbiota in the functioning of groundwater ecosystems

In pristine aquifers, micro-organisms are responsible for the major turnover of energy and matter. They play a key role in weathering and formation of minerals and they store in their biomass important quantities of carbon, nitrogen and phosphorus. Moreover, they contribute to the development in the subsurface of microhabitats chemically distinguished by their redox reactions. In the context of strong human impacts on the environment, the high purification potential of GW ecosystems is of increasing interest and importance. Micro-organisms provide this purification service generally. Protozoa may also participate in the biodegradation activities of the microbial communities via grazing on bacteria and viruses, resulting in a stimulation (Kinner *et al.* 1998) or a reduction (Kota *et al.* 1999) of actual bacterial degradation rates.

Subsurface microbial communities exhibit an unexpectedly high physiological diversity. In 1934, the Dutch microbiologist L.M.G. Baas-Becking introduced his concept for the cosmopolitan nature of bacteria, 'everything is everywhere, the environment selects', and this still summarizes in brief the recent opinion of many microbiologists that every natural sediment system harbours at least one cell of each physiological type (not necessarily the same species) or that such cells will pass by in a foreseeable time span (Staley 1999). However, we cannot be positive that this holds true for isolated deep subsurface. There is evidence for *in situ* biodegradation by highly active and well-adapted microbial communities present in contaminant plumes (Ludvigsen *et al.* 1999; Haack & Bekins 2000). The potential biological activity of microbial assemblages largely depends on the chemical structure of the various compounds and on actual environmental conditions of GW ecosystems and therefore differs from site to site. Generally, under fully oxic

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conditions the mineralization of most organic compounds proceeds at greater rates than in anoxic environments (Anderson & Lovley 1997). However, there are also known cases where organic degradation is efficiently produced by anaerobic microorganisms (Herman *et al.* 2001).

Relationship between groundwater and surface ecosystems

Hydrology controls the composition and functioning of aquatic and terrestrial subsurface ecosystems. The dynamic exchange processes between surface water and GW contribute much to the structure of subterranean communities.

Shallow subterranean ecosystems are directly connected to surface aquatic and terrestrial systems like rivers, lakes and wetlands (Figs. 1–3). Therefore, for a better understanding of the complexity of the GW domain, ecologists and hydrologists extend their cooperative studies to composite systems, such as river-aquifer systems (Castany 1985; Stanford & Ward 1993) or complex wetland areas along large rivers, which include both terrestrial and aquatic components (Gibert *et al.* 1990; Trémolières 2001). The importance of connectivity between karstic and interstitial habitats for the distribution of the fauna and the maintenance of a high faunistic biodiversity has been repeatedly documented (Malard *et al.* 1997). Also in vegetation science there is a consciousness that hydrology controls the composition of natural vegetation (and associated fauna) of a site through the water and solute budgets and through the conditions imposed upon the local nutrient cycling (Trémolières *et al.* 1997). In the Netherlands, the further integration between geohydrological, soil-chemical and ecological studies has contributed much to the management and protection of both epigean and subterranean ecosystems (Nieuwenhuis *et al.* 1991). Hence the approach that ecologists now favour is to treat GW ecosystems within a holistic framework that integrates the connectivity between the subsurface and the surrounding terrestrial and aquatic systems.

Into the relationships between GW and surface-water ecosystems it is important to integrate the ecological dimension played by human activities (Gibert 1992). In this enlarged ecological perspective we can better evaluate the actual ecological state of various GW systems viewed at different scales of generality from the local to worldwide.

PRESSURES ON GROUNDWATER SYSTEMS AND LONG-TERM ENVIRONMENTAL CONSEQUENCES

Human activities determine various types of pressures on the state of GW ecosystems. Their negative effects are visible on various space and temporal scales and are generally the result of synergistic actions (Rapport *et al.* 1998).

For the present discussion we group the environmental pressures (largely produced by human activities) in two major classes, namely (1) GW quantity problems, which lead to the critical depletion of aquifers in many parts of the world and (2) GW quality problems, where the systems are overloaded with contaminants which in high concentration change the quality of the subterranean water, impairing its function, harming organisms including humans and/or changing the ecosystem state. We will also present examples of the complex links between the quantity and quality problems, pointing out the negative environmental consequences of these.

Groundwater quantity problems (depletion of groundwater reserves)

The critical reduction in volume of available subsurface-water reserves related to a permanent increase in water demand will be one of the major environmental trends of the next 25 years. Postel *et al.* (1996) estimate that the human appropriation of water by 2025 will represent more than 70% of the total accessible run-off. This trend is due to various pressures, the most important being (1) the general world demographic increase with the corollary of a steady increase in water demand, (2) agriculture practices and landscape alteration, (3) increase in urban area and demand for domestic and public drinking water, (4) industrial activities including thermoelectric production and mining, (5) tourism and (6) climate change.

Table 2 The human population (at continental and global scales) and the volume of usable water supply in 1985 and projections for the year 2025 (Vörösmarty *et al.* 2000). The predicted supply/demand of water use for 2025 refers to data for scenario 2, which reflects only the rising demand, and scenario 3, which takes into consideration both climate and development effects (Vörösmarty *et al.* 2000, table 4).

Area	*Population (millions)*		*Usable water supply ($km^3\ yr^{-1}$)*		*Supply/demand in 2025 (%)*	
	1985	*2025*	*1985*	*2025*	*Scenario 2*	*Scenario 3*
World	4830	8010	39 300	37 100	50	61
Africa	543	1440	4520	4100	73	92
Asia	2930	4800	13 700	13 300	60	66
Australia + Oceania	22	33	714	692	30	44
Europe	667	682	2770	2790	30	31
North America	395	601	5890	5870	23	28
South America	267	454	11 700	10 400	93	121

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Table 3 Global annual renewable water supply per person in 1995 and projections for 2025 (from Revenga *et al.* 2000).

Water supply (m^3 caput^{-1} yr^{-1})	*1995 population (millions)*	*1995 (% of total)*	*2025 population (millions)*	*2025 (% of total)*
<500	1077	19.0	1783	24.5
500–1000	587	10.4	624	8.6
1000–1700	669	11.8	1077	14.8
>1700	3091	54.6	3494	48.0
Unallocated	241	4.2	296	4.0
Total	5665	100	7274	100

The world demographic increase and the general rise of water demand

The latest projections for the world's human population indicate it will grow to about 8 billion by 2025 (Vörösmarty *et al.* 2000). This represents an increase of 66% relative to the 1985 baseline (Table 2). The highest rate of population growth at a continental level is expected in Africa (165%) followed by South America (70%) and Asia (60%). For the same period the usable water supply is expected to decrease globally and at the continental scale (Table 2). This is mainly due to the rise in water demand relative to the possible water supply. The water demand at a world scale will increase by at least 50% (Vörösmarty *et al.* 2000) and if the effects of climate changes are added the predicted increase rises to more than 60% (Table 2). The highest rise in water demand by 2025 is predicted for South America, followed by Africa and Asia.

Revenga *et al.* (2000) calculated the percentage of world population living under various levels of water stress during 1995 and used this to project figures for 2025 by calculating annual, global per caput renewable water supply (Table 3). According to these calculations, at present about 41% of the world population lives in areas with chronic water shortages where the water availability is below 1700 m^3 yr^{-1}. An increase in the human population living in water-stressed regions from 2.3 billion in 1995 to about 3.4 billion is expected by 2025, especially in the less-developed countries (LDCs; Revenga *et al.* 2000; Johnson *et al.* 2001) (Table 3). The vulnerability of the global population to water supply deficits under a climate change scenario may be much higher in 2025, with about 4.8 billion people living under stressed and/or scarce water conditions (Somlyódy *et al.* 2001). It is important to stress that more than 50% of the world's human population affected by chronic water shortages is in the LDCs (Johnson *et al.* 2001), and this situation will, on the whole, impose additional stress on water resources as food security for these people has to be guaranteed. Even at present consumption levels, the pressures existing on cropland, water, and forest resources are already excessive in many of these countries (Falkenmark *et al.* 1998).

Using population projections, simple water intensity (for example, water per unit income) assumptions, and some basic estimates of future crop production as a function of irrigated area and crop yield, industrial, commercial and residential water use is expected to increase by 2025 (Table 4). Agriculture is likely to the most demanding of these domains by 2025, even if under high irrigation efficiency the volume of water used were drastically reduced (Seckler *et al.* 1998).

In the international debate, water requirements have been discussed in terms of safe water as a basic human need which is important for both food and environmental security (Gleick 1993*b*; Falkenmark 1998; Falkenmark *et al.* 1998). The world's share of drinking water covered by GW varies greatly among continents (Sampat 2000). About 500–600 million people in Europe and North America use 50%–75% of GW supply as drinking water compared to the 30% used by more than one billion people mainly in Asia and South America (Table 5).

Many countries, such as those in the Middle East and Africa, do not have any more water resources to develop. The only way of satisfying agricultural demand has been the use of fossil water reserves; in such cases GW is a non-renewable resource. During 1980, Libya extracted at least three times

Table 4 The global water use (by sector and total) in 1990 or 1996 and projections for 2025 (HIE = high irrigation efficiency; note that Seckler *et al.* 1998 present the volume of the industrial and domestic water use together).

