SIDE PUBLICATIONS SERIES :01

Groundwater and Global Change: Trends, Opportunities and Challenges

Jac van der Gun

UNITED NATIONS WORLD WATER ASSESSMENT PROGRAMME

United Nations Educational, Scientific and Cultural Organization
World Water Assessment Programme
UN WATER
United Nations Educational, Scientific and Cultural Organization
International Hydrological Programme
WWDR4

Published in 2012 by the United Nations Educational, Scientific and Cultural Organization
7, Place de Fontenoy, 75352 Paris 07 SP, France

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ISBN 978-92-3-001049-2

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Original concept (cover and layout design) of series: MH Design / Maro Haas

Layout: Pica Publishing LTD, London–Paris / Roberto Rossi

Printed by: UNESCO

Printed in France

Groundwater and global change:
Trends, opportunities and challenges

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Acknowledgements Alice Aureli (UNESCO-IHP), Richard Connor (UNESCO-WWAP), Michela Miletto (UNESCO-WWAP), Lucilla Minelli (UNESCO-IHP), Holger Treidel (UNESCO-IHP), Olcay Unver (UNESCO-WWAP)

Summary

Groundwater – containing by far the largest volume of unfrozen fresh water on Earth – is a hugely important natural resource. However, what the general public and most decision-makers know and understand about groundwater is usually very little. Today, knowledge of groundwater around the world, its functions and its use is increasing rapidly – and views about the many ways in which groundwater systems are linked with other systems are changing accordingly.

All around the world, groundwater is a resource in transition: its exploitation started booming only during the twentieth century ('the silent revolution'). This boom has resulted in much greater benefits from groundwater than were ever enjoyed before, but it also triggered unprecedented changes in the state of groundwater systems. On a global level, the key issues that need to be addressed to ensure the sustainability of groundwater resources are the depletion of stored groundwater (dropping water levels) and groundwater pollution. Climate change will affect groundwater, but because of its characteristic buffer capacity, groundwater is more resilient to the effects of climate change than

surface water. Therefore, in areas where climate change is expected to cause water resources to become scarcer than they are at present, the role of groundwater in water supplies is likely to become more dominant. Their buffer capacity is one of the major strengths of groundwater systems. It allows long dry periods to be bridged (creating conditions for survival in semi-arid and arid regions) and generally reduces the risk of temporary water shortages. It also smooths out variations in water quality and causes a portion of the stored water (medium-deep to deep groundwater) to be relatively insusceptible to sudden disasters, thus making this portion suitable as an emergency water source.

In terms of making a contribution to securing water availability and groundwater-related environmental values, managing groundwater resources sustainably is of vital importance to society and the environment. Nevertheless, there are situations where sustainable exploitation of groundwater is unlikely to be achieved. Such situations include, for example, cases of tapped non-renewable groundwater resources, and many of the intensely exploited renewable groundwater systems in arid and semi-arid zones. Such cases should be identified and the population of the areas concerned should be prepared in good time to adapt effectively to a future when these resources will be exhausted.

Groundwater governance is complex and needs to be tailored to local conditions. In the case of transboundary aquifer systems, the international dimension adds complexity. International cooperation and a wide range of international initiatives produce significant added value. This cooperation is instrumental in enhancing and disseminating information about groundwater, in developing and promoting approaches and tools for its proper management, and in raising global commitment for action on priority issues, such as the millennium development goals (MDGs) and sustainable development. Ensuring that groundwater is adequately incorporated into such global actions is a challenge for all groundwater professionals.

Table of Contents

SUMMARY i
1. GROUNDWATER IN A WEB OF INTERDEPENDENCIES 3
2. PANORAMA OF CHANGE 4
3. KEY ISSUES RELATED TO GROUNDWATER 12
4. CONCLUSIONS 31
REFERENCES 33

1 Groundwater in a web of interdependencies

In our rapidly changing world where there are many challenges regarding water, it is necessary to pay ample attention to groundwater and its role in securing water supplies and in coping with water-related risk and uncertainty. However, focusing on groundwater certainly does not imply that groundwater systems are self-contained, or that they can be understood and managed on the basis of hydrogeological information only. On the contrary, it cannot be overemphasized that groundwater is one component in the hydrological cycle – a component that interacts closely with other components in the cycle at various temporal and spatial levels. Groundwater is also involved in a number of other cycles – such as chemical cycles (solute transport) and biochemical cycles (biosphere) – and it is affected by climate change caused by changes in the carbon cycle. In addition, groundwater interactions and interdependencies are not limited to physical systems, such as surface waters, soils, ecosystems, oceans, lithosphere and atmosphere, but are also related to socio-economic, legal, institutional and political systems. Hence, groundwater is entrenched in a web of interdependencies. Changes in the state of groundwater systems are taking place due to these interdependencies, and causal chains link these changes to the drivers of change (root causes).

Different categories of drivers are behind the processes of change in groundwater systems. *Demographic drivers* include population growth, mobility and urbanization. Population growth leads to increasing demands for water and food and to bigger loads of waste and wastewater being discharged into the environment. Expanding urbanization and shifts in land-use patterns modify these pressures. The same is true for *socio-economic drivers* – to a large extent, they explain people's demands and behaviour with respect to groundwater. Intensive groundwater exploitation may be triggered by positive expectations on the economic profitability of groundwater, and by socio-economic conditions that allow the exploitation of this resource. Higher levels of social and economic development enable societies to adapt more easily to changing conditions (for example, by making the transition to a less water-dependent economy if water becomes scarce), and to pay more attention to sustainability. *Science and technological innovation* are other drivers that have put their mark on the utilization and state of many groundwater systems. For example, systematic aquifer exploration and improved technologies for drilling and pumping have contributed significantly to generating greater benefits from groundwater. But at the same time, the resulting intensive pumping has often increased stresses on groundwater systems, on related ecosystems and on the environment. Science – assisted by technical innovations in fields such as water use, water treatment and water-reuse – helps to define ways of controlling unintended negative impacts. *Policy, law and finance form* an important category of drivers of planned change, in the context of groundwater resources development and management. Finally, there are two categories of physical drivers. The first is *climate variability and climate change* – particularly as they affect aquifers in arid and semi-arid regions. Minor variations in climatic conditions there can have a pronounced influence on groundwater in three main ways: a change in the rate of groundwater renewal, a change in the availability of alternative sources of fresh water and a change in water demand. Climate change is also expected to contribute to sea level rise, which will affect aquifers in low-lying coastal zones, where a large percentage of the world's population lives. The second category of physical drivers is *natural and anthropogenic hazards*. This is different from other categories of drivers in the sense that hazards are strongly probabilistic (disasters may or may not happen), and usually cause a sudden change rather than a trend over time.

2 Panorama of change

2.1 Increasing our knowledge of the world's groundwater

In recent years, there have been significant advances in what we know about the world's groundwater resources. While these advances can be observed at all levels, the focus here is on the global and regional levels. There has been remarkable progress in many areas, including the global-level characterization of groundwater systems, their properties and their conditions. Important recent achievements include:

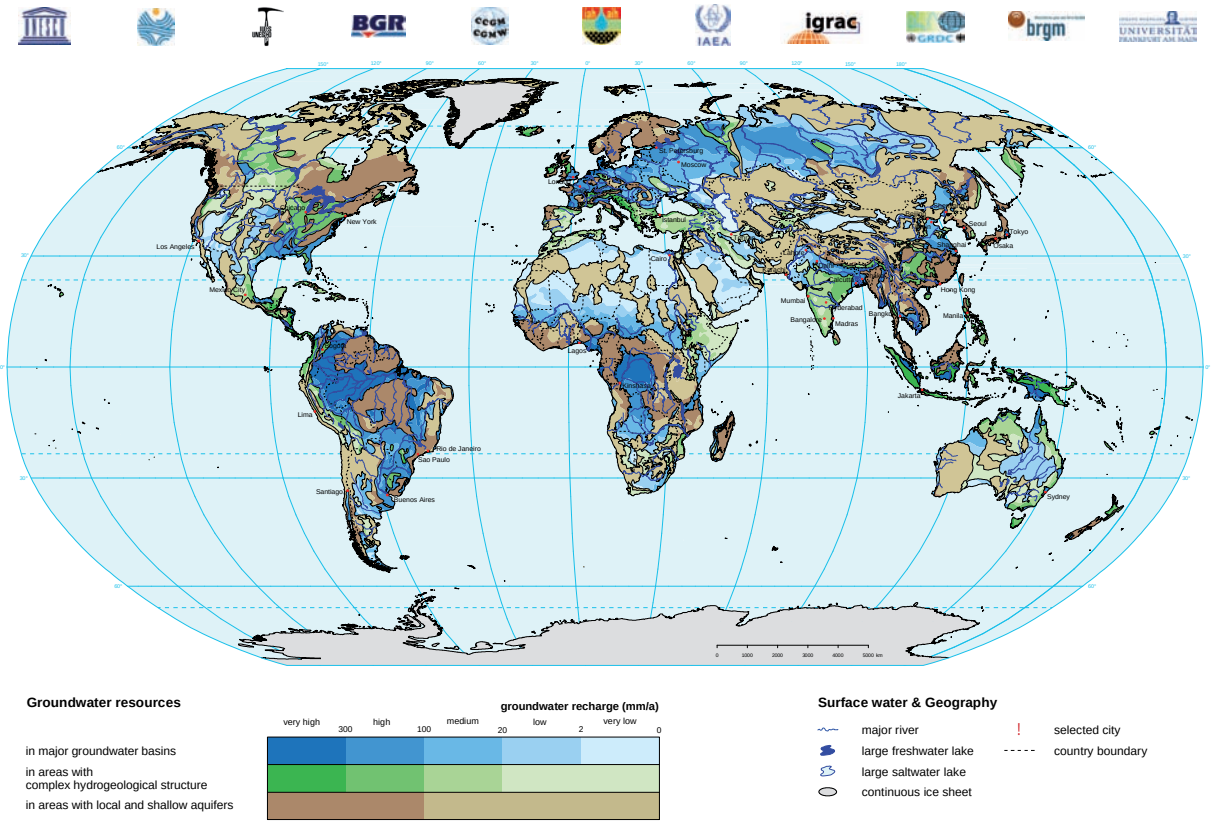
- the consolidated version of the Groundwater Resources Map of the World under the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP, 2008) (Figure 1);
- the outcomes of global-scale hydrological modelling, such as that on worldwide groundwater recharge with WaterGAP Global Hydrological Model (Döll and Fiedler, 2008) and with PCR-GLOBWB (Wada et al., 2010);
- a global assessment of current groundwater use for irrigation (Siebert et al., 2010);
- a comprehensive monograph on the geography of the world's groundwater (Margat, 2008).
- rapidly increasing documentation and tools on transboundary aquifers, resulting from numerous projects (see section 3.5).

The total volume of fresh groundwater stored on earth is believed to be in the region of 8 million km^3 to 10 million km^3 (Margat, 2008), which is more than two thousand times the current annual withdrawal of surface water and groundwater combined. This is a huge volume, but where are these fresh-water buffers located – and what fraction of their stock is available for depletion? Figure 1 answers the first question by showing the geographic distribution of the world's major groundwater basins (shown in blue on the map – and covering 36% of the land area of the continents). This is where the main groundwater buffers are located. Additional ones, which are less continuous and smaller, are present in areas with complex hydrogeological structures (shown in green on the map – and covering 18% of the total area). And further, to a lesser extent, are groundwater reserves present in the remaining 46% of the land area of the continents (shown in brown on the map).

The groundwater buffers allow periodic, seasonal or multi-annual dry periods to be bridged conveniently without the risk of sudden unexpected water shortages. In large parts of the world, sustainable groundwater development is possible by alternating storage depletion

FIGURE 1

Simplified version of the Groundwater Resources Map of the World (WHYMAP, 2008)



during dry periods and storage recovery during wet periods. Groundwater reservoirs are rather insensitive to variations in the length of the dry periods, and therefore resilient to this aspect of climate variation and climate change. In principle it is possible to ignore the sustainability criterion and exploit a large part of the stored groundwater volumes, but in practice it is difficult to do so and often not attractive, because depletion comes at a cost, (see Section 3).

Recent outcomes of the Gravity Recovery and Climate Experiment (GRACE) mark a major step forward in assessing groundwater storage variations in some of the world's major aquifer systems (Famiglietti et al., 2009; Rodell et al., 2009; Tiwari et al., 2009; Muskett and Romanovsky, 2009; Moiwo et al., 2009; Bonsor et al., 2010; Chen et al., 2009). The results of the experiment suggest that satellite mapping of the Earth's gravity field (satellite gravimetry) is a promising innovative technique that can be used in hydrogeological investigations in the near future.[1] It can be used for monitoring long-term trends, seasonal variations and change during droughts. Global simulation models that link the terrestrial and atmospheric components of the hydrological cycle are likely to become another important tool for enhancing our knowledge of groundwater regimes, in particular for exploring how they may respond to climate change (Döll, 2009).

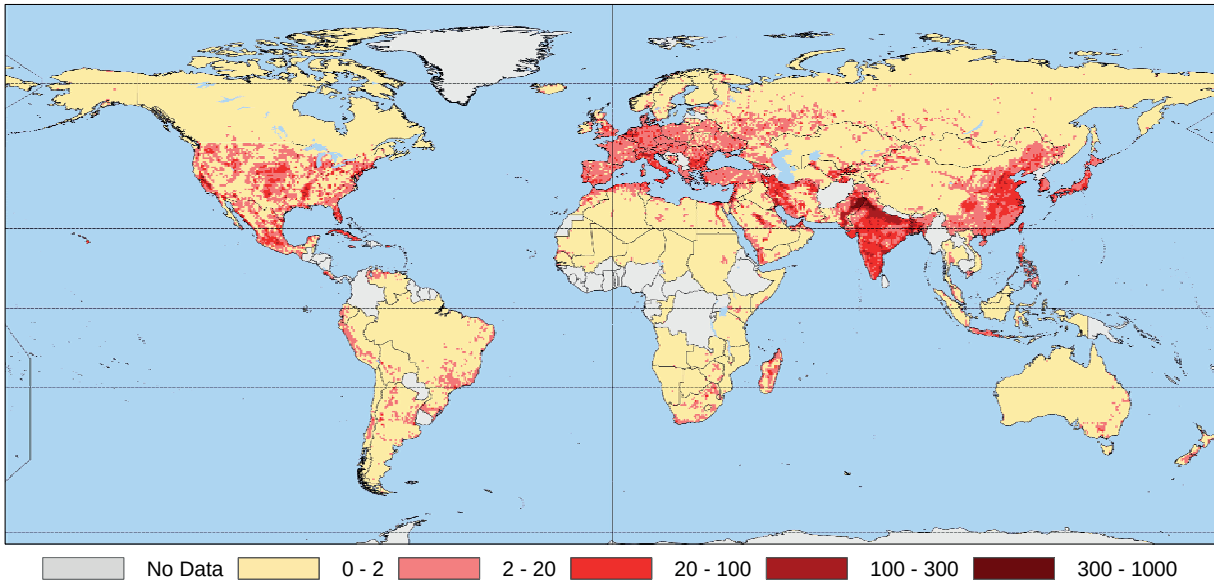
2.2 The silent revolution

During the twentieth century, groundwater abstraction across the world increased explosively. This was driven by population growth, technological and scientific progress, economic development and the need for food and income. By far the largest share of the additional volumes of water that have been abstracted has been allocated to irrigated agriculture. The boom in groundwater development for irrigation started in Italy, Mexico, Spain and the United States as far back as the early part of the century (Shah et al., 2007). A second wave began in South Asia, parts of the North China Plain, parts of the Middle East and in northern Africa during the 1970s, and this still continues today. The cited authors perceive a third wave of increasing abstractions in many regions of Africa, and in some countries such as Sri Lanka and Vietnam. This worldwide boom in groundwater abstraction is largely the result of numerous individual decisions by farmers – decisions made without centralized planning or coordination. It has been called the silent

1 In June 2010, NASA and the German Aerospace Centre (DLR) signed an agreement to continue the current GRACE mission through 2015 (http://www.jpl.nasa.gov/news/news.cfm?release=2010-195).