Estimation	*Water use (km^3 yr^{-1}) in the domain of*			*Total water use (km^3 yr^{-1})*
	Agriculture	*Industry*	*Domestic*	
Gleick (1996)				
1990	2680	973	300	3953
2025	2930	1000	340	4270
Alcamo *et al.* (1997)				
1996	2022	728	296	3046
2025	2022	2235	621	4580
Seckler *et al.* (1998)				
1990	2084	823		2907
2025	3376	1193		4569
2025 HIE	2432	1193		3625

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Table 5 Groundwater as a share of drinking water use by region and population size (modified from Sampat 2000).

Area	*Share of drinking water from groundwater (%)*	*Population (millions)*
Europe	75	200–500
North America (USA)	51	135
Asia-Pacific	32	1000–1200
South America	29	150
Australia	15	3

more water than the annual recharge and in the long term such declines represent a loss of the accessible GW resource. As an example, the water availability in Libya of 160 m^3 $caput^{-1}\,yr^{-1}$ in 1990 is expected to decline in 2025 to 60 m^3 $caput^{-1}\,yr^{-1}$ (Gleick 1993*b*). Water erosion also leads to reduction of surface stream flow, the drying up of lakes (such as the Aral Sea), ponds and bogs, and intrusion of salt water into freshwater aquifers in coastal regions with rapid subsidence of the GW table (Micklin 1988; Shah *et al.* 2000).

However, in North America and Europe, especially in the OECD (Organization for Economic Cooperation and Development) countries, the volume of water use per caput has decreased during the last 10–20 years, suggesting that human consumption of water can be decoupled from demographic growth in these regions (US EPA [United States of America Environmental Protection Agency] 2000; OECD Working Committees 2000).

Agriculture practices and landscape alteration

About 70% of the accessible world run-off is actually used for agriculture, mainly for irrigation of crops (Vitousek *et al.* 1997). The present day efficiency of cropland irrigation is 50–80% of the water used (Postel *et al.* 1996). The highest percentage of irrigated land lies in Asia (67%), followed by North America (12.6%) and Europe (11%) (Vörösmarty *et al.* 2000). The USA uses about 63% of the withdrawal GW for irrigation and about 3% for livestock watering (US EPA 2000). Using the year 2000 as a base line, Tilman *et al.* (2001) predicted a 30% increase in the world's irrigated land by 2020.

Technology transfer from the developed countries and aggressive marketing strategies are attempting to solve water scarcity in the LDCs (Gleick 1993*b*; Shah *et al.* 2000). In these countries more GW will be used for agriculture because more people will be able to afford water pumps. At present, increasing numbers of farmers in south and south-east Asia are harvesting GW from shallow aquifers and deep sources for agricultural purposes. This has led to depletion of GW reserves in many developing countries and today water tables are falling on every continent. Using recent data from India, China, the Middle East, North Africa and the United States, Brown (2001) has estimated that 160 billion m^3 of GW are being overpumped. The ability to drill deep wells and high pumping capacities have led to rapid depletion of GW resources. Such mining has resulted in rapid water table drops of as much as 30 m in some parts of Arizona and Texas (Ehrlich *et al.* 1977), or continuous drops of $>1\,m\,yr^{-1}$ in India, China (Shah *et al.* 2000; Yang & Zehnder 2001) and Indonesia. In the USA, the giant Ogallala aquifer supplies water over an area stretching from South Dakota to Northern Texas. Irrigation in the area quadrupled over the last 30 years and about half of the water resources have been consumed. In many areas (Oklahoma, Texas, Colorado, Kansas and Nebraska) wells have gone out of production due to water scarcity (Pointing 1992). Sophocleous (1981) has proposed strict management of GW resources, to restrict the depletion of aquifers to *c.* 40% of their water storage capacity, combined with programmes of artificial recharge, for some aquifers in Kansas.

Landscape alteration, which can in the long term reduce the GW resources of an area, includes deforestation and reuse of the land for agriculture or urban activities, plantation of vegetation that extracts too much water from aquifers, dehydration of wetlands, and alteration of river courses through regulation of their channels and construction of dams, dykes and levies that contribute to isolation of the aquifer from riverbeds. In all these cases, the volume of recharged GW from surface run-off declines with time. For instance, in the arid mid-west regions of the USA the degradation of vegetation led to a reduction of GW recharge, with up to 60% of the total run-off flowing at the soil surface (Le Maitre *et al.* 1999). The conversion of land in Brazil from a natural *cerrado* (savannah) in a *Eucalyptus* forest reduced the subsurface water recharge by nearly 60% (Le Maitre *et al.* 1999). However, it is expected that improvements in irrigation methods in the near future will reduce the total water use for agriculture in some countries (Correia *et al.* 1998; Seckler *et al.* 1998).

Increase of urban areas and demand for domestic and public drinking water

Rapid urbanization has led to the development of mega cities (cities with population over 10 million). In LDCs there were 18 mega cities in 2000, and these drain GW resources as well as fill streams that cross them with wastewater, both domestic and industrial; ultimately resulting in potential hydrocide (Lundquist 1998).

In 1990, urban dwellers comprised 43% of the world's total population, while in LDCs 35% of the population lived in cities. By 2020 the proportion of urban population in LDCs is predicted to surpass 50% and it is expected that 57% of the world's total population will live in cities (UN [United Nations] Report 1997). The additional urban population in the LDCs is likely to be 1.8 billion people, of which a large proportion will be poor. This increase also implies increasing pressure on domestic and drinking water supply, sanitation and food supply. In many urban areas of the world, the continual extraction of water for domestic and drinking purposes from underground aquifers is at such rates that the resources are rapidly being depleted. In London, the water

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table has fallen more than 72 m below the surface (Pointing 1992). In Bangkok, the water table has fallen by 25 m since 1958 and continues to drop now at a rate of *c*. 3 m yr^{-1}, and seawater intrusion in the aquifer advances at the rate of 450 m yr^{-1}. In Tamil Nadu, India, the water table has fallen more than 30 m in 15 years (Shah *et al.* 2000).

The rise of overexploitation of GW reserves for urban supply will continue. In 2025 it is expected that 60% of the world population, i.e. about five billion people, will live in cities, especially in LDCs (Young *et al.* 1994). Even in countries with high living standards, the consumption of GW for drinking purposes will increase, for example in 2020 water consumption in the Netherlands is expected to be 60% higher than at present (Correia *et al*. 1998).

Industrial activities including thermoelectric production and mining

Manufacturing and service industries have high demands for water, for cooling aggregates, for cleaning and manufacture of products. The quantities of water consumed strongly depend on the respective industrial sector and its activities, and can often be extremely high. Industrial water demand in Europe accounts for just over half of total water withdrawal, albeit mainly surface water is used. In the USA, GW withdrawal for industry, thermoelectric power production and mining represented 9% of the total volume of extracted subsurface water during 1995 (US EPA 2000). In wealthier countries, slowing of consumption for this sector is noticeable, while in LDCs with rapid industrialization the trend is in the opposite direction (Postel *et al.* 1996).

Tourism

Tourism affects, and is affected by the environment. Over the last 30–40 years, tourism has grown and thus is expected to continue. In Europe, the coastal zones of the Mediterranean region, and often extremely sensitive mountain areas, represent important tourist destinations where water supply is rather scarce (EEA 1999). Tourism causes very high pressures on GW, especially because of the additional water demand arising during the season when the GW situation may already be critical, as in the Mediterranean countries like Spain, Greece or southern Italy (EEA 1999). In addition, tourism-associated waste and sewage represent a potential source of GW pollution (see below). This trend will certainly continue during the next decades and will extend to areas that only recently discovered the economic advantages of the tourism industry, for example remote islands in the Pacific (Detay *et al*. 1989).

Climate change

The trend toward a global warming of the Earth's atmosphere is an important environmental force with significant implication for the state of GW ecosystems. The Earth's surface temperature during the last two decades has increased by about 0.5°C and an ongoing rise with similar amplitude is expected up to 2025 (IPCC [Intergovernmental Panel on Climate Change] 2001). The global warmth in 2001 was unusually high and is considered to be a consequence of anthropogenic greenhouse gases (Hansen *et al*. 2002).

Higher extreme temperature values, with annually more hot and fewer cold days are also expected over large land areas (IPCC 2001). This will cause increased summer continental drying, especially over most mid-latitude continental interiors (such as areas in Africa, Central Asia and the Mediterranean). More intense precipitation events (heavy rains and less snow) will affect many land areas over the Northern Hemisphere in mid- to high-latitude zones. Cyclones with very high wind and precipitation intensities are also expected over tropical and sub-tropical zones. In addition, it is likely that the warming trend will cause an increase of unpredictable Asian summer monsoon precipitation (IPCC 2001).