FIGURE 2

Intensity of groundwater abstraction by the year 2000, as allocated to 0.5° x 0.5° grid cells by the PCR-GLOBWB model, in mm/year



Source: Wada et al. 2010. ©2010 American Geophysical Union. Reproduced by permission of the American Geophysical Union.

revolution (Llamas and Martínez-Santos, 2005; Llamas and Martínez-Cortina; 2009).

Groundwater abstraction is very unevenly distributed across the globe. It differs not only from country to country, but also shows pronounced spatial variation within countries, as can be observed in Figure 2. Based on recent estimates at country level (IGRAC,2010; Margat; 2008; Siebert et al., 2010, AQUASTAT, n.d.; EUROSTAT, n.d.), the world's aggregated groundwater abstraction as per 2010 is estimated to be approximately 1,000 km^3 per year, of which about 67% is used for irrigation, 22% for domestic purposes and 11% for industry (IGRAC, 2010)[2]. Two-thirds of this is abstracted in Asia, with India, China, Pakistan, Iran and Bangladesh as the major consumers (see Table 1 and Table 2). The global groundwater abstraction rate has at least tripled over the last 50 years and still is increasing at an annual rate of between 1% and 2%.

Nevertheless, in some countries where intensive groundwater development started rather early, abstraction rates have peaked and are now stable, or even decreasing (Shah et al., 2007), as is illustrated in Figure 3. Although the global estimates are not accurate, they suggest that the current global abstraction of groundwater represents approximately 26% of total freshwater withdrawal globally (Table 2), and that its rate of abstraction corresponds to some 8% of the mean globally aggregated rate of groundwater recharge. Groundwater supplies almost half of all drinking water in the world (UNESCO-WWAP, 2009), and 43% of the global consumptive use in irrigation[3] (Siebert et al., 2010).

The silent revolution has contributed tremendously to economic development and welfare in many countries, especially in rural areas. Nevertheless, it has also introduced unprecedented problems that are difficult to control in some areas (see Section 3).

2.3 Changing views on groundwater

Groundwater has become an interdisciplinary subject. Professionally, it is no longer the almost exclusive domain of hydrogeologists and engineers; it is also receiving a good deal of attention from economists, sociologists, ecologists, climatologists, lawyers, institutional experts, communication specialists and others. Analysing groundwater from these different perspectives puts it in a wider context, resulting in changing views on this natural resource.

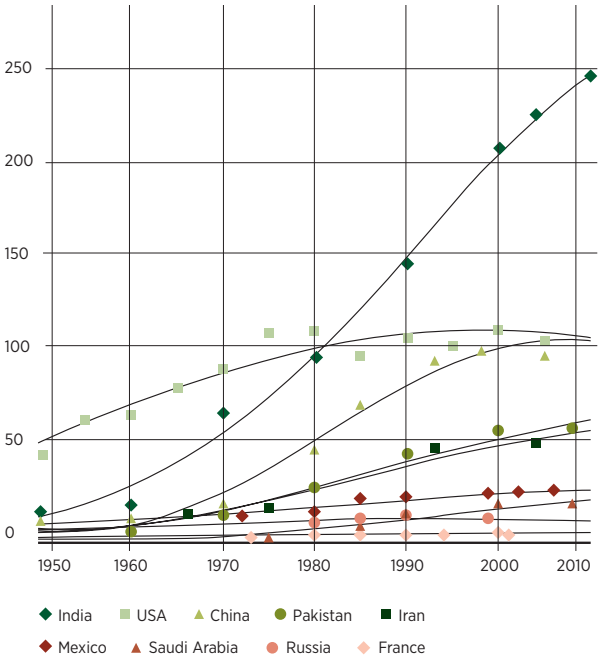
Changing views can be observed in the first instance in relation to the *functions and value of groundwater*. Measuring the importance of groundwater by comparing its recharge rate, withdrawal and stored volume to those of surface water is gradually being replaced by more economically and/or ecologically oriented valuing

2 Almost all values mentioned in this paragraph are globally aggregated or averaged, and thus cannot be used to draw conclusions about conditions at a local or regional level.

3 Siebert et al. (2010) estimate global consumptive irrigation water use to be 1,277 km^3 per year - or 48% of global agricultural water withdrawals. Their estimate for the share of groundwater in this figure is 545 km^3 per year, which is fairly consistent with the estimated global groundwater abstraction for irrigation, taking into account irrigation water losses.

FIGURE 3

Groundwater abstraction trends in selected countries (in km³/year, based on Margat, 2008, with modifications)



Source: Adapted from Margat (2 008, fig. 4.6, p. 107).

Table 1

Top ten groundwater abstracting countries (as per 2010)

COUNTRY	ABSTRACTION (km³/year)
1. India	251
2. China	112
3. USA	112
4. Pakistan	64
5. Iran	60
6. Bangladesh	35
7. Mexico	29
8. Saudi Arabia	23
9. Indonesia	14
10. Italy	14

Table 2

Key estimates of global groundwater abstraction (reference year: 2010)

CONTINENT	GROUNDWATER ABSTRACTION *					COMPARED TO TOTAL WATER ABSTRACTION	
	Irrigation km³/yr	Domestic km³/yr	Industrial km³/yr	Total km³/yr	%	Total water abstraction** km³/yr	Share of ground-water %
NORTH AMERICA	99	26	18	143	15	524	27
CENTRAL AMERICA AND THE CARIBBEAN	5	7	2	14	1	149	9
SOUTH AMERICA	12	8	6	26	3	182	14
EUROPE (INCLUDING RUSSIAN FEDERATION)	23	37	16	76	8	497	15
AFRICA	27	15	2	44	4	196	23
ASIA	497	116	63	676	68	2257	30
OCEANIA	4	2	1	7	1	26	25
WORLD	**666**	**212**	**108**	**986**	**100**	**3831**	**26**

* Estimated on the basis of IGRAC (2010), AQUASTAT (n.d), EUROSTAT (n.d.), Margat (2008) and Siebert et al. (2010).

**Average of the 1995 and 2025 'business as usual scenario' estimates presented by Alcamo et al. (2003).

approaches that are focused on 'added value' produced by groundwater. For example, studies in Spain (Llamas and Garrido, 2007) and India (Shah, 2007) have shown that when compared to surface water, groundwater produces higher economic returns per unit of water used in irrigation. The explanation is that groundwater usually presents considerably less water shortage risk than does surface water, as a result of the buffer capacity of its relatively large stored volume. Consequently, groundwater's share in the overall socio-economic benefit derived from abstracted water tends to be higher than its volumetric share in total water abstraction. Although groundwater quantity is still often assessed in terms of recharge and/or discharge rates only, it is clear that the volumes of stored groundwater are equally relevant in the assessment of this 'stock-and-flow' resource. Stored groundwater enables the functions or services of a groundwater system to go beyond the withdrawal of water for direct consumptive and productive use (provisioning services) and to include a number of *in situ* services (mostly regulatory services) as well. One of these *in situ* services is the reservoir function of groundwater systems, which allows dry periods to be bridged and – at a very large time scales – non-renewable groundwater to be available in areas where groundwater recharge is currently negligible (Foster and Loucks, 2006). Other *in situ* services are the support of ecosystems and phreatophytic agriculture, the maintenance of spring flows and base flows, the prevention of land subsidence and seawater intrusion, and the potential for exploiting geothermal energy or storing heat. All withdrawal and *in situ* services contribute to the value of a groundwater system and should be taken into account in groundwater resources management.

A second category of changing views refers to the *role of people*. Not long ago, the diagnostic analysis and management of groundwater resources tended to be based almost exclusively on an analysis of the physical components (groundwater systems and related ecosystems). There is broad consensus nowadays that socio-economic aspects deserve a share of the attention as well, preferably coupled with the physical components – for example, in a socio-ecological systems approach similar to the ecosystem approach adopted by the Convention for Biological Diversity in 1995 (Convention on Biological Diversity, n.d.). Groundwater resources management is likely to be successful only if stakeholders are cooperating fully. This is because the majority of groundwater management measures aim to influence or change people's behaviour. In addition, people may be better prepared to adapt to climate change and climate variability if they are aware of groundwater's potential to help them do so. Correspondingly, substantial efforts are made in many parts of the world to draft new groundwater legislation and related regulatory frameworks, to raise awareness of groundwater issues among stakeholders and to involve stakeholders in the management of their groundwater resources.

The debate on climate change has made it clear that hydrogeologists and hydrologists have to abandon their traditional implicit *assumption of the stochastic stationarity* of natural hydrological flow rates. The assumption that groundwater recharge rates assessed in the past would provide an unbiased estimate for future conditions is no longer appropriate. This makes a difference for actively recharged phreatic aquifers in particular – especially when they are shallow – and less of a difference for deep confined aquifers, which tend to react more smoothly to climatic variations because of their lower recharge rates and higher volumes in storage. It does not play a role in the case of non-renewable groundwater resources. Finally, there is a growing recognition of groundwater's relatively high resilience to climate change and climate variability. This special characteristic leads to the prediction that groundwater will play an important role in human adaptation to climate change (see Section 3.3).

2.4 Conjunctive management, integrated water resources management and beyond

The time when groundwater used to be explored and exploited as an isolated resource is long past. Although the advantages of using groundwater and surface water in combination were recognized at least as far back as the 1950s (Todd, 1959), the notion of joint management of these resources has been embraced much more recently. Under this paradigm, water resources are not only used but also *managed* as components of a single system. This generally leads to greater flexibility in water use, improved water security, cheaper water supply and more efficient use of available water resources – all of which together contribute to greater total benefits.

An interesting feature of conjunctive management is managed aquifer recharge (MAR), the intentional storage of water in aquifers for subsequent recovery or environmental benefit. It makes use of a variety of techniques and is being applied in countless small and large schemes around the world (Dillon et al., 2009). Box 1 provides an example of a proposed MAR application in Namibia. In the case presented in Box 2, the conjunctive management of groundwater and surface water does not focus primarily on water as an extractable resource, but rather on how to maintain environmentally optimal groundwater levels, which is widely practised in the Netherlands.

The next step is integration across water use sectors, as advocated by integrated water resources management (IWRM). The Global Water Partnership (GWP, n.d.) defines IWRM as the coordinated development and management of water, land and related resources, in order to maximize economic and social welfare without compromising the sustainability of ecosystems and the environment. In many countries, this cross-sectoral approach to water has replaced traditional, fragmented sectoral approaches that ignored the interconnection between the various water uses and services. Tendencies can be observed (for example,

Box 1: Water augmentation to Central Areas of Namibia through managed aquifer recharge

Namibia is the most arid country in sub-Saharan Africa, and it is largely dependent on groundwater. Perennial rivers are found only on the northern and southern borders, at a considerable distance from the major demand centres in the Central Areas of Namibia, including the capital city, Windhoek. Dams on the ephemeral rivers provide the main source of water for the country's more urbanized central regions. Inflow into these dams is irregular and unreliable, and evaporation rates in Namibia's arid climate are high. As a result, the assured safe yield of these dams is low. The region's growing demand for water will, in the near future, result in existing water resources not being able the meet expected demand in a sustainable way.

The best option for alternative water supply augmentation to the Central Areas of Namibia was found to be the creation of a water bank through managed aquifer recharge of the Windhoek Fractured Rock Aquifer, in combination with deep boreholes, to increase the access to a larger volume of stored reserves. This managed aquifer recharge option involves taking water (when a surplus is available) from the three-dam system on which the city relies, purifying it and injecting it into the Windhoek Aquifer via the boreholes. This reduces evaporation losses at the dams. In years when the surface sources are insufficient, the stored underground water can be abstracted. Securing water supply through managed aquifer recharge must be fast tracked as water shortages and non-availability in times of drought will have a devastating effect on the economy. Windhoek contributes approximately 50% of the N$5.26 billion manufactured goods (excluding fish processing on shore), and the closure of industry due to non-availability of water would result in a N$2.63 billion loss per year to Namibia (based on the 2006 Gross Domestic Product).

Windhoek owes its existence to the presence of springs, which provided an ample supply of water when settlement began. A well field was later established and, as the city grew, storage dams were built within the ephemeral rivers. Windhoek currently obtains its water from a three-dam system, a wastewater reclamation plant within the city, and from groundwater in a municipal well field. When the three dams are operated on an individual basis, the 95% safe yield is only 17 Mm^3 per year, mainly as a result of huge evaporation losses from the Omatako and Swakoppoort dams. Through integrated use of the three dams, water is transferred and stored in Von Bach dam, which has the lowest evaporation rate due to the dam basin characteristics.

This operating procedure improves the 95% safe yield from the three-dam system to 20 Mm^3 per year. It is forecast that annual water demand will increase from the current level of 25 Mm^3 to approximately 40 Mm^3 in 2021.

For additional water supplies to the Central Areas of Namibia, three main development options include:

- Managed recharge of the Windhoek Aquifer (using surplus water from the Central Area dams to increase underground reserves);
- Karst aquifers used only for emergency supply; and
- a pipeline link from the Okavango River to supply the Central Areas when required (see Figure).

Managed aquifer recharge is the preferred option. Over-abstraction of the Windhoek Aquifer since 1950 has created an underground storage facility estimated at 21 Mm^3 which can be filled through natural and artificial recharge. The total estimated storage that can be abstracted from existing boreholes is approximately 15 Mm^3, giving a total usable storage (water bank) of 36 Mm^3. Through the drilling of deep abstraction boreholes the size of the water bank will be increased to approximately 66 Mm^3, which can bridge 2.5 years of Windhoek's water demand (2010).

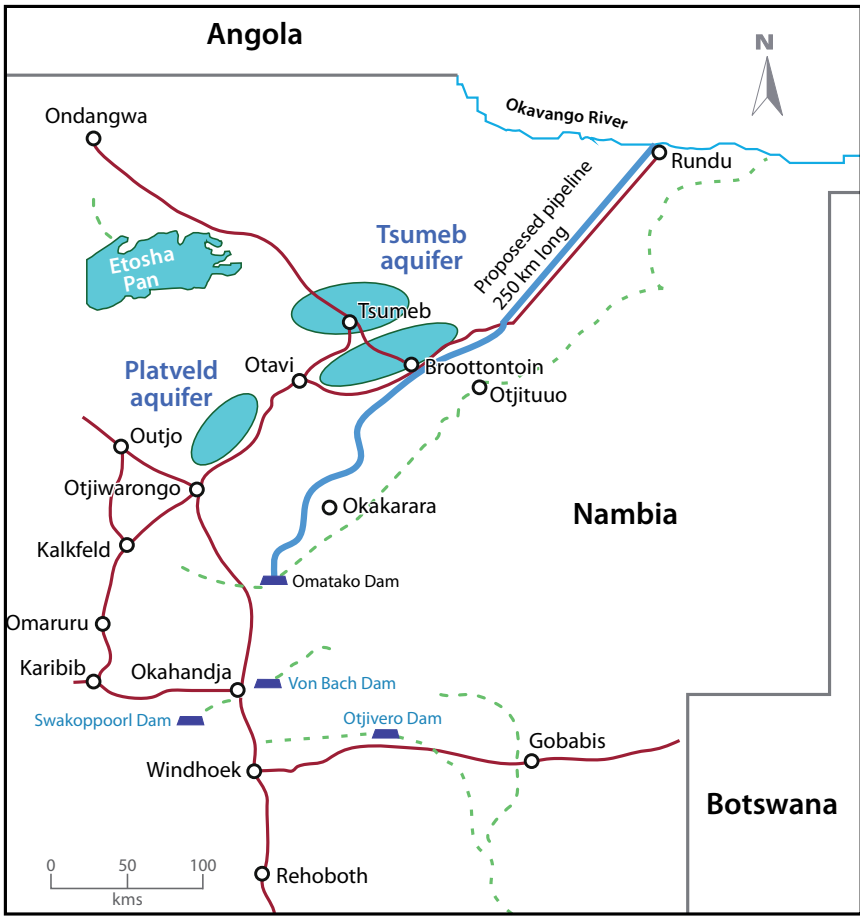
Contribution from Greg Christelis.