These climate changes will act negatively on the GW reserves of many aquifers. In the semi-arid and arid zones the recharge of aquifers will be reduced through decrease in run-off and through higher human water consumption, especially for agriculture. The GW reserves will continue to shrink. In areas with a high net humidity, the surface run-off will increase, but because of fast flow the water will not optimally recharge the depleted aquifers. This is the case in the Northern Hemisphere, where the recharge of aquifers will not be able to proceed through slow snow melting and over longer periods of infiltration into the soil over wide areas (see also Tockner & Stanford 2002). Also, in subtropical or tropical areas, a part of the huge quantity of water deposited by storms and by monsoon precipitation will flow at the soil surface instead of infiltrating underground, as shown by streams in Arizona (Grimm & Fisher 1991). During long arid periods, rivers and streams dry out, like the wadis in Sudan, causing an interruption of aquifer recharge (Elagib & Mansell 2000). In addition, the evapotranspiration of the surface vegetation and the water table decline to critical levels, with the corollary that many well fields remain without water.

An important consequence of the general increase of the temperature at the Earth's surface during the next 25 years will be a notable reduction of the sustainability of the earth's GW reserves in areas where the demographic density is already high or human populations need agricultural support that depends on water irrigation. Reduction in the usable GW due to climate change may produce not only strong ecological modifications on Earth, but also social and economic tensions between people and countries that could lead to water wars.

Groundwater quality problems (overload of aquifers with contaminant substances)

An impressive number of chemical and biological substances, mainly produced by human activities, accumulate in GW impairing the pristine quality of the water, producing changes in the structure and function of ecosystems and, very important, creating threats to human health. The most

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profound threats to GW quality are from fertilizers, pesticides, mineral oil products, chlorinated solvents, heavy metals and wastewater loaded with nutrients and pathogenic micro-organisms and viruses.

GW pollution is first on a list of environmental pressures caused by human activities especially in the urban areas of the European Union (EEA 1999). We give several examples of major pressures on GW quality having negative effects in many parts of the world and expected to remain a matter of concern for the next 25 years.

Agricultural practices

The steady increase in crop production during the last 40–50 years was possible only with the application of huge quantities of fertilizers, pesticides and intensive irrigation of cropland. Phosphate and nitrogenous fertilizers were used especially. Nitrates represent major sources of pollution for GW all over the world. In the year 2000, *c*. 87 billion tonnes of nitrogenous compounds were used for crop cultivation worldwide and a 60% increase in the use of these compounds is expected by 2020 (Tilman *et al*. 2001); there is thus a foreseeable rise in GW pollution.

The production of pesticides is expected to increase in volume by *c*. 74% by 2020 relative to 2000 (Tilman *et al*. 2001). Herbicides like atrazine, simazine and bentazone, and insecticides like parathion, are strong inhibitors of metabolic activity in both plants and animals (Notenboom *et al*. 1999). Some of these compounds, such as parathion and lindane, are potential carcinogens (Laws 1993). Excessive application of fertilizers and/or pesticides on wide field areas, also introduces toxic heavy metals like mercury, cadmium and selenium into GW and it may increase the salt concentration (US EPA 2000).

Organic pollution of GW is produced by animal feedlots and irrigation practices. Animal feedlots produce large amounts of liquid waste from the manure, and pose public health risks through the possible microbial contamination of drinking water.

There is also a large number of newly emerging contaminants in GW, such as steroids, antibiotics, non-prescription drugs and their metabolites. Two commonly-used classes of antimicrobials, sulphonamides and tetracyclines, have been reported in GW and surface water samples collected from sites throughout USA (Lindsey *et al.* 2001). They are used in animal feeding operations in large quantities (swine, poultry and other livestock), and thus may end up in wastewater and ultimately find their way into aquifers (Kolpin *et al.* 2002).

Urban and/or industrial activities

One of the most common forms of contamination of GW is through the seeping of oil products from fuel storage tanks. Petroleum products are complex mixtures of various weakly or highly soluble polycyclic organic compounds. Volatile compounds associated with solvent spills from electronic and aeronautic industries or from military facilities were repeatedly mentioned in US EPA reports. For instance, in Indiana during 1996 alone, approximately 160 million litres of chemicals were spilled into the soil (US EPA 2000). There are about 400 000 confirmed leaks from underground petroleum tanks in the USA and every second petrol station in the UK stands on contaminated soil and GW (Sampat 2000).

The increased quantity of wastewater in urban areas, combined with the leakage of sewage systems, allows the introduction of large quantities of dissolved organic matter, heavy metals, salts and pathogens into the GW (EEA 1999; US EPA 2000).

Hydrocarbons from various organic solvents, including benzene, chlorinated organic compounds (such as trichloroethene, tetrachloroethene, vinyl chloride or chlorobenzene) and nitroaromatic compounds (released from dyes, explosives, pesticides and pharmaceuticals) are potentially noxious, and may be carcinogens to humans and animals (Laws 1993).

Waste disposal (including waste injections) and waste treatment

Throughout history, civilizations have used the underground as a place for waste disposal and a very large number of subsurface sites are therefore now highly contaminated. There are estimated to be over 100 000 contaminated-GW sites containing toxic metals in the European Union, but most alarming is the situation in the USA, where 60% of the bulk hazardous liquid wastes (about 35 million litres of solvents, heavy metals and radioactive material) are injected into deep GW via wells below the deepest source of drinking water (Sampat 2000). The spread of contaminants, especially nitrates and pathogens from septic tanks, is another widespread form of GW pollution that can impair the quality of drinking water and produce outbreaks of disease (Laws 1993). Waste injections into aquifers are able to induce geochemical and biological changes in GW systems in the long term, for example in clogging effects or through rock dissolution. In an injection field in Hawaii, the injected wastewater clogged the subsurface system through strong microbial growth, chemical precipitation and gas accumulation (Oberdorfer & Peterson 1985).

Concern is growing about antimicrobial substances affecting water quality, as they can accelerate the evolution of resistant bacteria. Pharmaceuticals, other products in daily use and their metabolites have probably been in the environment for a long time, but only recently have analytical methods been developed to detect them at low levels (1 μg l^{-1}). This is true for recently reported N-nitrosodimethylamine (NDMA), a genotoxic human carcinogen that has an action level of 0.01 μg l^{-1} (NTP 2000).

Several hundred thousand sites are scheduled for clean-up all over the world, but new ones are still being created, with expected US$ or € costs of billions and a time span of dozens of years. As mentioned above, pollution of GW systems has already caused environmental problems at all levels (local, state, national and global) and clean-ups are required by local and state laws passed over the last two decades, mostly in response to public concern that drinking contaminated GW may cause cancer or other illnesses.

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Nitrate and nitrous oxide in groundwater

The excessive contamination of GW by nitrates merits analysis in more detail because these will continue to rise during this century. Excess nitrogen inputs into water bodies lead to unwanted eutrophication. Since the middle of the last century, nitrate contamination of rivers, streams and aquifers has become a common problem. In Europe, where riverbank filtrates are a primary drinking water source, 5–10% of the aquifers exceed the European Union nitrate limits (25 mg l^{-1}) and, in intensively cultivated areas, the NO_3-N concentrations are increasing by 1–2 mg N $l^{-1}yr^{-1}$. The other major sources of nitrate enrichment in GW are sewage disposal into rivers, septic-tank drainage, dumping sites and natural soils in certain arid environments such as central Australia (Dudley 1990). High nitrate concentrations are also associated with substandard well construction and improper siting of wells, which are quite common in many LDCs (Spalding & Exner 1993). Unsewered sanitation has been shown to cause increased nitrate concentration in the underlying GW in many countries in the world, for example in Africa, Asia and South America (Lewis *et al*. 1980, 1982; Smith *et al.* 2000).

Because nitrate-bearing wastes are one of the most important sources of GW contamination, nitrate compounds were added to the US EPA Toxic Release Inventory (Hansen 1997). Health issues related to high nitrate levels in aquifers are of concern (ECETOC [European Chemical Industry Ecology and Toxicology Centre] 1988; WHO [World Health Organization] 1993) where water supply is dependent on GW as the main source. For instance, the proportion of GW in drinking water supplies in 75% of European countries is well over 50% and in some as high as 89–99% (for example, Denmark 98%, Portugal 94% and Germany 89%).

Nitrous oxide (N_2O), another critical nitrogen species, has been found accumulating in organically-contaminated aquifers (Ronen *et al.* 1988). It derives from incomplete nitrate reduction by denitrifying bacteria. The mobile gas escapes from the saturated zone into the vadose and/or soil zone and subsequently into the atmosphere, where it is increasing in concentration. Nitrous oxide is a greenhouse gas, with negative effects on global climate change. The atmospheric global concentration of N_2O in 1998 was 314 ppb, of which 60% of the total by volume was produced in the Northern Hemisphere (IPCC 2001). The trend of increasing N_2O concentrations in the environment, derived from denitrification of soils rich in nitrates and organic wastes will probably continue, unless reversed by implementation of efficient policies.

New contaminants in groundwater: the methyl tertiary-butyl ether (MTBE) case

MTBE, in this context, is discussed as a model compound for hundreds of frequently introduced and distributed chemicals. MTBE is the most important fuel oxygenate and used since 1979 as a blending compound in gasoline to replace lead alkyls and enhance octane. The MTBE content in gasoline covers a range up to 12% (v/v) in European countries (Schmidt *et al.* 2001). With the introduction of the Clean Air Act in the USA in 1990, reformulated gasoline (RFG) contains even higher amounts of MTBE of up to 15%, to increase the oxygen level in the fuel for cleaner combustion and to reduce harmful air emissions (carbon monoxide and ozone). As early as 1980, MTBE was documented in GW and has become a ubiquitous GW contaminant since then. Local high concentrations (several mg l^{-1}) originate from point sources (underground tanks, leaks or spills), but the current low background concentrations in GW result from traffic emissions and subsequent atmospheric wash out through precipitation events and stormwater run-off. Due to its strong taste and odour it is likely to impair drinking water quality at aqueous concentrations of 10–100 μg l^{-1} (Schmidt *et al.* 2001). Adverse health effects can be suspected at concentrations in the milligramme range, and US EPA has tentatively classified this contaminant as a possible human carcinogen (US EPA 2000).

Microbial contamination and human health risks

Because of the natural purification processes in soil and subsurface sediments, GW is the cheapest source of drinking water. Nevertheless, along with the growing human population, agricultural production, and deposition and treatment of wastes (such as sewage and manure), there is an increased risk of infection and disease when consuming GW that has not been disinfected. Pathogenic bacteria, protozoa and viruses in GW may cause several serious diseases. There is an increased risk of potential contamination by pathogens of high-quality GW used for human needs. An estimated 25 000 people died every day in 1980 from the consumption of contaminated water (Gerba 1996) and 0.75–5.9 million illnesses per year result from contaminated GW in the USA, causing 1400–9400 deaths (Macler & Merkle 2000). Faecal contamination of well water is one of the most common health risks around the world. As recently as 1990, the US EPA Science Advisory Board cited drinking water contamination as one of the highest-ranking remaining environmental risks (US EPA 1990). From an ecological point of view, not only protection from waterborne disease, but also ecosystem protection activities to prevent faecal contamination of aquifers and wells, should be the goal for the next decades.

Other human activities

Aquifers artificially recharged with water used for cooling in power stations or for washing aggregates induce long-term change in the physicochemical conditions of groundwater (Balke 1978). Falling GW levels and changing GW flows as a result of dam construction and/or sealing walls along riverbanks leads to a reduction in the oxygen concentration of local aquifers, which induces the release of iron and manganese into the water (Trueb 1986).

Mining activities can contaminate GW in various ways. Extraction of gravel creates GW pits through which

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contaminants (like nitrates) and pathogens pollute aquifers. Mining for coal, copper or uranium induces acidification of the GW or releases toxic substances like arsenic, sulphuric acid, various heavy metals and radioactive chemicals (Laws 1993). Additional demand by tourism services also increases the potential contamination of GW, particularly endangering drinking water reserves.

Natural processes like climate change and polluted surface water infiltration put extra pressures on the GW. High amounts of phosphate and/or nitrate infiltrate the subsurface water after drying out of streams and the rewetting of the channels under arid climate conditions (Stanley & Boulton 1995; Turner & Haygarth 2001). Infiltration of polluted water into the sediments along rivers also raises the concentration of dissolved organic matter and/or heavy metals in the shallow groundwater of riverbanks, as in the case of the River Rhône near the Lyon (Gibert *et al.* 1995) and the Danube at Vienna (Danielopol 1983).

Complex linked quantity and quality problems

Salination problems

Unnatural increase in the salinity through human activities such as GW extraction has disturbed natural hydrological and salt cycles resulting in secondary salination. Today salination is an actual or potential environmental threat for a quarter of the world's total land area and water bodies within that area (Williams 2001).

Soetrisno (1998) highlights the degradation through salination of both GW quality and quantity in Indonesia and emphasizes the need for proper management of the GW resources from which the large population of the country will benefit. Through enhanced mining of GW during the last decades, saltwater intrusion to coastal aquifers has become a common problem in heavily populated large cities such as Jakarta (12 million), Surabaya (6 million) and Semarang (4 million). Similarly, a number of coastal aquifers in China, India, Egypt and Turkey are confronted with seawater intrusion (Shah *et al.* 2000). Cyprus, where water is a precious commodity (90% of water supply is used for irrigation), has experienced similar problems due to mining of GW resources for the irrigation of citrus plantations (Ergil 2000). The island is semi-arid (rainfall 50 year average is 320 mm yr^{-1}) and an added problem is the rising cost of crop production because of increasing salinity due to declining water tables. The Magusa coastal aquifer in the East is so contaminated that it is now completely out of use and the Guzelyurt aquifer in the North is facing similar problems.

For human needs in this century, green water (water lost through evapotranspiration) thus becomes an important component (Falkenmark 1999). Removing the natural vegetation on the slopes in the Murray-Darling basin in south-eastern Australia for agriculture induced GW salination in the valley bottom through the rising water table and the water-logged soil. Additionally, on the flood plain of the River Murray, many wetlands face salination, which also reduces the GW quality due to management practices involving lowering the GW table by pumping, with much of the pumped and slightly saline water stored at the surface in recharge (or evaporate) basins (Williams 2001).

Arsenic in groundwater

High concentrations of arsenic in drinking water represent a serious human health risk, being a potentially strong carcinogen (Smith *et al.* 2002). The wide distribution of this contaminant is causing problems in many parts of the world and merits a brief mention here.

For the past two decades, water from tube wells sunk into the alluvium of the Ganges delta has been slowly poisoning Bangladeshi and West Bengali villages with naturally occurring geogenic arsenic (Chatterjee *et al.* 1995; Das *et al.* 1995). Arsenic poisoning is affecting more than 80 million people (Sengupta *et al.* 2001) and thousands of villagers have been diagnosed with chronic symptoms of arsenic poisoning.

Today there are an estimated four million tube wells in Bangladesh and prior to the end of the 1990s there was no record of arsenic tests on any of those wells. Aquifers less than 300 m deep (mostly <100 m) provide Bangladesh and West Bengal with more than 90% of the drinking water. In Bangladesh, more than 20 million people are drinking water containing more than 50 μg l^{-1} of arsenic (McArthur *et al.* 1998; Nickson *et al.* 1998), which is five times the WHO's recommended limit, and more than a million may be drinking water a hundred times over the limit. Similar arsenic contamination of GW has been reported from other parts of the world such as the USA (Welch *et al.* 2000), Chile, China, Thailand (Christian 2001) and Vietnam (Berg *et al.* 2001).

ECOLOGICAL IMPACTS

Persistent or repeated environmental pressures as described above lead to changes in the structure and functioning of ecological systems. We will mention here four types of impacts visible at various ecological scales. The first two types, namely the generation of reduced GW zones and changes in organismic diversity in GW communities, concern changes in subsurface ecosystem states, while the other two, namely vegetation changes as agriculture practices shift and impacts at the biosphere scale, concern global changes of GW systems.

Generation of reduced groundwater zones

A wide variety of micro-, meio- and macro-organisms develop abundant populations in environments that contain oxygen because aerobic metabolism using molecular oxygen is energetically the most efficient process for oxidizing organic carbon. Under conditions of low or no oxygen, anaerobic processes dominate, which are energetically less efficient (Chapelle 2001). Most of the macro- and meio-organisms are eliminated, while various micro-organisms support hypoxic or anoxic environments well.

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GW systems overloaded with organic matter quickly become depleted in molecular oxygen due to increased microbial activity. Microbial mineralization of organic compounds continues by fermentation or oxidation with electron acceptors other than molecular oxygen (i.e. nitrate, ferric iron or sulphate), which in general are slower. In addition, during such anaerobic processes, by-products may be generated which are toxic at higher concentrations (such as hydrogen sulphide) and/or impair the GW quality necessary for human needs, as in the cases of dissolved manganese and ferrous oxides (Chapelle 2001). Reduced GW, resulting from so-called anoxification (Ronen & Magaritz 1991), occurs either within localized micro-niches or can spread to other large areas within aquifers during the dispersion of organically contaminated GW plumes (Schwille 1976).

Major types of environmental pressures which generate reduced GW are *inter alia* the infiltration of large volumes of sewage water during artificial recharge, as happens in some coastal aquifers in Israel used for intensive agriculture (Ronen & Magaritz 1991), the leaching of dissolved organic carbon from landfills, the infiltration of polluted surface water from rivers in and downstream of large urban areas (Danielopol 1983), hydrocarbon spills (Ghiorse & Wilson 1988), and colmation of riverbed sediments, which interrupts the recharge of aquifers with well-aerated water (Brunke & Gonser 1997). The construction of dams and various types of isolating walls necessary for the retention of water in reservoirs along rivers modifies the GW flow patterns, slowing water movement and generating areas with reduced GW, as along the Danube in Austria (Frishherz 1979). Water from cooling industrial aggregates or from heating pumps discharged into subsurface aquatic systems is able to heat the GW and to stimulate local deoxygenation of aquifers (Balke1978).

Reduced GW zones also develop in arid countries where during summer the recharge of the aquifers slows, the temperature of the subsurface water increases and oxygen is depleted through microbial activity. Such is the case for subsurface areas along the parafluvial sediments of Sycamore Creek in Arizona (Stanley & Valett 1991). It can be used as a model to predict what could happen during aridization induced by climatic change (Carpenter *et al.* 1992).

Changes in biological diversity

The quantity and quality of the various kinds of pressures on GW systems are able to induce drastic changes in the diversity of organisms living underground. We assess two types of such changes, namely (1) decline in GW-dwelling organism populations leading to species extinctions and (2) penetration of alien species belonging to surface-water communities. Both processes determine changes in the functioning of GW systems, generally reducing the efficiency of some ecosystem processes.