Consumption 2010: 25Mm^3

Cost of Water (2011)

Windhoek supplies	N$/$m^3$
Ground water	5.65
Surface water	7.20
Reclaimed	9.50
Re-use	5.70
Additional supplies	
Okavango pipeline	285.00
Karstic aquifer	34.20
Managed Aquifer Recharge (MAR)	16.10

Figure: Water supply to Windhoek and relevant cost



Source: Figure prepared by Greg Christelis

in the Netherlands) towards a higher level of integration in area-specific strategic planning – with the end of establishing more cohesion between policy domains such as water resources management, land use planning, nature conservation, environmental management and economic development. Other recent responses to complexity and uncertainty in water resources management are the adoption of adaptive management approaches and a stronger focus on the many dimensions of water governance.

2.5 Increasing international focus on groundwater

Groundwater, which is a local natural resource that produces mainly local benefits, is becoming more and more the subject of initiatives at the international level. Initiatives such as the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP), the International Groundwater Resources Assessment Centre (IGRAC), the Groundwater Management Advisory Team (GW-MATE), the International Waters Learning Exchange

Box 2: Water level control in the lower parts of the Netherlands: Evolution and innovation in the conjunctive management of groundwater and surface water

The control of water levels has been practised for almost a thousand years in the flat low-lying parts of the Netherlands. To make them suitable for human occupation, these vast, swampy lowlands were drained of excess water and the reclaimed land was protected against flooding. Drainage was enabled by the construction of embankments, artificial discharge structures and dense networks of ditches and canals. Over the centuries the Netherlands' water boards managed to acquire the correct equipment and develop the necessary skills for controlling the water levels in these open water courses. The areas that are under control in this way are known as 'polders'. It took some time before people became aware that controlling the surface water levels here implicitly means controlling the groundwater levels in the underlying aquifers as well. This is because of the strong hydraulic interconnection between the surface water and groundwater systems.

So, water level control in these polders can be considered to be an early form of *conjunctive management* of groundwater and surface water. Originally, the main purpose was defensive in nature: protection against flooding and preventing waterlogging on or near the ground surface. However, it was soon learned that the productivity of pasture-land and arable lands in these polders depends not only on adequate drainage, but also benefits from shallow groundwater tables close to the root zone. In this context, variations in groundwater level in the order of tens of centimetres, or even less, *do* matter. The physical infrastructure of canals, ditches and sluices allows the retention of water that has been generated inside the polder (autochtonous water) during the relatively dry summer period and – if needed – allows to supply water from outside (allochtonous water). Consequently, water management in the polders has evolved into an activity of controlling surface water and groundwater levels within strict ranges. In practice, for each canal section or system of ditches, two target water levels – a winter level and a summer level – were defined and maintained. These winter and summer levels were empirically defined as a best compromise between avoiding excess water and preventing harmful declines of groundwater levels.

Until recent decades, the water boards controlled the water levels rather independently, without much coordination with other government institutions in charge of spatial planning, strategic water management, public water supply, licensing groundwater abstractions, water quality management, nature conservation or other tasks related to the physical environment. This has changed gradually but significantly. In addition, the totally separate 'water quantity' water boards and 'water quality' water boards have been merged, which means that water quantity and water quality tasks are now under one roof. The tradition of discharging excess water as quickly as possible has been replaced by a new paradigm: 'first retain, then store, and after this, discharge only if needed'. This minimizes the movement of water and reduces water quality variations caused by allochtonous water.

Nowadays, water management in the Netherlands is closely linked to spatial planning, which implies that the land use functions of areas and sub-areas (urban areas, different types of agricultural area, aquatic and terrestrial nature, etc.) are a point of departure for defining a desired regime of groundwater and surface water levels. A new methodology – called 'Waternood' – has been developed to replace the empirical 'winter level' and 'summer level' by new target water levels defined on the basis of an optimization procedure that minimizes the impacts of violating the optimal water level regime for each of the functions assigned within the area. This methodology strengthens the cohesion between water level control and outcomes of spatial planning and groundwater abstraction licensing. The incorporation of simulation models allows future conditions to be taken into account, which, by definition, is impossible using the traditional empirical approaches.

Sources: Van de Ven (1993); Van der Wal and Helmyr (2003); Kuks (2002); Mostert (2006).

and Resource Network (IWLEARN), the Internationally Shared Aquifers Resources Management Programme (ISARM) and global hydrological modelling are based on the idea that exchanging, sharing, compiling and analysing area-specific information on groundwater contribute to the dissemination of knowledge and produce added value by providing views at a higher level of spatial aggregation. Several international initiatives are triggering or guiding action in the field of groundwater assessment, monitoring and management. Examples not specific to groundwater are the Millennium Development Goals (MDGs) and the European Water Framework Directive (WFD). Recent groundwater-specific initiatives in this category are transboundary aquifer projects in the International Waters (IW) portfolio of the Global Environment Facility (GEF), the new European Groundwater Directive as a 'daughter directive' of the WFD, the Draft Articles on the Law of Transboundary Aquifers and the establishment of the African Groundwater Commission (Box 3). Several recent international declarations, including the Alicante Declaration (IGME, 2006) and the African Groundwater Declaration (see Box 3) demonstrate a growing awareness of the relevance of groundwater and the willingness to address it.

Box 3: The African Groundwater Commission

At its sixth Ordinary Session in Brazzaville in May 2007, the African Ministerial Council on Water (AMCOW) adopted a number of key groundwater resolutions. In particular, it resolved that AMCOW would become the custodian of a continent-wide strategic groundwater initiative. As a result of these groundwater-related decisions and subsequent outcomes of the informal executive committee meeting held in Stockholm, in August 2007, the president of AMCOW requested UN-Water/Africa, in collaboration with the Government of Kenya, to organize a working session of experts and representatives of the AMCOW executive committee and the technical advisory committee. The brief was to prepare a proposal to establish the African Groundwater Commission (AGWC) for government consideration. Based on proposals made at this meeting, the AMCOW executive committee decided to establish a commission on groundwater management in Africa that would operate as an autonomous body reporting to the executive committee on a regular basis.

A roadmap of the constitution and functioning of an AGWC was launched at the First African Water Week in Tunis, in March 2008. This strategic step was also endorsed in the Head of States and Government Declaration during the AU Summit in Sharm El-Sheikh, Egypt in July of the same year. Its declared mission was, 'to strengthen AMCOW's initiative on sustainable management of water resources to implement its roadmap for the African Groundwater Commission.'

The first official meeting of the AGWC took place during the third African Water Week in Addis Ababa in November 2010, under the chairmanship of Omar Salem (Libya). The Commission's role was to provide strategic direction, facilitation and coordination of initiatives in Africa, and ongoing awareness raising.

The needs identified for the way forward were:

- the mapping of current activities and groundwater resources on a sub-regional basis;
- the securing of initial funding and the forging of links with major existing strategies (RWSSI, ISARM, climate change, IWRM plans);
- the establishment of focal points at country level;
- the establishment of task teams for specific outcomes (implementation committees); and
- the development of a communication strategy.

Contribution from Alexandros Makarigakis.

3 Key issues related to groundwater

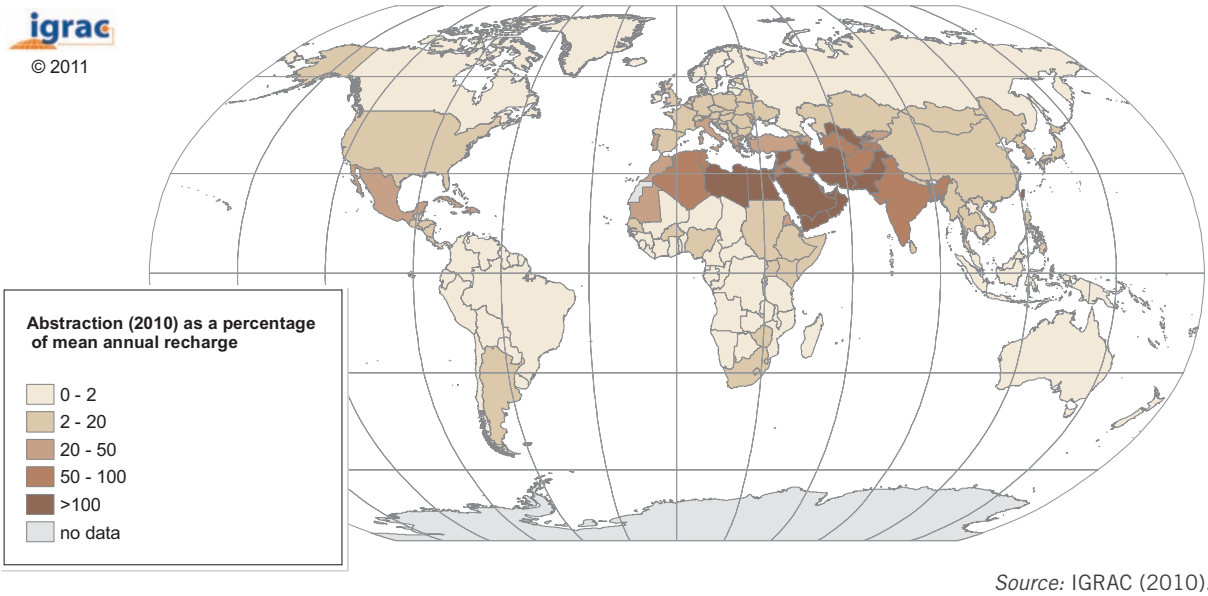
3.1 Falling groundwater levels and storage depletion

The silent revolution caused an unprecedented increase in groundwater withdrawal across the globe. It has produced and is still producing enormous socio-economic benefits around the world, but not without drastically modifying the hydrogeological regimes of many aquifers, particularly those that are recharged at a relatively modest rate, or not at all. The stress placed on groundwater systems by groundwater abstraction builds up when the ratio of abstraction to mean recharge increases. Figure 3 gives an impression of the geographical variation of the *groundwater development stress indicator*. The greatest stress evidently occurs in the more arid parts of the world. Because the groundwater development stress indicator shown here is averaged over entire countries, it cannot show stressed aquifer systems that are much smaller in size. As a result of intensive groundwater development, steady depletion of groundwater storage, accompanied by continuously declining groundwater levels, has spread over significant sections of the earth's arid and semi-arid zones. This produces a wide range of problems (Van der Gun and Lipponen, 2010), and in many areas a lack of control threatens to result in a complete loss of the groundwater resource as an affordable source for irrigation and domestic water supply in the long run. In the more seriously affected aquifer zones, multi-annual groundwater level declines are typically in the range of one to several metres per year (Margat, 2008).

Prominent aquifers that are characterized by very significant long-term groundwater level declines are almost all located in arid and semi-arid zones. In North America, they include the Californian Central Valley (Famiglietti et al., 2009) and the High Plains aquifer (McGuire, 2009; Sophocleus, 2010) as well as many aquifers scattered across Mexico, including the Basin of Mexico aquifer (Carrera-Hernández and Gaskin, 2007). In Europe, the following aquifers (all of which belong to Spain) should be mentioned: the aquifers of the Upper Guadiana basin, the Segura basin aquifers and the volcanic rocks of Gran Canaria and Tenerife. (Custodio, 2002; Llamas and Custodio, 2003; Molinero et al.,

FIGURE 4

Groundwater development stress indicator at country-level (based on groundwater abstraction estimates for 2010



Source: IGRAC (2010).

2008). Various zones in the huge non-renewable North-Western Sahara Aquifer System (Mamou et al., 2006; OSS, 2008) and the Nubian Sandstone Aquifer System in North Africa (Bakhbakhi, 2006) are affected by significant reductions in groundwater levels. On the Arabian Peninsula, there are unprecedented trends of strongly declining groundwater levels in the Tertiary aquifer system of the Arabian Platform, mainly in Saudi Arabia (Abderrahman, 2006; Brown, 2011) and in the Yemen Highland basins (Van der Gun et al., 1995). Further east, the Varamin, Zarand and many other mountain basins in Iran suffer from steadily declining groundwater levels (Vali-Khodjeini, 1995; Motagh et al., 2008), as do parts of the extensive aquifer systems of the Indus basin, especially in the Indian states of Rajasthan, Gujarat, Punjab, Haryana and Delhi (Rodell et al., 2009; Centre for Water Policy, 2005). The North China Plain aquifer has become notorious for its severe drop in groundwater levels (Jia and You, 2010; Kendy et al., 2004; Sakura et al., 2003; Liu et al., 2001; Endersbee, 2006). Finally, continuous groundwater outflow through numerous artesian wells has produced groundwater level declines in excess of 100 m in some zones of the Australian Great Artesian Basin (Habermehl, 2006). In addition to these documented examples, there are numerous other aquifers around the world where groundwater levels have declined or are still declining, with variable impacts on society and the environment.

Over the past few years, more information has become available on the magnitude of groundwater storage depletion. Konikow and Kendy (2005) draw attention to excessive groundwater depletion in several parts of the world and refer to it as a global problem. They estimate that about 700 km^3 to 800 km^3 of groundwater was depleted from aquifers in the United States during the twentieth century. One of the best documented cases is the 450,000 km^2 High Plains aquifer system, where the net amount of water removed from storage during the twentieth century was around 243 km^3 – a reduction of about 6% in the pre-development volume of water held in storage. Konikow and Kendy suggest that the most important impacts of groundwater depletion are not so much a lack of stored groundwater, but an increase in the cost of groundwater (as a result of larger pumping lifts), induced salinity and other water quality changes, land subsidence, reduced baseflows and other environmental impacts. They also conclude that, worldwide, the magnitude of groundwater depletion may be so large that it constitutes a measurable contributor to sea level rise. GRACE's recent assessments of the massive groundwater storage depletion observed in California's Central Valley and in north-west India have produced groundwater storage depletion estimates for some large groundwater systems (Rodell et al., 2009; Famiglietti et al., 2009; Tiwari et al., 2009). These estimates are shown in Table 3, together with estimated depletion rates for some of the other large aquifer systems around the world.

In a 2011 paper, Konikow presented an improved estimate for groundwater depletion in the United States during the twentieth century (799 km^3).This is based on comprehensive information regarding 41 aquifers and sub-areas. Using these estimates, along with depletion data for five large groundwater systems outside the United States and estimates of global groundwater abstraction, he estimates the global net groundwater depletion during the century to be around 3,400 km^3, and for the period 1900 to 2008, he puts the figure

Table 3

Groundwater depletion rates in selected large aquifer systems

AQUIFER OR REGION	LATERAL EXTENT	RATE OF DEPLETION (IN RECENT YEARS)		PERIOD OR YEAR	REFERENCE
	KM²	KM³/YR	MM/YR WATER*)		
RENEWABLE GROUNDWATER					
HIGH PLAINS, USA	483,844	12.4	26	2000–2007	McGuire, 2003;2009
CENTRAL VALLEY, CALIFORNIA	58,000	3.7	64	2003–2009	Famiglietti et al., 2009
NW INDIA	438,000	17.7	40	2003–2009	Rodell et al., 2009
NORTHERN INDIA & SURROUNDINGS	2,700,000	54	20	2003–2009	Tiwari et al., 2009
NORTH CHINA PLAIN	131,000	6.12	47	2004	Jia and You, 2010
NON-RENEWABLE GROUNDWATER					
NUBIAN SANDSTONE AQUIFER SYSTEM	2,200,000	2.36	~1	2001–2008	Bakhbakhi, 2006; Konikow, 2011
NW SAHARA AQUIFER SYSTEM	1,019,000	1.5	~1	2000	Margat, 2008
SAUDI ARABIA PLATFORM AQUIFERS	1,485,000	13.6	9.2	2001-2008	Abdurrahman, 2006; Konikow, 2011
GREAT ARTESIAN BASIN	1,700,000	0.311	0.2	1965-2000	Welsh, 2006

* Expressed as depth of an equivalent layer of water over the total horizontal extent of the aquifer system (scale-independent depletion indicator)

at slightly over 4,500 km³. Figure 5 summarizes the results of his assessment in the form of a picture of cumulative depletion since 1900, and its corresponding contribution to sea level rise. The volume and rate of estimated long-term global groundwater depletion can explain 6% or 7% of the observed sea level rise since 1900. According to these estimates, the average rate of global groundwater depletion was 102 km³ per year between 1991 and 2000, which rose to 145 km³ per year between 2000 and 2008. These rates are considerable, but substantially lower than the estimate by Wada et al. (2010), who concluded on the basis of a global model study that the annual global groundwater depletion rate by the year 2000 was 283 km³. Their methodology, however, includes highly simplifying model assumptions and is numerically ill-conditioned because the depletion is calculated by difference from variables with a significant margin of uncertainty, and averaged over large spatial units.