Microbes are highly abundant in subsurface waters. Although little is yet known about microbial diversity, contamination in almost every case causes a shift in the composition of the microbial community (Bekins *et al.* 1999; Ludvigsen *et al.* 1999; Rooney-Varga *et al.* 1999). Loading of the aquifer by hazardous chemicals also leads to a decrease or increase in abundance (Haack & Bekins 2000). Changes in abundance and diversity of GW organisms are also suggested in the case of overpumping, which also induces structural changes in the water-saturated habitat. A reduction in the self-purification potential and therefore water quality was observed within the bank filtration area along the Danube at Vienna after the major part of the sediment-associated microbial biomass was removed together with the habitat, namely the fine sediment fraction, by overpumping of the water (Frischhertz 1979). Intensive withdrawal of GW for irrigation purposes leads to local decline in animal communities as in coastal aquifers of Greece or alluvial aquifers in southern France (Danielopol 1981; Dumas 2002). The overexploitation of the GW of the Balcones Fault Zone in the Edwards artesian aquifer (Texas) endangers one of the world's most species-rich subterranean assemblages, including many endemic stygobitic crustacean, fish and amphibian species (Longley 1992). Plans for dewatering of local confined aquifers for ore exploitation in Western Australia could lead to the extinction of a unique subterranean crustacean fauna of great scientific value (Humphreys 1999).

Organic loading of the subterranean environment may lead, to extinctions of stygobitic animals (Elliott 2000). Apparently, subterranean animals are sensitive to toxic chemicals like pesticides (chlorophenols), various salts (potassium chloride, potassium nitrate) and heavy metals (Notenboom *et al*. 1992; Mösslacher 2000). In organically polluted habitats located close to surface water there is also potential invasion of cosmopolitan surface dwelling species, which outcompete or temporarily replace the stygobites. Such is the case with a karstic stygobitic fauna in southern France near Montpellier, where the arrival of organic liquid waste caused the colonization of the subsurface system by ubiquitous surface-dwelling species like the tubificid worm *Tubifex tubifex* or the crustacean copepod *Acanthocyclops robustus* (Malard 2001). At the unimpacted sites, many stygobitic species continued to exist.

GW habitats along large rivers, like the Rhône or the Danube, which are polluted not only by organic matter but also by toxic heavy metals, display low biological diversity and are represented mainly by surface-dwelling taxa. The interstitial fauna of the riverbanks in the city of Lyon represent such a case (Gibert *et al.* 1995).

River regulation combined with the negative effect of organic pollution alter GW habitats; for example, through stronger siltation and oxygen depletion of the interstitial voids, the free- moving crustaceans (such as stygobitic copepods and isopods) are replaced by assemblages dominated by epigean animals such as nematodes and oligochaetes (Danielopol 1976, 1983).

Arid climates like those prevailing in Northern Africa or in Arizona (USA), determine the drying of streams and the

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interruption of water infiltration into adjacent-shallow subsurface areas. The fauna of hyporheic habitats in such cases is represented by a few epigean species that can survive the dry period until the next rewetting (Boulton & Stanley 1995).

Vegetation changes with modification of agriculture practices

Excessive GW withdrawal lowers water tables of many shallow unconfined aquifers. This modifies the surface vegetation, especially leading to the disappearance of phreatophilous species in wetlands (González Bernáldez *et al.* 1985; Brinson & Malvárez 2002). Locally humid areas in the Mediterranean region, for example around Madrid, in Spain, are characterized by different types of vegetation depending on the connectivity between the surface landscape and the GW systems. Surface habitats where the shallow GW predominantly discharges during the summer have a humid microclimate favourable to plants, animals and humans, while landscape areas where GW systems mainly recharge during the winter are characterized by different plants with specific adaptations for this type of environment (González Bernáldez *et al.* 1985). For the Madrid case, the excessive withdrawal of GW in the discharge area during the summer (like El Pardo) has transformed the ecological system to a recharge type with negative consequences for the vegetation and fauna; several species of phreatophytes have disappeared, and there has been an increase in parasitic attacks and diseases in various plants (González Bernáldez *et al.* 1985).

Water erosion in many semi-arid and arid regions has lead to decrease of soil fertility followed by agricultural abandonment and switch to pastoralism, as in the Mediterranean zone (Barić & Gašparović 1992). Because the trend toward GW depletion in arid and semi-arid regions is expected to continue, there has been increased effort to improve agricultural practices, for example shifting irrigation systems from the surface to the rhizosphere (Postel 2001).

Deforestation and intensive land-use for agriculture along streams and rivers often induces soil erosion and colmation of shallow GW habitats with fine sediment, a negative consequence being drastic decrease in the diversity of subsurface (interstitial) dwelling fauna (see Hahn 2002).

Impacts at the biosphere scale

Shallow aquifers loaded with high concentrations of organic matter from anthropogenic activities (i.e. in areas of organic waste disposal) release nitrous oxides by denitrification (Ronen *et al.* 1988). The concentration of this gas in contaminated aquifers is up to three orders of magnitude higher than that expected in equilibrium with the atmosphere. This gas has a potentially high greenhouse effect, about 275 times greater than the CO_2 (IPCC 2001), and is also able to destroy ozone in the atmosphere (Ronen *et al.* 1988; IPCC 2001; Malmqvist & Rundle 2002). Reactions of NO in the atmosphere produce HNO_3, which is a component of acid rain (Schlesinger 1991).

During the second part of the 20th century there was a net increase in the total volume of GW discharged into the sea (Sahagian *et al.* 1994). The direct input of salts from GW to the oceans was about 50% of the total salt loading by rivers (Zektser & Loaiciga 1993).

In conclusion, the strong environmental pressures on GW constitute a world-scale water crisis that threatens human existence. In addition, environmental pressures are partly or wholly impacting the structure and/or function of various ecological systems. This trend will continue to the 2025 time horizon and beyond if new environmental policies to manage the world's GW reserves ecosystems are not implemented.

STRATEGIES FOR THE MANAGEMENT AND PROTECTION OF SUSTAINABLE GROUNDWATER SYSTEMS

The need for sustainable groundwater management

Sustainability of the GW ecosystem means the maintenance of its functioning at a level suitable for the organisms which play important ecological roles and/or for the humans who potentially exploit it (Lubchenco *et al.* 1991). The concept of environmental sustainability is related to global life-support systems functioning on a long-term basis (Goodland 1995). It presumes the maintenance of the natural capital of an ecological system where the degraded products are absorbed by the local environment and the renewable resources are perpetuated. However, not only are many being exploited at a faster rate than their capacity to recover but large volumes of GW are polluted and can not be further used for human ecosystem needs. A water crisis seems inevitable in the 21st century (OECD Working Committees 2000; Revenga *et al.* 2000; World Water Council 2000; Foundation for Environmental Conservation 2001; Pimm 2001), being partly alleviated by implementation of environmental policies that consider the development of sustainable GW systems and/or better protection of the subterranean ecosystems within a long-term perspective. This means a reduction of water withdrawal from aquifers combined with an increase in the water recharge of subsurface systems as well as a reduction of GW contamination.

Central to the problem of the use of GW in a sustainable way is the maintenance of the integrity of structural and functional traits of groundwater ecosystems (Notenboom 2001). Within this framework we should consider not only the water aspects, but also the various species living within the subsurface. In order to achieve such a goal, we need to protect the environmental quality above and below the soil surface and apply a sound management strategy for the exploitation of water resources at relevant sites.

The problem of developing environmental policies for the implementation of sustainable GW systems and/or for protection of such ecosystems requires two main approaches,

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one relying more on the socioeconomic and political contexts and related to the sustainability of the water production, and the other insisting more on ecological criteria and related to the sustainability of the whole ecosystem. We will show that the present day options retained more and more by environmental planners and various agencies (see EEA 1999), are to develop an integrated system combining the two approaches. Within such system we will propose an agenda of measures for the groundwater problems that we expect to see at least partially implemented by 2025.

The socioeconomic approach

As an important resource GW has a quantifiable value like oil or coal; it can be traded on the market, or represent a source of political power (Gleick 1993*b*). Moreover, it is related to human cultural attitudes and to technology (Table 6).

Economic aspects

The present market value of the high-quality water necessary for human needs is too low as compared to other Earth resources and it should be increased following classic economic criteria (OECD Working Committees 2000; World Water Council 2000).

Growth in the human population and amelioration of the consumed food in terms of total calories per caput will put an extremely heavy pressure on the availability of world water resources (Table 7). This situation presumes that the consumption of renewable water per caput will increase unequally, with more intensity in LDCs. Therefore, in order to obtain enough food to sustain the increased world population it will be necessary during the next decades to increase financial investment in the environmental resources sector relative to the agricultural sector, especially for the development of efficient infrastructures necessary for human water supply and sanitation (Table 8).

The human appropriation of renewable freshwater reserves is one of the major aspects of the so-called water crisis (Postel *et al*. 1996; Vitousek *et al*. 1997; Vörösmarty *et al*. 2000; Johnson *et al*. 2001). Several socioeconomic scenarios to improve this situation exist: for instance (1) to implement an open water market and to use full-cost pricing for the supplied water; (2) to reduce or eliminate perverse subsidies in the agricultural sector.