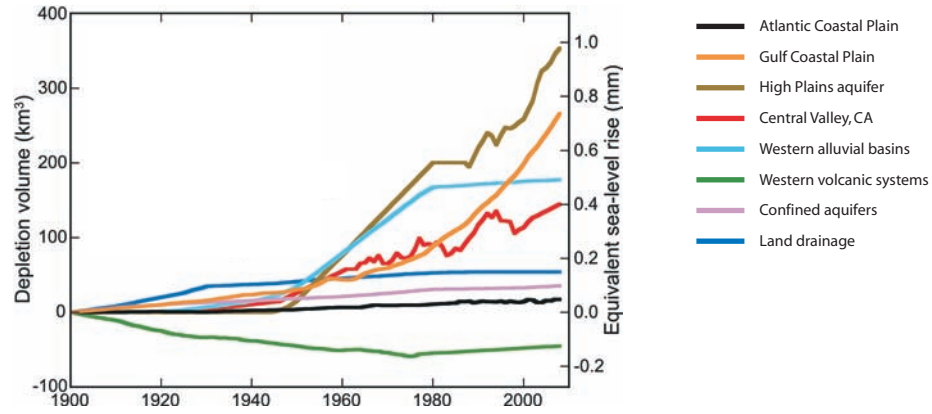
Depleting groundwater storage comes at a cost. This cost is not only limited to permanently higher unit cost of pumped groundwater but may also include negative impacts on the environmental and other *in situ* functions of the groundwater system, water quality degradation and even – in the long run – physical exhaustion of the aquifer. Nevertheless, in some cases, there may be good reasons to implement planned groundwater depletion for a finite period, and for accepting the associated negative consequences. This may be so in the case of sudden disasters or if there is a need to buy time for a smooth transition to sustainable groundwater development after dynamic equilibrium conditions have been disturbed by exploding pumping intensities or by climate change.

The risks and problems that result from declining water levels vary from aquifer to aquifer – as do options and current control practices. This is illustrated in Boxes 4, 5, 6 and 7. The situation depicted for the High Plains (Box 4) is typical of numerous intensively exploited aquifers in the world, large and small alike. On the one hand there is a growing awareness of the need to stop depleting the resource; on the other hand, reducing groundwater abstraction to a sustainable level often seems disastrous for the local economy and is not readily accepted by many individual stakeholders who stand to lose income if

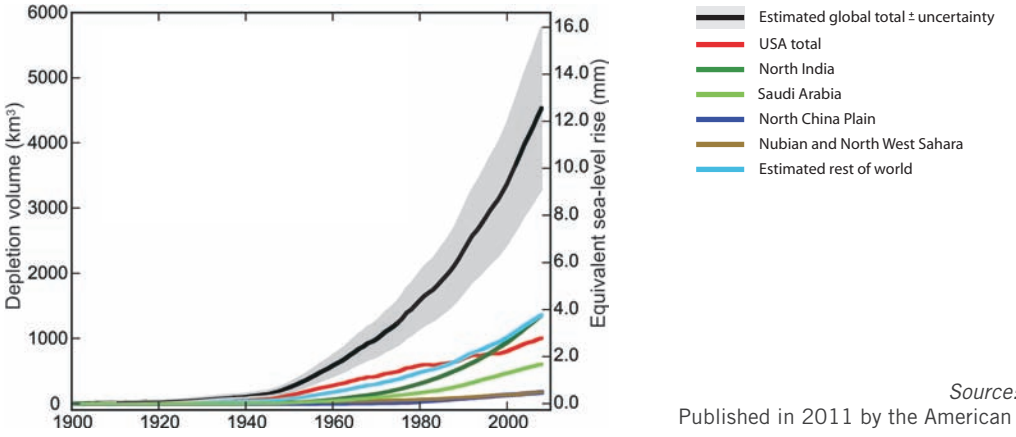
Figure 5

Cumulative net groundwater depletion 1900–2008

(a) in major aquifer systems or groups in the United States



(b) estimated for the entire world.



Source: Konikow, L. 2011.
Published in 2011 by the American Geophysical Union.

groundwater abstractions are curtailed. A similar dilemma is present in the much smaller Sana'a basin (Box 5), where large rates of depletion call for strong measures to prevent catastrophic water shortages in the near future. In the Umatilla basin, a community-based approach is attempted to manage conflicts resulting from aquifer depletion (see Box 6). The Great Artesian Basin (Box 7) is completely different: here depletion can be reduced by technical solutions that eliminate massive water wastage. Although their implementation is expensive, these measures are less controversial because there is no explicit conflict of interests. Paradoxically, they might even render the exploitation of this so-called non-renewable groundwater resource into a sustainable activity.

Shallow alluvial aquifers in arid and semi-arid zones form a special category. Because of their limited storage capacity, they are affected by seasonal rather than long-term depletion problems. Increasing abstraction rates shorten the period between the recharge season and the moment during the season when wells run dry. People's awareness of this phenomenon motivates them to conserve water, even more so if springs and qanats[4] are linked to the system. Finally, groundwater depletion risks tend to be insignificant for groundwater systems in humid climates. The control of groundwater levels, however, may still be very important in these climates, especially to prevent undesired environmental impacts, such as sea water intrusion, other induced changes in groundwater quality, land subsidence and wetland degradation.

The two basic options for controlling the decline of groundwater levels are augmenting the groundwater resource and restricting its discharge. Resource augmentation measures are technical in nature and include MAR techniques (artificial recharge) and land use management. Once decided upon, their implementation is relatively straightforward. Different types of measures are

4 A *qanat* or infiltration gallery is a traditional system used to withdraw groundwater without requiring external energy. A typical infiltration gallery or *qanat* is constructed as a slightly sloping tunnel, tapping groundwater at its upflow end (by means of a 'mother well') and conveying it via gravity – often over large distances – into an open section from which it can be diverted for use.

Box 4: Declining groundwater levels in the High Plains aquifer in the United States

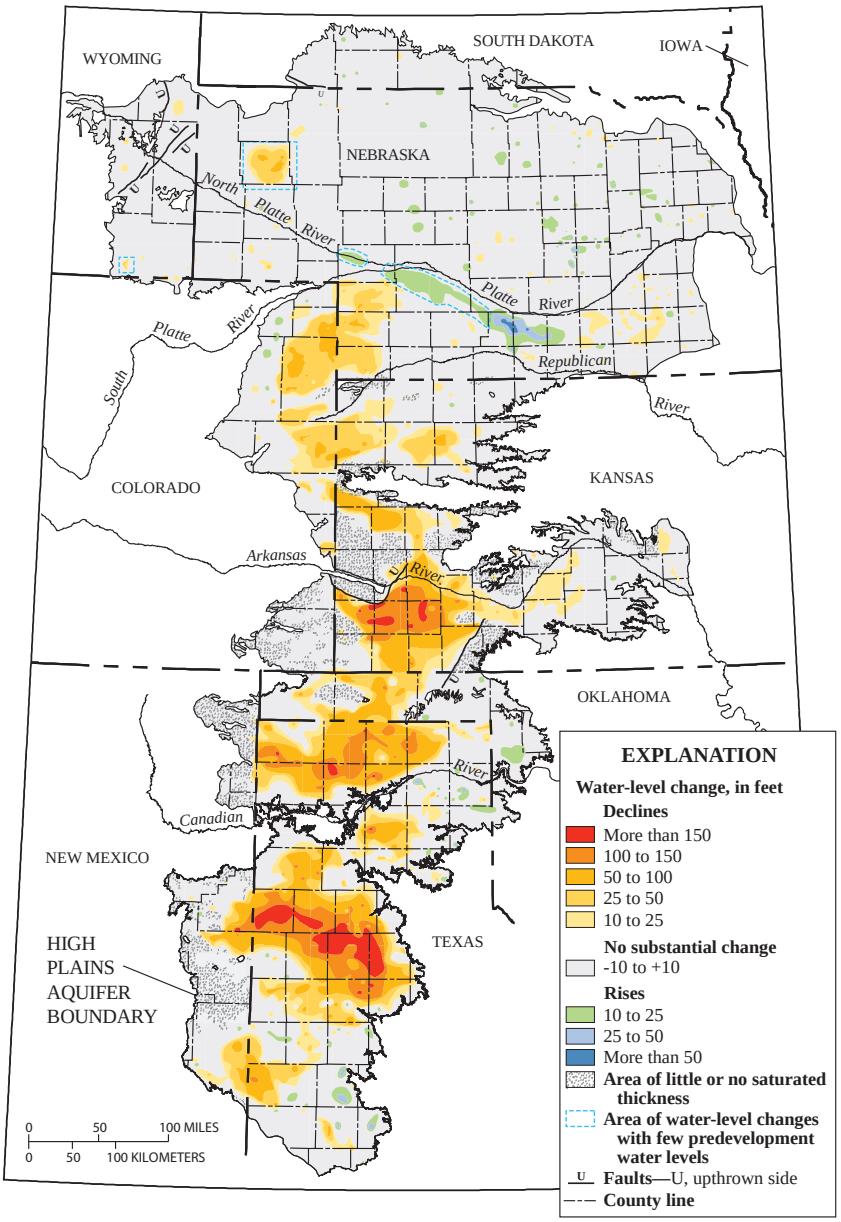
High Plains was once a barren and agriculturally marginal area that covered parts of eight states from South Dakota to Texas. But since the 1940s, it has become an economically flourishing region. The introduction of mechanical pumps enabled large quantities of groundwater to be abstracted from the underlying High Plains aquifer (or Ogallala aquifer). This very large phreatic aquifer covers around 450,000 km^2 and is currently the most intensively used aquifer in the United States, providing 30% of the total withdrawals from all aquifers for irrigation. Some 94% of the groundwater withdrawn from the aquifer is used for irrigation, and the aquifer provides drinking water for 82% of the 2.3 million people who live in the area. The benefits accruing from this aquifer system are huge, and made the High Plains one of the most productive agricultural areas in the world.

Intensive pumping has resulted in steady declines of groundwater levels in the High Plains. From pre-development up to 2007, the decline averaged over the area is 4.34 m, but because of large spatial variations (see Figure) there are zones where groundwater levels have dropped by up to 60 m. The declines have caused a reduction in stream flows in the area, the degradation of riparian ecosystems, an increase in the cost of groundwater and a reduction in the aquifer's saturated thickness. In spite of attempts to control and manage groundwater quantity, the downward trend of the levels continues across most of the area, threatening the long-term viability of an irrigation-based economy.

However, it is not easy to bring groundwater level declines to a standstill. This will require sacrificing a considerable portion of the groundwater benefits currently being enjoyed, and current laws and institutions are not well suited to this task. American law favours individual water rights (rather than permits for a limited period) and defers matters of water allocation, use and management to the individual states. The eight High Plains States each use different approaches and doctrines to develop and manage the aquifer, which complicates cohesive aquifer-wide water management efforts. In spite of some interesting innovations, such as Colorado's water augmentation programme, the Intensive Groundwater Use Control Area policy in Kansas and Wichita's Aquifers Storage and Recovery Programme (ASR), it seems that management focuses on 'planned depletion' rather than on making the groundwater resources sustainable.

Sources: Peck (2007); McGuire (2009); Sophocleous (2010).

Figure: Groundwater level changes in the High Plains aquifer, from pre-development up to 2007



Source: McGuire, V.L., 2009.

Box 5: Declining groundwater levels in the Sana'a basin in the Republic of Yemen

The Sana'a basin, part of the Sana'a Governorate and the seat of the capital city, is located in the Central Highlands of Yemen. This basin covers an area of 3,200 km^2 – or approximately 6.4% of the total area of the country. It has 2 million inhabitants, which is 8.7% of the country's total population.

The present pattern of water use in Sana'a is clearly unsustainable, and if allowed to continue, the exhaustion of this valuable and scarce resource is inevitable. Action is required to stop depletion of the basin's water resources (in practice, its groundwater resources). This action should be guided by the analysis of the water-saving potential and feasibility of individual water management options.

The strongly increased rates of groundwater abstraction (for both irrigation and domestic water) in the basin has drastically changed the regimes and conditions of the main groundwater systems. The most obvious effect is that groundwater levels have dropped and are likely to continue dropping in the future. Declining annual trends of between 2 m and 6 m are commonly observed, and serious shortages of water occur at present.

The total production of urban drinking water comes from 83 functioning wells and amounts to around 27.28 Mm^3 per year, while the consumed water (sold water) is around 18.2 Mm^3 per year. The rate of drawdown in the production wells between 1985 and 2007 varied from a few metres to approximately seven metres a year. The accumulated effect and hence the decrease in pumped yield is most pronounced in the well field. Considering the domestic water demands of the growing population of Sana'a, the non-domestic demands and the losses in the system (water that's unaccounted for), the current water supply corresponds to no more than half the amount that would be consumed if there were no shortages. There are around 89,610 house connections and 1,600 public ones (mosques, schools, government buildings, etc.). Unaccounted for water is estimated at 33%.

The main causes of the groundwater decline are:

- rising demand as the population grows and market-led agriculture develops;
- groundwater exploitation getting out of hand; and
- policies that have promoted expansion rather than efficient use and sustainable management.

Yemen, however, stands out among countries in water crisis. First because of the gravity of the problem – in no country in the world is the rate of depletion of aquifers proceeding as fast, in no country is the capital city literally going to run out of water in a decade. Second, Yemen stands out because of the lack of governance structures that would allow anything approaching a real solution to be simply imposed from the top. The only conceivable way to control groundwater use is to take users into partnership – as joint trustees of the resource. But even these solutions will inevitably be arduously brokered and slow to bear fruit. But if the country is not to become a desert, the challenge has to be met. Even if the results of action can be no better than a partial solution, the results of inaction would be catastrophic.

Contribution from Abdullah Abdulkader Noaman
Source of information: Hydrosult et al., 2010.

Box 6: Groundwater level decline and recovery in the Umatilla Basin in the United States

Over the past 50 years, groundwater declines of up to 150 m have occurred in the deep basalt aquifers underlying the Umatilla basin in the north-western United States. These have been caused by intensive exploitation of the aquifers for public drinking water and irrigation. The aquifers are shared by Washington and Oregon, and include lands ceded by and reserved for the Confederated Tribes of the Umatilla Indian Reservation (CTUIR).

Between 1976 and 1991, the State of Oregon Water Resources Commission designated a number of areas in the Umatilla Basin as 'critical' – thus precluding the drilling of additional wells for public drinking water and irrigation. However, wells designated for domestic use remain exempt from the rules in the critical areas. Exempt wells are those that do not require water rights, and are commonly used to supply domestic water to rural Umatilla County.