Scenario (1). Exploited water is in many countries undervalued (World Water Council 2000; OECD Working Committees 2000), as pricing does not take into consideration the additional costs related to the safe maintenance of well-functioning ecosystems or the infrastructure necessary for water supply and sanitation. An increase in the water price could cause people in many parts of the world to reduce water consumption. We consider that the suggestion to increase the price of GW and thus develop an economic market for the distribution of high-quality GW will have negative consequences exactly in those parts of the world where water is most needed, namely in the LDCs with high-density populations, where people with very low incomes will not be able to purchase the water needed (Shah *et al*. 2000). The increase in the difference between rich and poor people would inevitably lead to further social and political tensions.

Scenario (2). The reduction or elimination of incentives that sustain economic development but are detrimental to the water supply and sustainable ecosystems has been proposed repeatedly (Myers 1998; OECD Working Committees 2000). In the future, it will be necessary to reduce the financial support for fertilizers and pesticides, because, used in large amounts they will continue to pollute aquatic systems, including GW.

Cultural attitudes

Many springs, particularly in semi-arid areas, were protected for centuries against environmental pollution or overexploitation of water. Mythological representations exist which often helped strengthen notions of protection of water and/or the environment (Kula 2001). Additionally in areas with chronic water scarcity, as around the Mediterranean, traditional societies adapted through low and efficient water

Table 6 Criteria for valuation of groundwater systems.

Socioeconomic criteria	*Ecological and cultural criteria*
Need for drinking water	Ecosystem services
Need for food production	Ecosystem goods
Need for industrial water	Ethical aspects
Need for domestic water	Scientific and aesthetic aspects

Table 8 Annual investments in water use for agriculture, environment, energy, industry, and water supply and sanitation for 2000 and projections for 2025 (from World Water Council 2000).

Domain of water use	*Annual investment (10^9 US$)*	
	2000	*2025*
Agriculture	30–35	30
Environment, energy and industry	10–15	75
Water supply and sanitation	30	75
Total	70–80	180

Table 7 Comparative demography and food consumption between OECD and developing countries in 1995 and projections for 2025 (data from World Water Council 2000).

Regional domain	*Population (billions)*		*Food consumption (average calories caput^{-1} day^{-1})*	
	1995	*2025*	*1995*	*2025*
OECD countries	0.87	0.93	3300	3550
Developing countries	4.76	6.53	2600	>2750

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consumption. The opposite occurred in the areas that progressed economically during the last centuries, especially in the industrial countries (Gleick 1993*b*). In the latter, it now becomes necessary to change human attitudes towards water, i.e. to rediscover the ancestral values of frugal water consumption and to spare or protect it as much as possible for posterity.

Technology aspects

The water crisis is partly due to the technological solutions to GW extraction and distribution, which improved during the last 50 years and became through their low costs widely available especially to agriculture, but also to industry (Shah *et al.* 2000). In semi-arid countries like Iran or Greece, drilling deeper wells for mass cultivation of plants determined the depletion of aquifers and/or the deterioration of their water quality. This trend will most probably continue on a worldwide scale during the next 25 years due to the globalization of economic sectors like agriculture. Therefore if we want to reduce the volume of GW withdrawals up to the 2025 time horizon it will be necessary *inter alia* to use new technologies in water distribution, like root-zone irrigation of crops on a wider scale (World Water Council 2000) or, more radically, to offer to human populations new alternatives promoting reduced water consumption. For instance, replacing a high number of leaky house toilets with more efficient ones in Mexico City saved enough water for the needs of more than 200 000 new residents (Brown 2002).

The ecological approach

Ecologists as compared to economists generally adopt a broader view of the value of environmental systems (Table 6), combining utilitarian criteria with ethical and/or aesthetical criteria based on ecological principles (Shrader-Frechette & McCoy 1993).

The value of groundwater ecosystems

GW ecosystems provide generally important services and goods to humans (Table 9). The water filtration process in groundwater systems due to removal of microbial pathogens allows production of high-quality drinking water, a good of immense benefit to human welfare (Daily *et al.* 2000). Beside the utilitarian arguments, there are arguments for the protection of subterranean habitats, especially cave systems, as well as the diverse organisms living in karstic and/or porous ecosystems, because they are the product of a long evolutionary history and in many cases are beautiful and/or offer to their observers interesting subjects for contemplation and/or scientific research (Danielopol 1998; Krajick 2001).

The value of healthy GW systems has also to be seen as an intergenerational capital to which precautionary protective measures should be applied (Lingner 2000). An additional argument is the moral duty to maintain the biosphere as a global long-term sustainable system for the smooth continuity of life. This position is challenged by the anthropocentric view that the soil and its resources are a common property. As the soil and GW have tradable values, these resources are exploited following a business-as-usual strategy, threatening the future of existing aquifer reserves (Shah *et al.* 2000).

Table 9 Services and goods provided by groundwater ecosystems.

Ecosystem services	*Ecosystem goods*
Purification of water (microbiological and physicochemical processes)	Safe drinking water for human consumption
Attenuation and/or elimination of chemical contaminants	Stable supply of water for human needs (agriculture, industry, domestic needs)
Contribution to the sustainability of surface ecosystems (such as wetlands)	Water for sustainable life of micro-organisms, plants and animals

The need for groundwater ecology research

Compared with other domains of aquatic ecology, GW ecological research deserves much more support in order to progress (Gibert 1992; Stanford & Ward 1992). Recently, international programmes have been promoted to address inventory of subterranean organisms, such as the EU PASCALIS project (Gibert 2001*b*) or GW biomonitoring projects (for review see Mösslacher *et al.* 2001). There has also been intensive research into developing new ecological engineering tools, including *in situ* remediation methods for contaminated GW ecosystems.

There is a stringent necessity to intensify research dealing with ecological impact assessment on aquatic systems, including GW (Revenga *et al.* 2000; World Water Council 2000). Extensive monitoring programmes are needed to obtain better quantitative data for LDCs, which will improve predictions for the future.

The ecological consequences of natural and artificial recharges of aquifers need to be better understood for the effective management of GW reserves (Peters 1998). Another ecological research area with important consequences for the management of sustainable water resources lies in the protection measures required for GW systems. The production of safe high-quality drinking water remains a worldwide priority (WHO 1993) and research on alternative agricultural practices like the organic farming (Mäder *et al.* 2002) could, in the long term, improve the GW quality of large areas, many now strongly polluted.

Development of new tools for ecological engineering

Ecological engineering of GW systems has expanded strongly recently (see Dreher & Gunatilaka 2001; Gunatilaka & Dreher 2001). Here we will exemplify the type of progress realized by ecological engineering, in the form of the natural attenuation concept for remediation of anthropogenically and/or naturally introduced contaminants into GW. Following the definition of the US EPA OSWER (Office of

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Solid Waste and Emergency Response) Directive (1997), natural attenuation (NA) stands for the capability of an aquifer to reduce the toxicity, mobility or volume of the contaminant in GW by biological degradation, dispersion, dissolution and sorption to a degree where it is no longer harmful to humans and/or to the environment. The European definition is more straightforward and emphasizes the need for a reduction in the contaminant total mass. The NA strategy is based on the already high potential of natural systems to degrade, mineralize or immobilize pollutants, the key role being played by indigenous subsurface microorganisms. These are able to degrade and/or immobilize all prominent kinds of contaminants introduced to the underground, such as monoaromatic benzol-toluene-ethylene-xylenes (BTEXs) and polycyclic aromatic hydrocarbons (PAHs), solvents and other chlorinated organic compounds (for example TCE [trichloroethene], PCE [tetraperchloroethene] and VC [vinyl chloride]), nitroaromatic compounds (dyes, explosives, pesticides and pharmaceuticals), heavy metals like Hg, Pb, Cd, Se and Cr, and even radionucleids (Anderson & Lovley 1997; Hazen 1997; Holliger *et al.* 1997; White *et al.* 1997). The reduction and/or elimination of pathogenic organisms is part of the high purification capacity of sedimentary environments. There is also a strong ecological argument in support of NA, in that site remediation efforts by conventional methods (92% of all Superfund sites in the USA are treated by pump and treat; NRC 1997) may reduce or even destroy the natural biodegradation potential present in the subsurface, whereas the goal must be to achieve full restoration of ecosystem function (Herman *et al.* 2001). Most of the acts passed to protect and restore GW sources acknowledged the value of GW but failed to emphasize the importance of healthy subsurface ecosystems (Herman *et al.* 2001).

In the USA, application of monitored NA achieved regulatory acceptance in the early 1990s as a biologically efficient method, and its implementation became comparatively cheap and, in certain cases (deep plumes), the only feasible remediation strategy (Hazen 1997). In Europe, NA is still to be authorized as a sanitation strategy. However, a recent network of projects, like KORA (Kontrollierter natürlicher Rückhalt und Abbau von Schadstoffen bei der Sanierung kontaminierter Grundwässer und Böden), funded by the German Ministry for Education and Research, focuses on that topic and will hopefully lead to an integration of the NA concept in terms of guidelines and recommendations within remediation activities and environmental laws.

Another approach to sustainable GW systems involves managed depletion and subsequent natural or artificial recharge of aquifers (Ambroggi 1977). Much water is lost as run-off at the soil surface in the monsoon areas during the humid period. Controlled depletion of aquifers before the arrival of the monsoon allows more water to be used for longer because the aquifer has a larger capacity to be replenished during the humid period.

Protection measures for groundwater systems

Relevant to the protection of GW ecosystems is the adoption of policies based on ecological risk assessment and prevention of GW pollution. Ecological risk assessment related to GW problems is *inter alia* an effective tool to structure and compile scientific information on the aquifer sensitivity and GW vulnerability to various pollutants, such as pesticide contamination (Notenboom 1995). There are now methods for establishing priorities in GW monitoring and/or protection, as well as providing a basis for regulatory actions and development of strategic plans (Job & Simons 1994; Simons & Notenboom 1997).

Recently, it has become obvious that remediation of polluted GW sites is much more expensive than the implementation of preventive protection programmes (Job & Simons 1994). For instance, the total costs of cleaning up a municipal well contaminated by petroleum was US$ 657 000 while the estimated costs for a wellhead protection plan of the same surrounding area was estimated to be US$ 20 000 (US EPA 2000).

It is impossible to protect the whole GW domain, therefore we need to restrict the protection zones to those areas that are most profitable for the development of sustainable GW reserves. Hence plans for controlled degradation and/or protection zones have to be developed in as many areas as possible (Miller 1979).

GW systems should be included in the plans for the establishment of protected areas and nature reserves. This applies particularly to karstic systems, such as caves, with remarkable aquatic fauna, as in the Slovenian Karst and eastern North America (Sket 1997, 1999; Culver *et al.* 1999), in coastal areas and on oceanic islands (Sket 1996; Humphreys 2000). Accordingly, these measures can be extended to alluvial plains and their aquifers (Danielopol & Pospisil 2001).

In order to protect GW systems it is vital to start with protection of whole landscapes, including GW and, if possible, whole catchment areas relevant to GW sustainability (De Marsily 1992). Simons and Notenboom (1997) proposed such protection measures for the ecological integrity of GW surface water ecotones, and Frisell and Bayles (1996) stressed the importance of integrating the whole river watershed.

Education activities

In Europe, we are experiencing an increased public interest in nature protection (Van den Born *et al.* 2001). Hence, educated individuals and associations are potentially in a better position to adopt effective environmental decisions. The last few years have seen the establishment of courses in GW ecology at an increasing number of institutions and/or agencies. For instance, the European Commission sponsored such a course at the Austrian Academy of Sciences in Vienna in 1999 within its Environmental and Climate Programme (Danielopol 2001) and the Environmental Protection Agency in the USA provides a wide range of information to specialists and the public. We need to develop the means of disseminating information dealing with GW resources and

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their management and/or protection, particularly in LDCs. A large number of professionals are needed by the LDCs to cover all aspects dealing with GW, including hydrology, water management, GW ecology and environmental protection (Falkenmark & Lindh 1993).

AN OPEN VISION FOR 2025

We consider that environmental issues related to GW systems should be valued by combining socioeconomic, ecological and cultural criteria. This should, in principle, lead to better environmental policies with a broader vision, and should form the backbone of environmental policies related to GW during the 21st century.

Combining socioeconomic with ecological criteria

The socioeconomic approach to sustainable GW systems is complex (Fig. 4). Policies to obtain enough usable GW for the increased human populations during the next 25 years must take into consideration the interactions which exist between the subsurface/GW domain, the economics and demography of a given land area, the cultural and social attitudes of various human communities and the retained technological developments. All these facts contribute to the regulation of the water consumption and/or to the measures that are able to ameliorate the efficiency of maintenance or production of GW of sufficient quality and quantity for human needs. To be effective, these aspects have to be combined with sound ecological plans.

The Dutch National Institute of Public Health and Environmental Protection and the Institute for Inland Water Management and Wastewater Treatment (RIVM/RIZA) proposed an ecological scheme to policy makers in the European Union that should insure the sustainability of GW use (RIVM/RIZA 1991). Two basic activities should be implemented: (1) the prevention of a loss of functionality of GW (see below), and (2) the maintenance of the diversity and connectivity of groundwater ecosystems within large areas (Fig. 5).

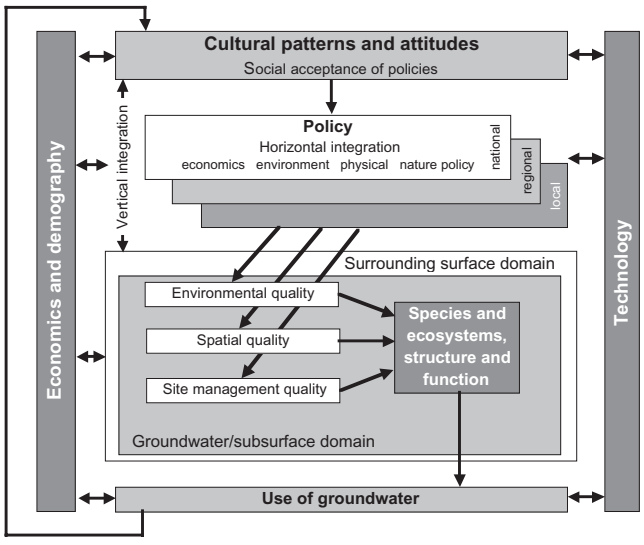


Figure 4 Groundwater policy planning in the socioeconomic context (modified from Notenboom 2001).

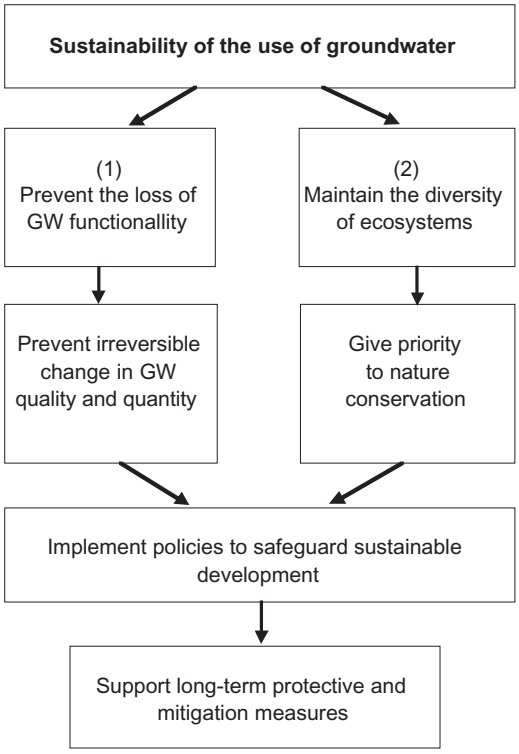


Figure 5 The RIZA/RIVM model for development and management of sustainable use of groundwater (modified from Notenboom 2001).

The importance of connectivity between GW and surrounding surface aquatic and/or terrestrial ecosystems for water circulation, energy transport and matter recycling has been emphasized above. Therefore, areas containing well-connected ecosystems, like those existing in alluvial valleys and wetlands should be conserved as a matter of priority. The good connectivity between surface backwater systems and the GW systems allows the local aquifers to be rapidly replenished with well oxygenated water after dry periods and in this way local groundwater ecosystems recover rapidly from the previous poorly aerated state (Danielopol *et al.* 2000, 2001).

The prevention of loss of functionality of the GW (Fig. 5) means the maintenance of a water quality and quantity useful for the various sectors where the water is needed. Moreover, within this environmental framework we should also consider the maintenance of species richness (Notenboom 2001) as in the important role of diverse microbial communities in the NA of organic pollutants in GW systems.

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Ecosystem-based management using multi-criteria analysis

Multi-criteria analysis of the various attributes of an ecosystem allows a catalogue of optional alternatives to be developed (Munasinghe 1993), and this helps us to decide on the greatest good value for large societal communities. Further policy analysis should consider public preferences and outweigh economic criteria reflecting corporate interests (Shrader-Frechette & McCoy 1993). This is to say that decisions on water policies should be participatory and in order to get a sound policy implementation we need better public information on environmental aspects of GW systems.

Environmental issues in the technological data and existing plans for economic use of GW have to be combined. One of the basic questions is how to quantify the value of GW systems effectively for the implementation of environmental plans. Do GW systems have an economic value based on their use? If affirmative, standard valuation techniques for economic analysis apply. Beside this, qualitative criteria for environmental attributes that have no clear economic-use value have also to be used. For instance, a scale of valuation for the protection of GW organisms which have a scientific value and exist within some regional GW systems can be established, the latter being of interest not only for their intrinsic scientific value, but also for economic exploitation. This is the case with several aquifers in Western Australia, which could be mined because of their economic value, but also have scientific value because of the large number of rare stygobitic species (Humphreys 1999; Playford 2001).

An example of the multi-criteria analysis approach to achieving a sustainable GW system is in Spain, within the Upper Guadiana Basin in the Central Meseta, which has a semi-arid climate (Fornés & Llamas 2001). A trade-off hydrological scenario is proposed to avoid conflicts between the overexploitation of the regional aquifer for irrigation purposes and the wetland conservation within the La Mancha Húmeda Biosphere Reserve. The environmental policy foresees a reduction of GW abstraction achieved by common agreement between the various local communities. This will allow an improvement of the conservation of wetland area and restore the degraded surface soil (Fornés & Llamas 2001).