In 2003, Umatilla County established the 20-member Umatilla County Critical Groundwater Task Force to find solutions to short-term and long-term water quantity issues in the county, especially within the 'critical' groundwater areas. The primary mandate of the Task Force was twofold: to fix the current groundwater problems plaguing west Umatilla County; and to design a long-term plan to ensure that current and future water use would be managed in a sustainable manner. The Task Force's goal was to develop a '2050 Plan' – a plan that would govern water use up to the year 2050. The four general approaches to addressing the water deficits identified by the Task Force and the public included:

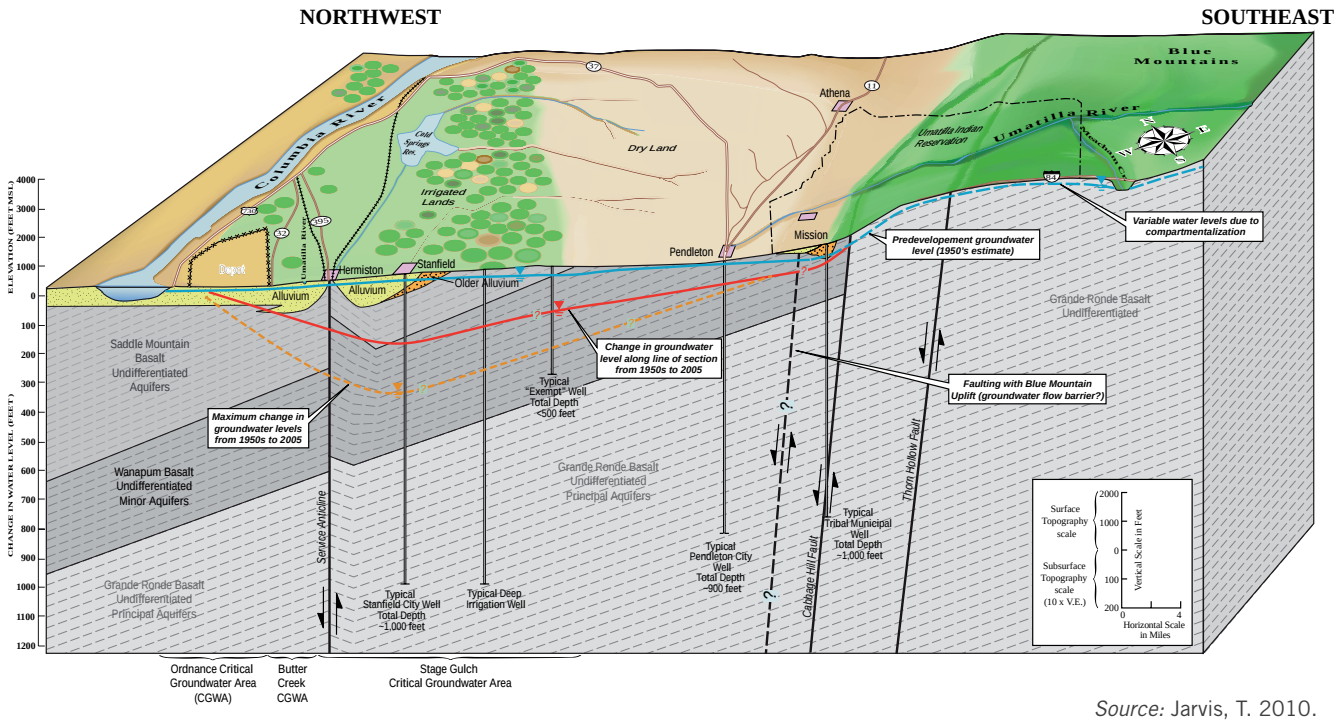
- augmenting groundwater supplies with surface water supplies from the nearby Columbia River – either through undeveloped options associated with existing US Bureau of Reclamation projects or through regional investments in delivery and storage infrastructure;
- funding more intensive investigations into groundwater resources to better determine the estimates of groundwater reserves;
- exchanging water rights to acknowledge CTUIR water rights and fisheries; and
- adopting more aggressive management of the existing water rights.

In 2009, the Umatilla Basin Water Commission was formed to implement a series of supply, storage, recovery and distribution projects which had been designed to divert water from the Columbia River water for aquifer recharge. The first project was initiated in 2011.

Contribution from Todd Jarvis.

Figure: Block diagram of Umatilla basin hydrogeology.

The red and orange lines depict the changes in water level across the basin since the 1950s. Water level declines range from about 30 m near Pendleton to over 60 m near Hermiston. Elsewhere in the basin water levels have declined by between 125 m and 150 m.



Source: Jarvis, T. 2010.

Box 7: Groundwater level decline and recovery in the Great Artesian Basin in Australia

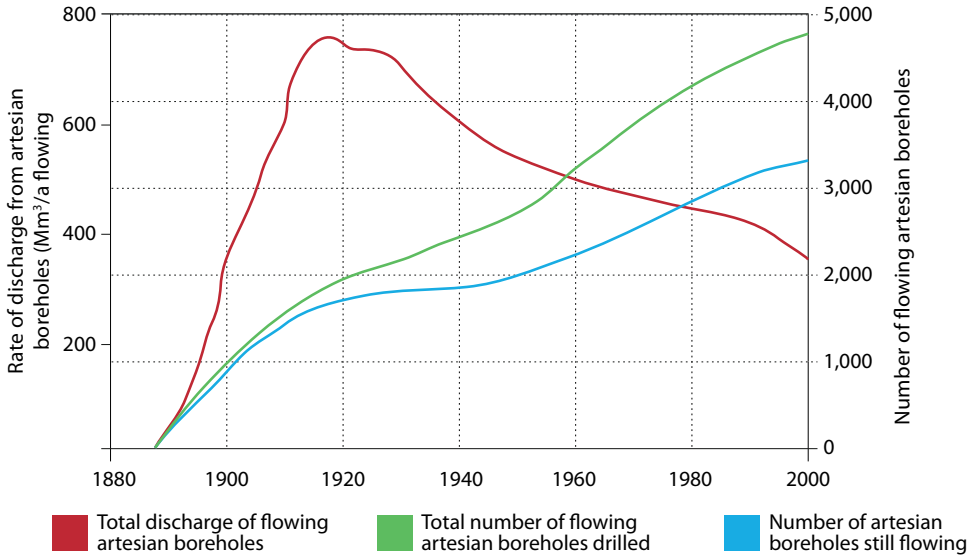
The Great Artesian Basin underlies 1.7 million km^2 of arid and semi-arid land – or some 22% of the continent of Australia. It is one of the world's largest artesian basins and is believed to contain some 64,900 km^3 of stored water. Its estimated mean recharge (produced along the edges of the basin) is 0.45 km^3 per year, hence the groundwater resource tends to be classified as non-renewable. The basin's water resources have allowed a major part of arid Australia to be turned into productive grazing land.

Before artesian conditions were discovered in 1878, using the aquifer's water was restricted to diverting water from springs in the natural discharge zones. However, towards the end of the nineteenth century, the there was a boom in drilling wells, many of them artesian. The total artificial discharge of groundwater through artesian wells peaked in 1918 at around 0.73 km^3 per year. This was discharged through about 1,500 flowing wells. Ever since, the number of artesian boreholes has been increasing, but because of declining artesian heads, they produced a steadily decreasing total flow (see Figure). During the 1970s, it was recognized that favourable conditions in the Great Artesian Basin were gradually disappearing, with repercussions for the withdrawal of water through artesian and pumped wells, and for the sustainability of the more than 600 spring complexes scattered throughout the basin. In addition, it was observed that the bulk of the discharge of the artesian wells was going to waste because of permanently flowing wells and huge losses of water in the often very long drains that bring water to the point of use. This prompted some capping and piping programmes in different states, in order to promote the sustainable use of the groundwater resources of the basin.

A Great Artesian Basin Consultative Council was established in 1997. This led to the development of a 15-year strategic management plan, which was agreed to by the states involved in September 2000. In parallel, the Australian Government launched the Great Artesian Basin Sustainability Initiative, which aims to recover and preserve the pressure in the basin by capping uncontrolled artesian wells and replacing bore drains with polyethylene pipes. The water-saving target to be achieved by 2014 is 0.211 km^3 per year, while the considerable costs involved are shared by the state governments (80%) and land holders (20%). Results up to mid-2008 suggest that the target is realistic.

Sources: Habermehl (2006); Herczeg and Love (2007); Sinclair Knight Merz (2008); GABCC (2009).

Figure: Trends in artesian groundwater overflow in the Great Artesian Basin, 1880–2000



Source: Habermehl, M., 2006.

available for restricting the artificial discharge from aquifers (demand management). The first type of measure is enforcing regulations such as licensing well drilling and groundwater abstraction. A second type of measure is discouraging groundwater abstraction selectively, e.g. by financial disincentives, by restricting energy supply or by enhancing people's awareness of sustainability problems. A third type of measure for restricting groundwater outflow is to reduce water losses at the well-head and during transport (as in the case of the Great Artesian Basin in Australia), or where it is being used (for example, by enhancing irrigation efficiency or recycling used water). Although resource augmentation is highly relevant and interesting, controlling groundwater abstraction is often essential for preventing or stopping undesired groundwater level declines. Experiences so far in different parts of the world show that this is extremely difficult. It is particularly difficult if existing withdrawals have to be reduced and alternative sources of water are not available. What's crucial is that stakeholders have a common understanding of the problem, and a firm commitment to support a chosen solution. In spite of increasing awareness, it is likely that in many aquifers around the world, ongoing storage depletion will not be stopped before the resource becomes economically or physically more or less exhausted. Such 'creeping' problems should be identified in time in order to be prepared and to implement adaptation and mitigation measures for the longer term, if control in the shorter term is not feasible.

3.2 Groundwater quality and pollution

Although most of the world's groundwater at conventional well drilling depths is of good quality, it remains a major concern to protect this water against quality degradation and to prevent poor quality groundwater from entering active freshwater cycles.

Often unrelated to human activities, but important nevertheless, is the occurrence of brackish and saline groundwater, which renders the resource unfit for most intended groundwater uses. Most groundwater at great depths is saline, but brackish and saline water can also be found closer to the surface. According to a recent global inventory (Van Weert et al., 2009), at shallow and intermediate depths (say, up to 500 m deep) bodies of brackish or saline groundwater are found under 13% of the area of the continents (excluding Antarctica). Only 8% of the identified brackish or saline bodies has an anthropogenic origin, with mineralization by irrigation return flows as the predominant causal mechanism. Risks of adding 'new' saline or brackish water to the groundwater domain are present near the coast (sea water intrusion), in zones of irrigated land and at locations where liquid waste is produced or dumped. Being aware of these risks and adopting adequate practices should reduce the salinization processes there to a minimum. As most of the saline or brackish groundwater bodies are more or less immobile, it is usually a good strategy to keep them in that state. The same is true for bodies of groundwater with excessive concentrations of other natural constituents, such as fluoride or arsenic (Appelo, 2008). Implementing such strategies requires detailed information on the local groundwater quality and hydrogeology, as well as a good understanding of groundwater flow and transport processes.

Anthropogenic groundwater pollution and its control have been major issues for many decades. It is a complex field because of the many sources of pollution, the myriad substances that may be involved, large variations in the vulnerability of aquifers, the lack of monitoring data and uncertainties on what impacts excessive concentrations of pollutants have – in addition to the usual dilemmas and problems involved in designing and implementing programmes for protection and control (Morris et al., 2003; Schmoll et al., 2006). Because groundwater usually moves very slowly, groundwater pollution is almost irreversible, or at least, very persistent. Consequently, monitoring pollution influxes and preventing them are basic components of any control strategy. In Europe, the recent Groundwater Directive – introduced in 2006 as integral part of the Water Framework Directive – is an important step forward. The Groundwater Directive obliges European Union member states to move towards compliance with good chemical status criteria by the end of 2015 (EC, 2008). Box 8 presents some information on its implementation.

Groundwater quality is also an important aspect of MAR. This management tool is, in some instances, used purposely to improve or control water quality, making use of the aquifer's capacity for attenuation and decomposition of substances, or using the injected water to prevent excessive shrinkage of exploited fresh water lenses overlaying saline groundwater. In all cases, however, one should be aware that managed aquifer recharge may introduce risks as well, including the risk of groundwater pollution. Box 9 presents an example of an approach to assessing such risks.

In recent years, there is growing attention for micro-pollutants, in particular for pharmaceuticals and personal care products (PPCPs) and for endocrine disruptive compounds (EDCs) (Schmoll et al., 2006; Musolff, 2009; Stockholm World Water Week, 2010). Disseminated by sewage, landfills and manure, these substances occur in natural waters in very low concentrations only (pg to ng per litre range) and are not removed by conventional wastewater treatment plants. There is still much uncertainty on their possible effects. Pharmaceuticals are designed to be bioactive, and although in groundwater they are too diluted to provide therapeutic doses to humans and animals in the short term, it is unknown as yet what effects they may have after long-term exposure. EDCs – present in steroid-based food supplements, drugs, fungicides, herbicides and a range of household and industrial products – have the capacity to interfere with the functions of hormones that control growth and reproduction in humans and animals. PPCPs and EDCs are ubiquitous in the surface water and shallow groundwater of densely populated areas, and progress in analytical methods is

Box 8: Groundwater quality management under the European Water Framework Directive

The European Union (EU) Water Framework Directive, adopted in 2000, is an important legal instrument that sets ecological and chemical objectives for Europe's freshwater to be achieved by 2015. The EU Groundwater Directive was issued in 2006 to complement the Water Framework Directive. It requires the following from member states:

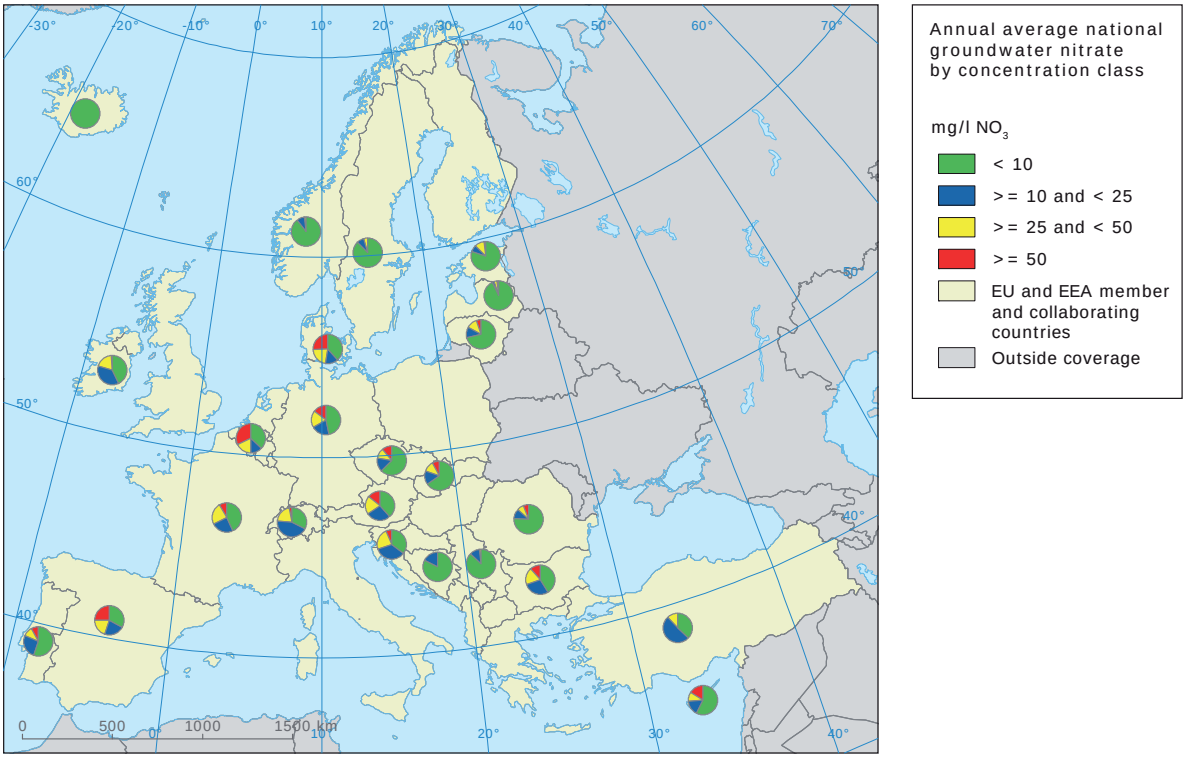
- that groundwater threshold values should have been established by the end of 2008;
- that pollution trend studies be carried out (using 'baseline level' data from 2007–2008);
- that pollution trends be reversed by 2015 in order to comply with environmental objectives;
- that measures to prevent or limit the input of pollutants into groundwater be made operational in order to allow the Water Framework Directive environmental objectives to be achieved by 2015;
- that the directive's technical provisions be reviewed in 2013, and every six years thereafter; and
- that there be compliance by 2015 with good chemical status criteria (based on European Union standards for nitrates and pesticides and on threshold values established by individual member states).

The EU Groundwater Directive has triggered concerted efforts to assess, monitor and manage groundwater quality across Europe. The methodology that has been adopted focuses on groundwater bodies defined by each of the countries.

Much information has emerged about the groundwater quality status of these groundwater bodies (see Figure) and the related sources of pollution. Pollutants of both surface water and groundwater include nutrients, metals, pesticides, pathogenic micro-organisms, industrial chemicals and pharmaceuticals. These can have adverse effects on aquatic ecosystems and also raise concern for human health.

Sources: EC, 2006; EC, 2008; EEA, 2010.

Figure: Annual average national groundwater nitrate by concentration class



Source: European Environmental Agency. EEA ©2010.

likely to reveal their presence even more widely in the future. They form a real challenge for today's and tomorrow's pollution control scientists and managers.

In Europe, the most important pollution sources are produced by agriculture and the urban environment. So far, a reversal of pollution trends has been observed in surface waters only (for example, a drop in phosphorus levels and an improvement in the quality of bathing water). These effects are largely the result of more wastewater being treated – as pursued by the Urban Waste Water Directive and comparable non-EU legislation. No reports on this reversal of trends in groundwater pollution have yet been encountered, which is no surprise given that the Groundwater Directive is still very recent, and that groundwater systems are rather inert. There is still considerable scope to reduce pollutants at source, and levying the full-cost of wastewater services on polluters ('polluter-pays principle') is expected to be helpful in reducing pollution.

Reporting up to 2010 has revealed that a substantial proportion of Europe's freshwater is unlikely to achieve the envisaged 'good quality status' by the year 2015. Some 40% of surface water basins and 30% of groundwater bodies are expected to fall short of the standard. The EU Water Framework Directive and Groundwater Directive are flexible and offer the member states two options in such instances: adjusting the targets to more feasible values and delaying compliance until 2021 or 2027. Member states therefore have to continue implementing strong, cost-effective and timely measures, addressing all relevant pollution sources. They have to take into account new driving forces that could affect water quality over the coming decades, such as climate change, increasing global food demand and an expansion of the cultivation of bio-energy crops.

3.3 Climate change, climate variability and sea level rise

Climate change modifies groundwater recharge. Global hydrological models have recently produced estimates of mean annual global groundwater recharge ranging from 12,700 km^3 per year (Döll and Fiedler, 2008) to 15,200 km^3 per year (Wada et al., 2010) – which is at least three orders of magnitude smaller than the estimated total groundwater storage. However, these recharge estimates, and the corresponding spatial patterns, are based on the mean climatic conditions that prevailed during the second half of the twentieth century. For the future, new estimates will have to be produced, taking into account the possible impact of climate change.

Climate change has been the subject of recent model investigations carried out by Döll (2009). These are based on four emissions scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) and comparing the model outcomes with those of the reference period 1961–1990. Döll concludes that by the 2050s, groundwater recharge is likely to have increased in the northern latitudes, but greatly decreased (by at least 30% to 70%) in some currently semi-arid zones, including the Mediterranean, north-eastern Brazil and south-western Africa (see Figure 6). Simulations for ten other climate scenarios produced different trends for some regions, but not for the Mediterranean region and the high northern latitudes. The four simulated scenarios shown in Figure 6 suggest a decrease of more than 10% in long-term mean groundwater recharge globally. Climate change is difficult to predict and at a scale of just tens of years, it is hard to distinguish it from the climate variability produced by El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multi-decadal Oscillation (AMO) and other inter-annual to multi-decadal climate oscillations (Gurdak et al., 2009).

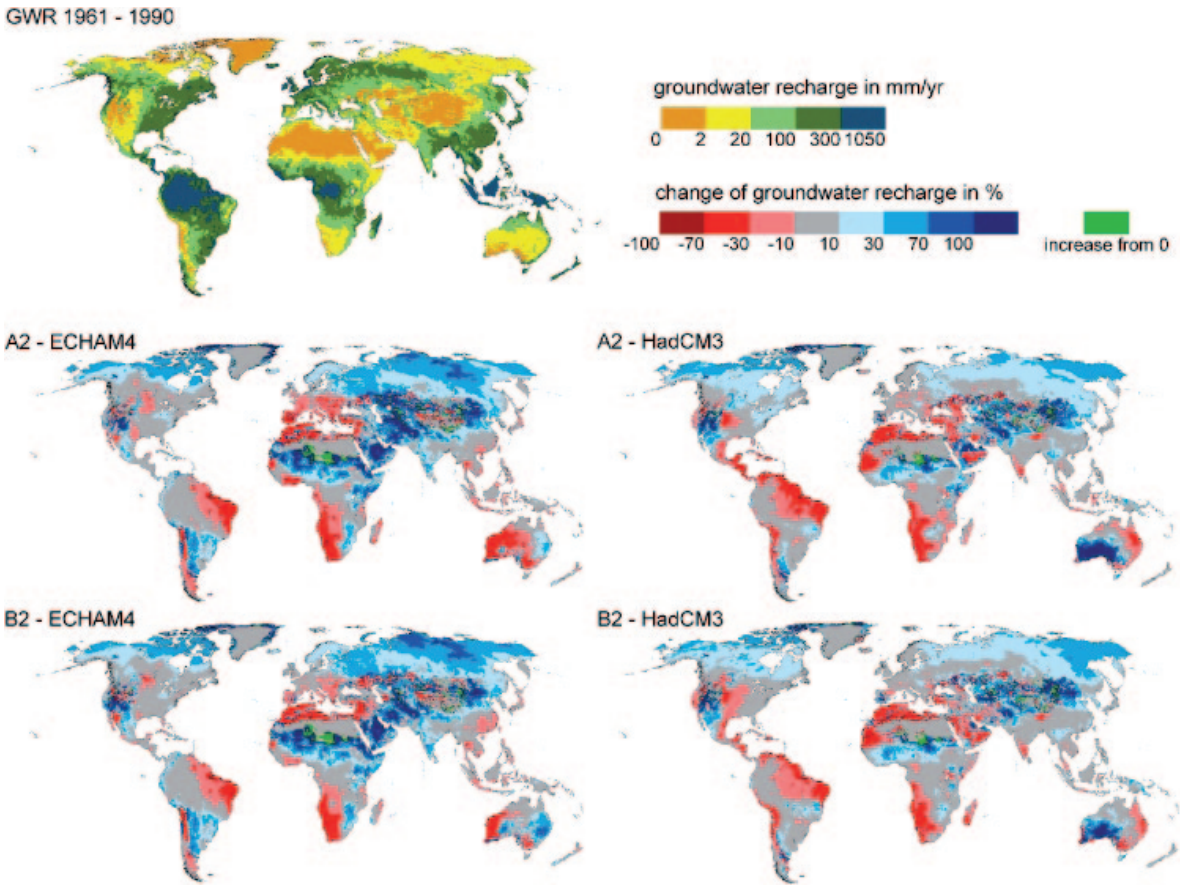
Not only will climate change alter mean annual groundwater recharge and mean annual surface water flow, it is also expected to affect their distribution in time. Wet episodes may become shorter in many regions, while dry periods are expected to become longer. However, because of their buffer capacity, this will not significantly affect the water supply capacity of most groundwater systems. The buffers cannot prevent long-term reductions in groundwater availability if climate change causes a reduction of the mean recharge rate, but they can facilitate a gradual adaptation to new conditions.

Climate change will also modify water demands and water use. Because the patterns of change in mean groundwater recharge shown in Figure 6 show a positive correlation with patterns of change in mean precipitation and mean runoff as predicted by the IPCC (Bates et al., 2008), it may be concluded that higher water demands will particularly affect areas where mean groundwater recharge is expected to decrease. This may produce severe problems – probably most of all in the numerous small and shallow wadi aquifer systems scattered across arid and semi-arid regions (Van der Gun, 2009). Nevertheless, it is expected that in many increasingly water-scarce areas around the world, dependency on groundwater will increase because storage buffers render groundwater more resilient than dwindling surface water sources. This is one more reason to manage groundwater carefully in such regions.

To a large extent, ongoing and predicted sea level rise is caused by climate change, but progressive groundwater depletion contributes to it as well. Konikow and Kendy (2005) argue that the oceans are the ultimate sink for groundwater that's removed from the aquifers by depletion. Accordingly, Konikow (2011) calculates that groundwater depletion in the United Sates contributed 2.2 mm to sea level rise during the twentieth century, while the contribution of total global groundwater depletion during the same period would have been 9.3 mm. For the period 1900–2008, the corresponding figures are 2.8 mm and 12.6 mm, respectively (see Figure 5). The estimated long-term global groundwater depletion thus balances 6% to 7% of the observed sea level change

Figure 6

The global pattern of estimated mean groundwater recharge during the period 1961–1990 and the percentage change between the periods 1961–1990 and 2041–2070 for four IPCC climate change scenarios.



(The climate scenarios were computed by the climate models ECHAM4 and HadCM3 on the basis of IPCC's greenhouse gas emission scenarios A2 [emissions increase during 1990–2050 from 11 Gt C/yr^{-1} to 25 Gt C/yr^{-1}] and B2 [increase from 11 Gt C/yr^{-1} to 16 Gt C/yr^{-1}]).

since 1900. The corresponding mean annual rate is currently some 0.403 mm (2001–2008), or about 12% of the current rate of sea level rise estimated by the IPCC. Although all these estimates are subject to considerable uncertainty, it may be concluded that groundwater storage depletion contributes significantly to sea level rise. However, it should be noted that another type of human intervention in the hydrological cycle – the expansion of surface water storage by the construction of dams – has an opposite effect on sea level.

In relation to groundwater, the main impact of sea level rise is the intrusion of saline water into coastal aquifers. Worldwide, sea water intrusion is a real threat to coastal aquifers and may have huge repercussions because a large percentage of the world's population lives in coastal zones. A series of papers in a recent issue of Hydrogeology Journal provides a geographic overview of saltwater-freshwater interactions in coastal aquifers (Barlow and Reichard, 2010; Bocanegra et al., 2010; Custodio, 2010; Steyl and Dennis, 2010; White and Falkland, 2010). A recent study on the impact of sea level on coastal groundwater in The Netherlands (Oude Essink et al., 2010) concluded that the expected sea level rise will affect the Dutch coastal groundwater systems and trigger saline water intrusion, but only in a narrow zone within 10 km of the coastline and main lowland rivers.

3.4 Groundwater and emergency situations

Not all changes present themselves slowly in the form of trends: certain events may change local living conditions drastically in a very short time. Suddenly occurring natural and man-made disasters – such as floods, droughts, tsunamis, storms, earthquakes, volcanic events, landslides and armed conflicts – often cause damage to water supply systems which results in acute shortages of drinking water. Bringing water from elsewhere – in cisterns or in bottles – during emergencies is usually feasible for a limited period only, while restoring the damaged water supply sources or technical infrastructure may take quite some time. In such cases, one should be prepared to

Box 9: Groundwater quality control in managed aquifer recharge projects: An Australian risk assessment approach related to recycling urban stormwater and wastewater

Managed aquifer recharge is increasingly being used to facilitate water recycling in areas where it is possible to improve scarcity by harvesting urban stormwater and wastewater. Pre-treating the water that's to be injected into the aquifers is not uncommon, and in some countries this is even obligatory. For example, in the United States, the federal Clean Water Act requires extensive pre-treatment to bring water in line with drinking water standards before being injected and stored.

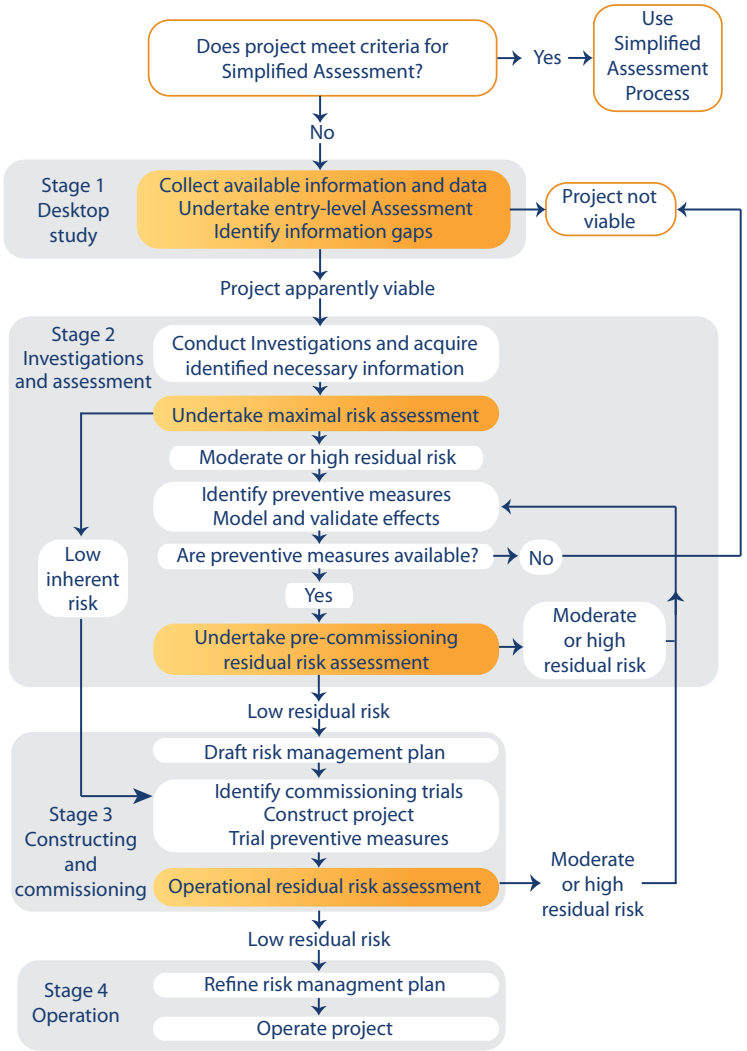
It has been reported that natural treatment can be achieved in the aquifer during managed aquifer recharge, resulting in the removal of pathogens, nutrients and micro-pollutants. However, sub-surface storage can also add hazards to the stored groundwater and create environmental risks. A staged risk assessment framework has been developed in the context of the recent Australian Guidelines for Water Recycling, (see Figure) This addresses not only water quality aspects, but also other hazards related to managed aquifer recharge projects (for example, water-logging, aquifer dissolution and the stability of aquitards and wells, and the effects on ecosystems).

The first reported application of this risk assessment framework to a case study has been at an aquifer storage transfer and recovery (ASTR) trial being conducted at Parafield in South Australia. In contrast to ASR (aquifer storage and recovery), ASTR uses separate wells for injection and for recovery – allowing an attenuation zone to exist around the recharge zone, beyond which water quality standards have to be met. In this specific case, the aim was to investigate the viability of storing urban stormwater, which had been pre-treated in a wetland, in a brackish aquifer and to see whether it could be recovered at a quality that would meet potable standards.

The managed aquifer recharge staged risk assessment that was carried out for the Parafield site demonstrated that the outcome of the assessment was uncertain, even though the risks from organic chemicals, turbidity, and inorganic chemicals were acceptable in the early stages of operation of the ASTR scheme. More work needs to be done to reduce uncertainty and to better define residual risks from these hazards. However, it is clear that managed aquifer recharge is a potentially useful tool for the natural treatment of stormwater that is intended to be used for potable water supplies in areas where mechanical and chemical treatment is not available or is too costly.

Contribution from Todd Jarvis

Figure: Four-stage risk assessment designed for managed aquifer recharge project development



Source: NRMMC et al, 2009.

quickly establish alternative drinking water supplies to satisfy urgent needs on a temporary basis. Groundwater often offers opportunities for establishing such emergency water supplies.

Under the umbrella of UNESCO's International Hydrological Programme, the project 'Groundwater for Emergency Situations' (GWES) was initiated to address this issue.