At a regional, or even global, scale, the management of GW resources should be integrated within a biosphere framework. Multi-criteria analysis in this case deals with trade-offs between the management of GW and other environmental resources. For instance, in California, energy demand versus pump irrigation costs have also to be evaluated against GW shortages and aquifer depletion. It is the task of various agencies, local, national or international, to propose environmental programmes using multi-criteria analysis framed within an interdisciplinary approach.

At a global scale, we can propose an integrated policy based on the comparative analysis of different biomes or different environmental realms as well as on the various human needs (Revenga *et al.* 2000). The sustainability of global water resources implies trade-offs between different interests like those asking for enough safe drinking water, for sustainable urban and/or rural development, for food production, for human recreation and for scientific research (Scheumann & Klaphake 2001).

A practical agenda activities to alleviate the pressure on groundwater systems by 2025

One of the questions asked by environmental planners confronted with degraded GW systems is what kind of measures they should adopt for the improvement of the present situation. Following the DPSIR framework (see also Fig. 6), it is possible to offer a catalogue of responses focused on the reduction of environmental pressures on GW. We consider that between the various remedial possibilities for eliminating negative environmental drivers or restoring impacted GW systems, the reduction of the environmental pressures is, in the long term, the most realistic solution and also facilitates better protection and management of GW resources. It is also cheaper to try to reduce the sources of environmental stress acting on GW than to implement technical solutions for impacted ecological systems.

Table 10 summarizes the environmental pressures acting on GW systems. In order to alleviate them, we propose a series of measures that could help, at least until 2025, to ameliorate the state of GW systems and achieve the goal of sustaining stable GW reserves with acceptable water quality (Table 11). However, the measures can be effective only if they are integrated in a global political framework within which the control of the world's human population increase and the decrease in its common poverty can be achieved. In order to measure

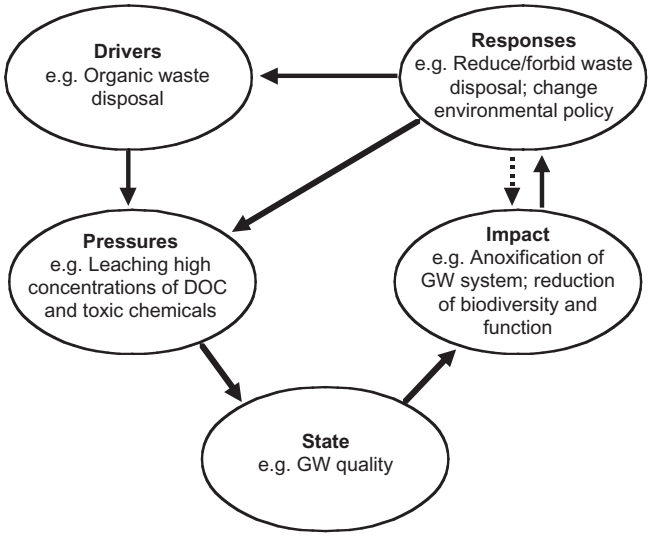


Figure 6 The DPSIR framework (arrows indicate direction of actions; continuous arrow = the best remedial/response action; dashed arrow = possible action for remediation, more expensive to implement as compared to the former action). GW = groundwater, DOC = dissolved organic carbon).

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Table 10 Summary of drivers and associated pressures on the quality and quantity of groundwater.

Drivers	*Pressures*
Human activities and infrastructure	
Agricultural practices	Leaching of pesticides, herbicides and metabolic products; accumulation of nitrate and metals from fertilizers and manure; groundwater withdrawal for irrigation
Urban and/or industrial activities	Seeping of oil products from fuel storage tanks; accumulation of salts, leakage of polycyclic organic compounds, heavy metals and other contaminants; leakage of water from sewage systems; introduction of faecal coliformes from wastewater distribution systems; rise of water demand
Waste disposal (including waste injections) and waste treatment	Direct introduction of contaminants, changes in GW physicochemical conditions; leaching of pollutants from waste-disposal sites, accumulation of particulate and dissolved organic matter and generation of reductive zones within aquifers
Infiltration of heated surface water	Changes in physicochemical conditions of GW, such as deoxygenated groundwater
Infrastructure building along rivers and/or below ground	Lowering groundwater levels and changing groundwater flows, changes in physicochemical conditions (for example, lowering the oxygen concentration)
Water extraction	Overexploitation, saltwater intrusion, upwelling of mineral rich groundwater, decline of groundwater table, changes in physicochemical conditions
Mining	Lowering groundwater levels and changing flows, changes in physicochemical conditions, pollution with mining spoils (heavy metals), infiltration of chemical contaminants (nitrate)
Tourism	Additional water demand, accumulation of waste and sewage in sensitive areas
Natural processes	
Climate changes	Changes of the intensity of water recharge and discharge; input of organic and inorganic chemicals
Surface water infiltration	Salination and nutrient enrichment of groundwater, infiltration of pollutants

Table 11 Possible activities to alleviate the pressure on groundwater systems by 2025 (for the main driving forces and pressures see Table 10).

Activities to alleviate the pressure on groundwater systems
1. Create new incentives for artificial recharge activities in both semi-arid and monsoon areas. For monsoonal regions, development of strategies to replenish the pre-monsoon draw down from enhanced recharging from rainwater. Storage development. Drought prevention through underground storage
2. Ameliorate the water distribution. For example, reduce consumption, increase the use of recycled water
3. Reduce the volume of wastewater
4. Decrease the tourism pressure in GW vulnerable areas
5. Reduce the amount of fertilizers and toxic substances use, such as pesticides
6. Use new technologies for irrigation to avoid waterlogging or intense evapotranspiration and salination problems
7. For water-stressed areas import water in form of grain (or vegetables and fruits) from water-rich regions
8. Improvement of waste treatment techniques
9. Better control of waste disposal, for example, for long-term spread of highly toxic pollutants reduce the volume of injected material; select suitable areas for dumping sites, use improved technologies for landfill construction
10. Educate people to reduce the volume of wastes
11. Find remediation treatments for contaminated areas and brown fields sites that endanger aquifers
12. Avoid mining in areas important for drinking-water purposes or in landscapes with high value for biological conservation
13. Define protection zones for GW aquifers using holistic approaches, such as aquifer basin management
14. Implement sustainable GW management, to balance water withdrawal and recharge
15. Avoid constructions along rivers that diminish the quality of the GW
16. Control the surface water quality and protect the zones of surface infiltration

these latter objectives a framework for quality of life indicators was developed and can be used in combination with environmental indicators (Smeets & Weterings 1999). It is considered (Dasgupta 2001) that the reduction of poverty and an increase in quality of life, especially in the LDCs, could widely ameliorate the efficient use and/or protection of the world's natural resources like GW.

CONCLUSIONS

(1) In the subterranean aquatic domain, water, geological substrata and organisms form complex ecosystems. Their connection to surrounding ecosystems influences their biotic structure and biogeochemical functioning. As part of the hydrological cycle, subterranean aquatic ecosystems are important for the circulation of matter and energy.

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(2) The human dimension implies that socioeconomic activities have to be considered as driving forces that contribute to changes in GW ecosystems. GW ecosystems also influence the quality of GW, a freshwater resource of utmost importance for human societies now and in the future.

(3) At the beginning of the 21st century, degradation of GW resources and ecosystems is widespread, driven by strong environmental pressures that are mainly anthropogenic. We forecast a further rise in the volume of human GW extraction and continuing deterioration of GW quality at least until 2025, unless new far-reaching environmental policies change this state of affairs.

(4) Management programmes for the protection of GW have to incorporate both socioeconomic and environmental targets. To harvest sufficient GW of good quality in the future, management programmes should unify resource sustainability and GW ecosystem integrity. The low reaction time between measures and noticeable GW resource improvements implies that quick action is needed to stop further deterioration.

(5) Human population growth and increasing poverty will continuously exert pressure on the sustainable use of GW. Without fundamental changes in the relationship between man and environment, the possibilities for sustainable GW management programmes are limited. In the developing countries especially, urgent action is needed to reduce anthropogenic threats to GW systems and policy makers should tackle this problem at grassroot level.

(6) Application of the knowledge of GW biota and their ecology in sustainable GW management should be used to provide early warning signals of functional loss of GW ecosystems, as well as for the development of new tools for ecological engineering in the subsurface domain. Possibilities are limited, however, because GW ecosystem knowledge lags behind surface water ecosystems. Hence, funding for research is needed to improve the comprehension of the structure and function of GW ecosystems in relation to various environmental conditions and anthropogenic influences.

(7) The socioeconomic targets in GW management programmes imply educational programmes for public awareness in order to help laymen and politicians to better appreciate the value of GW systems, as providers of goods and services. Educated people are in a better position to adopt sensible environmental decisions about GW reserves and ecosystems, which constitute an intergenerational capital.

(8) The subterranean environment has fascinated humans since ancient time and this cultural aspect should be actively sustained. The discovery of an exceptional biodiversity in the subterranean aquatic realm lends support to this fascination.

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