During its first phase, the GWES project, implemented by an international working group, produced a framework document (2006) and conducted several workshops (Mexico, 2004; India, 2005; and Tehran, 2006). As part of its second phase (2008 to 2013), a methodological guide (Vrba and Verhagen, 2011) has been prepared, while other planned activities include additional workshops for exchanging area-specific information and experiences, an inventory of disaster-proof groundwater bodies in selected pilot regions, and the development of a methodology for groundwater vulnerability maps that depict emergency groundwater resources. Envisaged is the enhancement of effective co-operation with partners who are active in this field, such as UNESCO's International Centre for Water Hazard and Risk Management (ICHARM), the United Nations International Strategy for Disaster Reduction (UNISDR) and the United Nations University–Institute for Environment and Human Security (UNU-EHS).

Preparedness is the key to enabling groundwater to play an effective role in emergency situations. As pointed out by Vrba and Verhagen (2011), this means that governments and inhabitants of disaster-prone areas have to be aware of the risks and be motivated to anticipate emergencies by taking appropriate action. Such action includes building adequate institutional and technical capacity, assessing risks, identifying and investigating suitable groundwater resources for use in emergency situations, protecting these resources and monitoring them adequately. Although there are exceptions, groundwater resources that are suitable for use in emergency situations are usually found in relatively deep aquifer zones, where groundwater plays a less active role in the hydrological cycle than groundwater of shallow aquifers and where confining layers or a very thick unsaturated zone prevent direct interaction with processes at or near the surface. The quality and quantity of such groundwater resources are relatively insensitive to the disasters that may occur while the near-surface effects of their temporary exploitation – even at rates exceeding sustainable ones – are considerably delayed and attenuated (Vrba and Verhagen, 2011). Box 10 presents some examples of action that has been taken and lessons that have been learnt in relation to groundwater in emergency situations.

3.5 Transboundary groundwater resources

The behaviour and functions of transboundary aquifers do not differ from those of other aquifers, but administrative borders that divide them render the coordinated development and management of their groundwater resources more complex. Borders complicate the acquisition of consistent information on the entire aquifer, and allocating aquifer segments to different jurisdictions is at odds with the transboundary effects of pressures within each of these segments. Information gaps, conflicting interests and a lack of coordination across the boundaries easily lead to problems that are preventable if transboundary aquifer management approaches are adopted.

Enormous progress has been made since transboundary aquifers were put on the international agenda at the end of the twentieth century. Regional inventories and the characterization of transboundary aquifer systems have been conducted under the umbrella of the United Nations Economic Commission for Europe (UNECE) in Europe (UNECE, 1999) as well as in the Caucasus, central Asia and south-east Europe (UNECE, 2007; 2009); and under the umbrella of the ISARM programme in the Americas (UNESCO, 2007; UNESCO 2008), Africa (UNESCO, 2010a) and Asia (UNESCO, 2010b). The map 'Transboundary Aquifers of the World' (IGRAC, 2009), which shows the locations and selected properties of 318 identified transboundary aquifers across the world, and ISARM's Atlas of Transboundary Aquifers (Puri and Aureli, 2009) are both largely based on the outcomes of these regional activities.

At the level of individual aquifers, important projects have been carried out or are still ongoing in the framework of the GEF's International Waters focal area. Box 11 gives an impression of the transboundary aquifer management instruments that have been developed and adopted for the transboundary Guaraní Aquifer System in South America, as outcomes of the Guaraní Aquifer project. Institutional arrangements and legal instruments are part and parcel of transboundary aquifer resources management.

A study on groundwater in international law by Burchi and Mechlem (2005) shows that until recently, international law has taken little account of groundwater. It also shows that even as recently as 2005, only a few legal instruments existed that were designed exclusively with groundwater in mind. The few legal instruments that have been drawn up are for the Geneva Aquifer, the Nubian Sandstone Aquifer and the north-west Sahara Aquifer System. The development of such instruments is expected to be catalysed by the Draft Articles on the Law of Transboundary Aquifers, jointly elaborated by the United Nations International Law Commission (UNILC) and the UNESCO International Hydrological Programme (IHP) and adopted by resolution A/RES/63/124 of the UN General Assembly in December 2008 (Stephan, 2009). Important principles included in these draft articles are the obligation to cooperate and to exchange information, the no-harm principle and the objective to protect, preserve and manage the aquifer resources. At its sixty-sixth session in December 2011, the UN General Assembly reaffirmed the importance of transboundary aquifers and the related draft articles. In a new resolution, states are further urged to make appropriate bilateral or regional arrangements for managing their

Box 10: Examples of groundwater in emergency situations: Using emergency groundwater resources and rehabilitating affected wells

Natural disasters that have disrupted domestic water supply systems on a grand scale include the Hanshin-Awaji earthquake of January 1995 (Kobe, Japan), the super cyclone that hit the coast of Orissa (India) in October 1999 and the December 2004 tsunami in the Indian Ocean. Important lessons that relate to groundwater can be learned from the emergencies created by each of these disasters.

The huge Hanshin-Awaji earthquake that struck Kobe in January 1995 (magnitude 7.3) killed 6,400 people and cut off water supplies to more than one million households. The lack of clean water also disrupted the rescue work being undertaken in many hospitals. It was three months in some districts before municipal water supplies were restored. Bottled water and tank water were what was generally used as an emergency supply. However, it was possible to pump groundwater from several wells immediately after the earthquake.

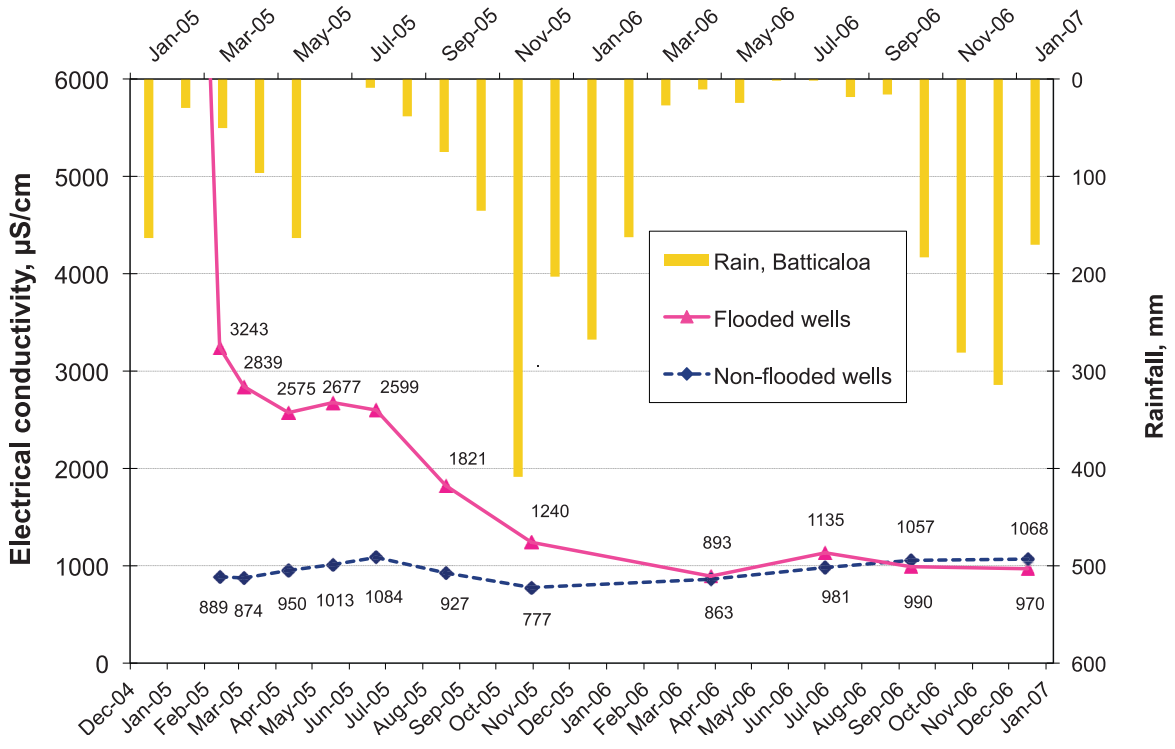
The disaster inspired the registration of citizens' wells that would be suitable for use in disasters. By October 1998, 517 suitable emergency wells were registered in Kobe. Similar registration systems have been launched by other local governments, especially in mega-cities such as Tokyo and Yokohama. These registration systems, along with regular monitoring of groundwater levels and water quality in the corresponding wells, form an important measure for securing groundwater supply in the wake of an earthquake.

The super cyclone that hit the coast of the Indian state of Orissa in October 1999 caused many casualties and brought misery to 13 million people. The cyclone was associated with seven-metre-high storm surges that reached 15 km inland, resulting in saline inundation along with intensive rain. Some 426 mm fell in a single day, causing flooding, which was accompanied very strong winds battering the infrastructure – including the drinking water supply infrastructure. A hydrochemical survey conducted immediately after the cyclone in the worst-affected areas revealed unchanged groundwater chemistry in deep wells, but a large increase in chemical concentrations in shallow groundwater (salinization). Guided by available local hydrogeological knowledge and by geophysical, isotope and other surveys, the Central Groundwater Board drilled a number of wells in the medium-deep freshwater aquifer. The drinking water supply was fully restored within four months, giving relief to approximately one million people.

The December 2004 tsunami in the Indian Ocean flooded many coastal zones in Asia and even in East Africa. Numerous wells were flooded and salinized. Rehabilitating these wells was a challenge. In the case of the sandy unconfined permeable aquifers along the coast of eastern Sri Lanka, it was observed that rainfall was the primary agent for restoring the aquifers and reducing well-water salinity. While early pumping for a short period (immediately after the flooding) contributed somewhat to salinity reduction, prolonged cleaning by continued pumping rather seemed to disturb the natural ambient flushing and remediation processes. Under local conditions, pre-tsunami salinity levels tended to be restored after about 1.5 years, as shown in the Figure.

Source: Tanaka (2011); Sukhija and Narasimha Rao (2011); Villholth et al. (2011).

Figure: Average well-water salinity and monthly rainfall after the tsunami in the Batticaloa area of eastern Sri Lanka. Non-flooded wells are assumed to represent the background salinity level



Source: Villholth et al. 2011.

transboundary aquifers, and UNESCO-IHP is encouraged to continue providing its scientific and technical support to the states concerned. In addition, the General Assembly decided to include The Law of Transboundary Aquifers on the provisional agenda of its sixty-eighth session, in order to examine – among others – the final form that will be given to the draft articles (see Box 12).

In 2010, activities in the Guaraní aquifer project resulted in an agreement being signed between Argentina, Brazil, Paraguay and Uruguay – which was, in terms of its content, in line with the draft articles (see Box 13).

The momentum produced by all ongoing activities on transboundary aquifers is transforming these aquifers from potential problems into opportunities for international cooperation.

3.6 Earth Summits, the Millennium Development Goals and groundwater

Global political commitment for action on the world's most important development issues is being mobilized at the highest levels by Earth Summits on Sustainable Development, organized by the United Nations. The UN Conference on Environment and Development, held in Rio de Janeiro in 1992, was a landmark in this regard: world leaders came together to create a roadmap for sustainable development – a plan known as Agenda 21. After subsequent Earth Summits in New York (1997) and Johannesburg (2002), another United Nations Conference on Sustainable Development (CSD) – also called Earth Summit 2012 or Rio+20 – is scheduled to be held in Brazil in June 2012. Each of the successive conferences has contributed to the renewal of political commitment and to the incorporation of new elements – such as the Millennium Development Goals – into the framework for action.

Earth Summit 2012 aims to secure political commitment to sustainable development, to assess progress towards internationally agreed commitments and to address new and emerging challenges. It will focus on two main themes:

- the Green Economy, in the context of poverty eradication and sustainable development; and
- an institutional framework for sustainable development.

The Millennium Development Goals are eight targeted development aims adopted in 2000 by all United Nations member states and designed to free humanity from extreme poverty, hunger, illiteracy and disease by the year 2015. The goals are interlinked and break down into 21 quantifiable targets. These targets specify improvements to be achieved by 2015 as compared to conditions in 1990. Progress is monitored on the basis of 30 indicators (UNDP, 2010).

Water is most directly addressed by Millennium Goal No 7 (Ensure environmental sustainability), in particular by its targets 7A (Integrate the principles of sustainable development into country policies and programmes) and 7C (Halve by 2015 the proportion of people without sustainable access to safe drinking water and basic sanitation). However, given the role of water in hygiene, the incidence of diseases, income generation and the time it may take in some areas to fetch water, it is evident that water is a relevant factor for all MDGs.

In relation to MDG 7, the UN (2011) reports that the limits for sustainable water resources have already been exceeded in western Asia and northern Africa, while two other regions (southern Asia and the Caucasus/central Asia region) are approaching a critical state regarding sustainability. This is concluded on the basis of the withdrawal of surface water and groundwater as a percentage of internal renewable water resources. In around 2005, the values of this indicator were for the regions mentioned 166%, 92%, 58% and 56%, respectively. Although the report does not refer to it explicitly, there is little doubt that groundwater depletion is a dominant cause of sustainability becoming critical.

Overall progress in reducing the proportion of the population that does not have sustainable access to safe drinking water is good in all regions (see Figure 7). The expectation is that the global MDG target will be actually exceeded by 2015, but not without leaving 672 million people still without access to improved sources of drinking water. An estimated 1.1 billion people in urban areas and 723 million people in rural areas gained access to an improved source of drinking water between 1990 and 2008. Nevertheless, progress is uneven and in all regions, coverage in rural areas is lagging behind that of cities and towns (UN, 2011; WHO/UNICEF, 2010). In an attempt to catch up in the rural areas, groundwater has the potential to play a primary role as a source of water, but it is not clear whether all actors involved are fully aware of this. Often, groundwater is easily accessible, reliable, of good quality (with little or no treatment required) and can be withdrawn locally, close to where it is needed, hence transport costs to satisfy spatially scattered demands may be minimal.

A less positive picture is offered with regard to sanitation. At the current rate of progress, the world will miss the target of halving the proportion of people without access to basic sanitation by 2015. In 2008, an estimated 2.6 billion people around the world lacked access to an improved sanitation facility. If the trend continues, that number will grow to 2.7 billion by 2015. Most progress in sanitation has occurred in rural areas. Between 1990 and 2008, sanitation coverage for the whole of the developing regions increased by only 5% in urban areas and by 43% in rural areas, but the gap between urban and rural areas remains huge, especially in southern Asia, sub-Saharan Africa and Oceania. Improvements in sanitation are bypassing the poor (UN, 2010). Apart from producing health risks and limiting comfort and decorum, poor sanitation conditions also have a negative

Box 11: Management instruments for the transboundary Guaraní Aquifer System in South America

During the preparation process of the strategic action programme (SAP) for the Guarani Aquifer System (SAG) – which was carried out by Argentina, Brazil, Paraguay and Uruguay – four instruments were designed and approved for the protection and management of the aquifer. The SAP was developed under the framework of the project Environmental Protection and Sustainable Development of the Guarani Aquifer System, which was supported by the Global Environment Facility, the World Bank and the Organization of American States (March 2003–February 2009).

The first instrument is The Geographic Information System SISAG. Its objective is to compile information on more than 8,000 wells and make it available to stakeholders. The system will include 32 workstations based in federal and state water management institutions and will use geographical information from 191 local maps. The instrument has a technical advisory committee, which includes representatives of the institutions responsible for water information. Operational support, technical updating and supervision of the maintenance of SISAG will be provided by Argentina.

The second instrument is Monitoring Network and Mathematical Modelling. Using information on 1,800 wells, the SAG was subdivided into seven main zones, with different hydrogeological characteristics. Regional and local models were developed to predict groundwater flows, including interferences between wells in critical areas (pilots), in terms of water levels, temperature and quality. A monitoring network of 180 wells, distributed over the delineated aquifer zones, was designed on the basis of technical criteria. Each country is responsible for data collection and may add new monitoring wells. A joint monitoring and mathematical modelling committee will address monitoring network needs and model evaluation, while overall support will be provided by Brazil.

The third instrument is the Local Management Support Commissions. These commissions, with the participation of municipalities, users, academic institutions and civil society, were established in four critical areas and with different goals (the country responsible for supporting each local commission is underlined):

- Concordia–Salto (Argentina and Uruguay): definition of a minimum distance between wells to avoid water level interferences and temperature decreases;
- Ribeirao Preto (Brazil): landscape zoning (including protection areas and groundwater abstraction restriction zones) to deal with observed large water level declines in the city centre;
- Itapua (Paraguay): management of water-supply wells and creation of a watershed committee; and
- Rivera–Santana do Livramento (Uruguay – Brazil): to find solutions for the lack of sewage systems (almost 50% in both cities) and water supply.

The fourth instrument is Capacity Building for Groundwater Management and Knowledge Dissemination: The four countries recognize that the dissemination of knowledge and the empowerment of institutions are crucial for the management of the Guarani aquifer's resources. Press officers, environmental journalists, non-governmental organizations and academic sectors should participate in communicational actions. As a first step, the capacities of the press officers from the responsible national institutions need to be strengthened. Paraguay will provide overall support to the implementation of planned activities.

The development of the Guarani aquifer management instruments will require substantial cooperation efforts from the sub-national level to the regional levels, supported by appropriate institutions. At the local level, institutional involvement will be promoted by the local management support committees. At the national and state/provincial levels, management support units will be strengthened. According to the Guarani Aquifer Agreement, signed in August 2010, a commission in which the four countries are represented has to coordinate the joint efforts. This commission will be established under the umbrella of the Treaty of the River Plate Basin (1969).

Contribution from Luiz Amore

Box 12 Resolution on the Law of Transboundary Aquifers adopted by the United Nations General Assembly in its sixty-sixth session (9 December 2011)

The General Assembly,

Recalling its resolution 63/124 of 11 December 2008, in which it took note of the draft articles on the law of transboundary aquifers formulated by the International Law Commission,

Noting the major importance of the subject of the law of transboundary aquifers in the relations of States and the need for reasonable and proper management of transboundary aquifers, a vitally important natural resource, through international cooperation,

Emphasizing the continuing importance of the codification and progressive development of international law, as referred to in Article 13, paragraph 1 (a), of the Charter of the United Nations,

Taking note of the comments of Governments and the discussions in the Sixth Committee at its sixty-third and sixty-sixth sessions on this topic*,

1. Further encourages the States concerned to make appropriate bilateral or regional arrangements for the proper management of their transboundary aquifers, taking into account the provisions of the draft articles annexed to its resolution 63/124;
2. Encourages the International Hydrological Programme of the United Nations Educational, Scientific and Cultural Organization, whose contribution was noted in resolution 63/124, to offer further scientific and technical assistance to the States concerned;
3. Decides to include in the provisional agenda of its sixty-eighth session the item entitled 'The law of transboundary aquifers' and, in the light of written comments of Governments, as well as views expressed in the debates of the Sixth Committee held at its sixty-third and sixty-sixth sessions, to continue to examine, inter alia, the question of the final form that might be given to the draft articles.

** Official Records of the General Assembly, Sixty-third Session, Sixth Committee, 26th meeting (A/C.6/63/SR.26), and corrigendum; and ibid., Sixty-sixth Session, Sixth Committee, 16th and 29th meetings (A/C.6/66/SR.16 and 29), and corrigendum*

Box 13: Agreement on the Guaraní Aquifer System

In August 2010, the presidents of Argentina, Brazil, Paraguay and Uruguay signed an agreement on the transboundary Guaraní Aquifer System (GAS). This is a noteworthy achievement since agreements on transboundary aquifer systems are rare, even though there are hundreds of transboundary aquifers in the world. One reason for this rarity is that a treaty makes sense only if sufficient reliable information is available on the physical, social, environmental, cultural and economic aspects of the transboundary system being considered.

The 'Project for Environmental Protection and Sustainable Development of the Guaraní Aquifer System' (GAS project), which was carried out by the four countries with support from the Global Environment Facility (GEF), the World Bank and the Organization of American States (OAS), has produced such information. During its seven years of operation the project built and strengthened technical and political trust among the countries involved. The signing of this agreement undoubtedly benefited from previously signed agreements between these countries on related issues – agreements such as the Treaty on the River Plate Basin (1969) and the Framework Agreement on the Environment of MERCOSUR (2001). After concluding the GAS project, it took more than a year of discussions before the countries agreed to sign the agreement.

The GAS agreement takes into account Resolution 63/124 of the UN General Assembly on the Law of Transboundary Aquifers and deals with general management guidelines only. It emphasizes the sovereign territorial control of each country over its respective portion of the GAS and avoids including subjects that could weaken sovereign rights. Nevertheless, the countries commit themselves to conserving and protecting the GAS, and to use its groundwater resources on the basis of multiple, reasonable, equitable and sustainable use criteria, without causing significant harm to the other parties or the environment. Should nonetheless any harm occur, then the country causing it should adopt all necessary measures to eliminate or mitigate it. The agreement gives instructions on how to act in case of controversy between the countries on the GAS. The agreement obliges the countries to exchange technical information on studies, activities and works related to the GAS and to inform each other of intended activities that may have transboundary effects.

Finally, the agreement facilitates the implementation of earlier agreements on the division of administrative responsibilities among the four countries – on matters such as information systems, monitoring networks, communication, local issues in pilot areas and an institutional cooperation mechanism.

Contribution from Júlio Thadeu Kettelhut

impact on the quality of shallow groundwater, especially in terms of bacteriological pollution.

Groundwater undoubtedly has a role to play in sustainable development and in achieving the MDGs, but there is little explicit reference to this role in the many related documents. Therefore, the International Association of Hydrogeologists (IAH) recently took the initiative to establish a network for Groundwater and the Millennium Development Goals. The mission of this network is, 'to better understand and effectively promote the role groundwater plays to help achieve the MDGs'. It will try to achieve this by:

- disseminating the outcomes of studies on the effectiveness and impact evaluations of the groundwater investments;
- promoting communication and support networks/facilities on the role of groundwater in sustainable human development;
- advocating education and the provision of information on the rights and responsibilities, and the nature and extent of groundwater resources; and
- supporting investment in development innovations that cover not only hydrological, social and economic aspects, but also cultural, legal and institutional dimensions of groundwater use and management.

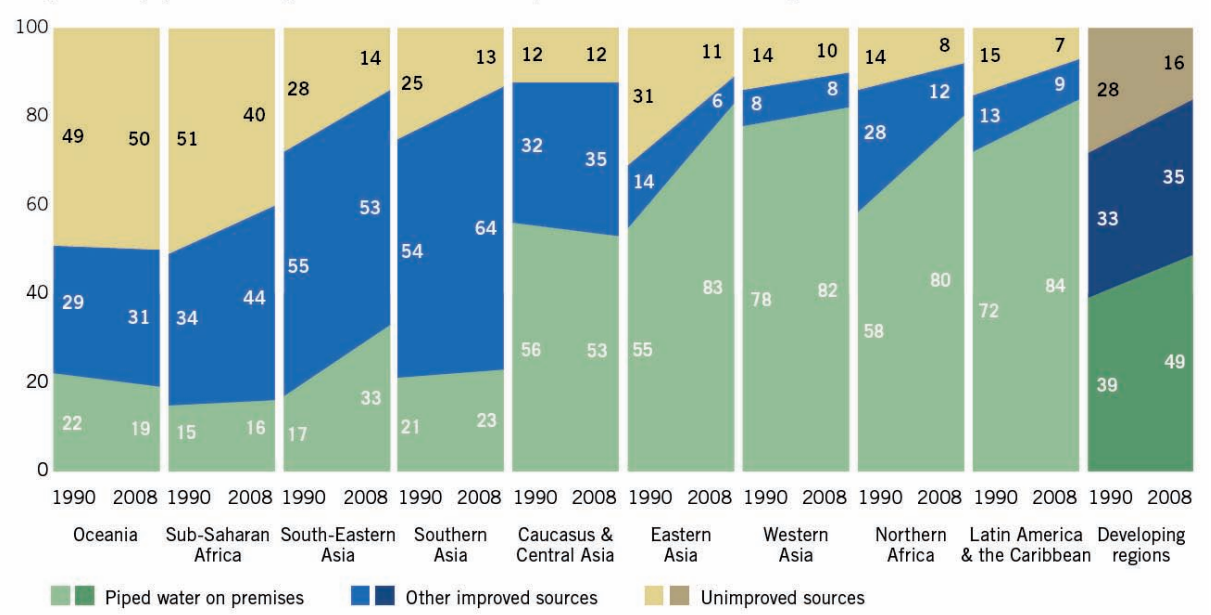
An Asia–Africa link is planned for the exchange of knowledge on groundwater use and its sustainable management. This activity will be carried out in cooperation with a large number of international organizations (IAH, 2011).

Although 2015 was set as the deadline for the MDGs, activities should not slow down when that date has passed – not only because some of the targets may not have been fully achieved by 2015, but also because the current targets aim for significant reduction rather than for complete eradication of extreme poverty, hunger, illiteracy and disease. As formulated in the Stockholm Statement to the 2012 United Nations Conference on Sustainable Development (UNCSD) in Rio de Janeiro: 'Over and above achieving the Millennium Goals, we call for a universal provisioning of safe drinking water, adequate sanitation and modern energy services by the year 2030.' (Stockholm World Water Week, 2011).

A recent resolution passed by the UN Human Rights Council at its 18th session in October 2011 similarly emphasizes the universal human right to safe drinking water and sanitation, calling states to go beyond the MDGs (UNGA, 2011). On top of this, global conditions are changing rapidly and new challenges related to water have been, and will continue to be, identified. One of these challenges is the transition to a Green Economy – one of the main themes at the Rio+20 Summit. It is up to the global partnership developed by the Earth Summits to address these challenges effectively. Groundwater specialists have to indicate how to fit groundwater into the initiatives.

Figure 7

Proportion of population using different sources of water, 1990 and 2008 (Percentage)



Source: UN 2011.

4 Conclusions

Groundwater – containing by far the largest volume of unfrozen fresh water on Earth – is an enormously important natural resource. But it is hidden to the eye, and until today poorly known and understood by the general public and most decision-makers.

Hydrogeologists and other scientists have made remarkable progress over the last few decades in collecting information on the world's groundwater systems, in understanding their role and functions, in observing changes over time and in identifying options for enhancing benefits from groundwater as well as threats that need to be addressed to safeguard the resource's sustainability. Gradually it has become clear to them how strongly the development and state of groundwater systems are interrelated with other systems and external drivers. It has also become clear that the value of groundwater is not limited to its abstraction for multiple uses (provisioning services), but includes a range of valuable *in situ* services (regulatory services), such as supporting wetlands, springs, baseflows and the stability of the land surface. As a result, the management of groundwater resources has evolved into a multidisciplinary activity that addresses multiple objectives. It does not focus solely on physical systems and technical measures, but pays also significant attention to demography, socio-economics and governance. Modern groundwater resources management approaches incorporate the principles of conjunctive management and integrated water resources management. Adaptive management and water governance are emerging paradigms.

Globally aggregated values and shares in total water supply are indicators of the relevance of groundwater, but it is worthwhile looking beyond the volumes of water used. Without groundwater – with its storage buffer – many parts of the earth's dryer regions would be uninhabitable as a result of the seasonal lack, or permanent lack, of fresh water. The supply of water to rural areas that are remote from permanent streams would be extremely expensive without groundwater. Because of its greater dependability, the economic returns per unit of water used for irrigation and for other uses tend to be higher for groundwater than for other sources of water.

Globally, groundwater is a resource in transition. As a result of the 'silent revolution' and of the progressive pollution that's inherent to modern lifestyles, current stresses on groundwater systems are without precedent in many parts of the world. These stresses are still increasing and produce considerable risk and uncertainty. The questions that need to be answered are whether there will be enough groundwater available in the future, and whether its quality will meet requirements. Once it has

been defined how to strike a balance between using groundwater and conserving it, then the question arises how to induce a corresponding change in human behaviour in relation to this open-access resource. Finally, the question how to reduce the inflow of anthropogenic pollutants into aquifers should be addressed. Such questions pose enormous challenges to the groundwater community, water managers and local stakeholders. Solutions have to be tailored to the specific conditions of each area. Basic to the success of these solutions are a good understanding of the trade-offs between groundwater abstraction and other services of the aquifer, and the selection of measures that are compatible with the socio-political setting. The risks are, in principle, manageable, but their control is usually difficult and requires significant management efforts.

On the other hand, the buffer capacity of groundwater systems offers unique opportunities for the overall reduction of risk and uncertainty regarding water availability, both now and in the future. Changes to the availability and quality of groundwater proceed very slowly compared with those of the components of the water cycle that have smaller mean residence times. And, in the case of groundwater, it is much easier to predict these changes. This buffer capacity allows groundwater to be used to bridge prolonged dry periods. It also buys time for a smooth adjustment of overall water use in areas where sustainably available water resources have been reduced by the intensification of water use in upflow zones or by climate change. In addition, groundwater that has relatively large mean residence times – usually found at medium to great depths – is invulnerable to most disasters and may therefore be an invaluable emergency resource in situations where public water supplies based on surface water or shallow groundwater are suddenly disrupted by disasters.

It is not easy to define and implement measures that enable making optimal use of groundwater and that control its quantity and quality. In the first place, it requires solid knowledge of local groundwater resources and alternative water resources, the water demands, the current role of water and potential benefits, socio-economic and political preferences and realities, conflicts of interest, important drivers of change and many other factors. Based on this knowledge, an area-specific vision should be developed and shared among the main groups of stakeholders. This can serve as a basis for strategic and operational plans, including the corresponding measures. Knowledge and vision both need to take into account the large spatial and temporal dimensions that are relevant for groundwater-related issues.

In general, it is the aspiration of countries and water management institutions to ensure the sustainability of their groundwater resources. Adequate water resources management measures are needed to achieve this, and the expectation is that many of the corresponding endeavours will be successful. However, in some situations it is not realistic to expect that the gradual degradation of the groundwater resources can be stopped or even reversed. One such situation is the shallow fresh groundwater of small and topographically very flat islands (such as atolls in the Pacific Ocean and the Indian Ocean). If sea level rise causes the permanent inundation of part of such islands, then the fresh groundwater lenses will shrink irrevocably. Another such situation is where the groundwater is non-renewable: its exploitation necessarily depletes the resource. A third situation concerns intensively exploited renewable aquifers in arid and semi-arid regions. In theory, they can be exploited at a sustainable rate, but in practice this is often an illusion, given the huge socio-economic importance of the current groundwater withdrawal and the absence of alternative sources of water. A fourth situation is where shallow groundwater in urbanized and industrial areas is exposed to severe pollution. All these cases of degrading fresh groundwater resources constitute 'creeping' problems that remain dormant for some time, but may produce disasters over the long term. It is extremely important to identify them and prepare for a future that's independent of these dwindling groundwater resources. This may require a complete transformation to a less groundwater-dependent economy in the regions concerned.

Finally, the role of cooperation needs to be emphasized. At the local level, it has long been the experience that field investigations and diagnostic studies benefit considerably from smooth cooperation between the relevant parties, and that the implementation of measures can only be successful when there is cooperation between decision-makers, the institutions that are mandated to implement policies, scientific and technical specialists, and stakeholders. But cooperation is equally effective at the international and global levels. This is demonstrated by the outcomes of the numerous initiatives undertaken by UNESCO-IHP, the IAH, the FAO, the WWAP, the World Bank, the GEF and other international organizations. These bodies amass and disseminate information and knowledge on groundwater and on how to use and manage it. They provide legislative and other tools to facilitate the management and governance of groundwater. They trigger commitment at the highest levels for global priorities (such as Agenda 21, the MDGs and various UN resolutions), and forge global partnerships to help achieve the targets. Professionals active in the field of groundwater should be aware of the role and strength of cooperation and should be keen to ensure that groundwater is fully incorporated in the initiatives wherever this might be beneficial.

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