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Global Water Balance

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Abstract

Global freshwater resources and fluxes are poorly quantified and large differences exist between various published estimates. This is particularly pronounced for continental groundwater, which is estimated to make up between 0.3–1.6% of the global water budget. Only a fraction of this groundwater is useable, however, due to high salinity of mostly deeper groundwater. In addition, most subsurface processes are slow and memorize impacts over generations, so that only far-sighted groundwater use and protection is sustainable. Higher expected future water demands for irrigation, industrial, and household purposes require more investment in freshwater characterization and quantification. Factors including climate change, large-scale reservoirs, re-channeling of streams, expansion of urban centers as well as chemical and microbial loading need to be taken into account. Promising methods to reduce pressures on freshwater include prevention of chemical and biological input, desalination, artificial groundwater recharge, and economic use of water, such as drip irrigation.

Introduction

In the United Nations Millennium Declaration, adopted in September 2000, and during the Johannesburg Earth Summit held in 2002, an initiative, known as the "Water for Life" decade, was announced (Gardiner 2002). The primary goal of this was to contribute to a more sustainable use of global water resources, with particular emphasis on the access to safe drinking water. The initiative is justified by the fact that today close to 1 billion people do not have access to drinking water of a reliable quality (Diamond 2005). In addition, the number of people with poor access to proper sanitation was recently unveiled at the World Water Week 2008 in Stockholm to be over 2.5 billion. Despite the announcement of ambitious plans to halve the number of people with poor access to safe drinking water by 2015, it has become increasingly evident that these goals will not be reached. One reason is the absence of clear incentives for different nations to implement such plans. This may be further restricted by lack of

From the Strüngmann Forum Report, Linkages of Sustainability
Edited by Thomas E. Graedel and Ester van der Voet. 2010.
© MIT Press ISBN: 0-262-01358-4

wealth, rapid population growth, urbanization, climate change, and economic development, among other factors. Above all, however, better quantification and understanding of the natural water cycle is needed on local, regional, and global scales as a basis for action.

Water is by far the most abundant substance on our planet's surface (Berner and Berner 1996). It is stored on the continents, in the marine environment, and in the atmosphere. The key compartments for storage on the continents are ice and snow, aquifers, surface waters, soil moisture, the biosphere, water bound in non-aquiferous rock formations, and juvenile water released through rock-forming processes. Today's global water resources are thought to have formed from meteorites, vaporization, and subsequent condensation during Earth's early stages of formation (Berner and Berner 1996; Shiklomanov and Rodda 2003). The total estimated volume of available global water ranges between 1300–1500 million km^3 (Berner and Berner 1996; Shiklomanov 1996; Shiklomanov and Rodda 2003; UNEP 2008; UNESCO 2003). However, the quantification of water resources needs to focus on freshwater for potential human use. For this, one commonly cited estimate describes the stocks of freshwater with an estimated volume of 35–40 million km^3 (UNESCO 2003). Among these, almost 70% are stored in the form of ice and snow, with the remaining part attributed predominantly to groundwater resources. Foster and Chilton (2003) outline that globally groundwater provides 50% of drinking water, 40% of industrial water, and 20% of the water used for irrigation. Other figures produced by Struckmeier (2008) and UNEP indicate that today more than 25% of the world population (i.e., 1.5–2 billion people) relies on groundwater with expected future rapid growth (UNEP 1996).

Struckmeier et al. (2005) estimated renewable volumes of useable water to be about 43,000 km^3 yr^{-1}. This number seems plausible as it roughly matches the outcome of global water balance models by Döll and Fiedler (2008). Compared to this, current and future estimates of total global water use differ greatly. For instance, the annual global withdrawal of all types of freshwater is estimated at 4000 km^3, approximately 17% of the volume of Lake Baikal, which has a volume of 23,600 km^3 and is globally the largest open freshwater reservoir. Many experts predict an increase in annual global freshwater withdrawals to about 5300 km^3 by 2025 (Seiler and Gat 2007; Shiklomanov and Rodda 2003). The latter number corresponds roughly to 22% of the volumes of Lake Baikal. Other studies estimate the annual need of freshwater withdrawals to be 12,000 km^3 by 2050 (Nature 2008), approximately the volume of Lake Superior or about 51% of Lake Baikal (Figure 12.1).

One other promising avenue to stabilize the freshwater supply is through water desalination. It is considered to be an increasingly attractive option to compensate for excessive large dams, pipelines, or canals but needs careful consideration in terms of energy efficiency (Schiermeier 2008). Several promising technological solutions for producing freshwater include forward osmosis, aligned carbon nanotubes, and polymer membranes. Nonetheless,

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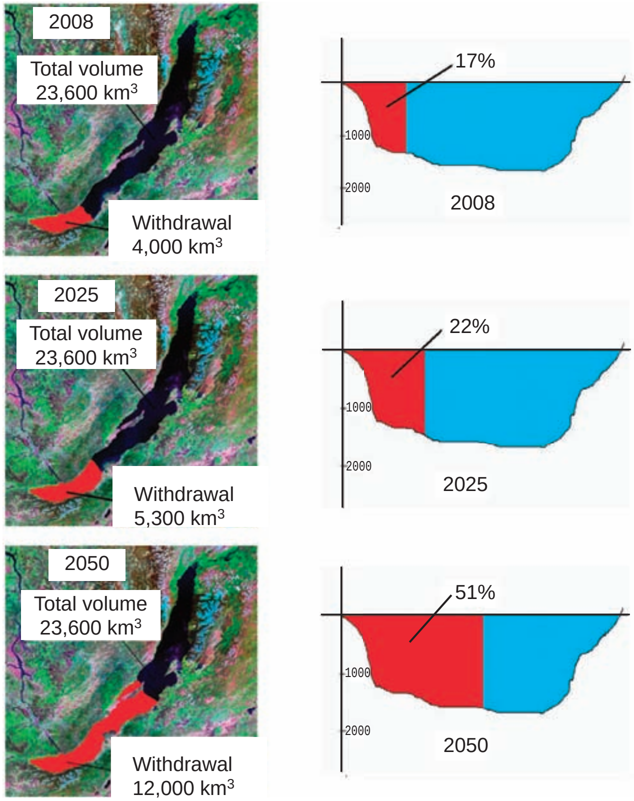

Figure 12.1 Scenarios of annual global freshwater withdrawals compared with the volume of Lake Baikal. Red shows the approximate magnitude of freshwater withdrawal.

on average these techniques are still more expensive than freshwater supply through groundwater extraction (Schiermeier 2008; Shannon et al. 2008). For instance, Diamond (2005) stated that such techniques remain 3.5 times more expensive than pumping groundwater from aquifers. Moreover, the problem of brine and other residues formed during the process of desalination needs to be taken into account. Residual brines and salts need to be stored, or else their concentrations need to be diluted to make them harmless to ecosystems. Finally, even though the highest population density exists in coastal areas, saltwater is often not available in remote areas within the continents, thus rendering local desalination impossible in these regions.

Although globally, humankind seems to consume less water than is being renewed by global continental precipitation and large reservoirs of freshwater exist, projected shortages of available and good quality water are expected to worsen in the future. This is rooted in the fact that water renewal and storage is unevenly distributed on Earth. For instance, arid regions suffer most from water shortages, but even areas with good water renewal rates are increasingly

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affected by water shortages if hygienic and chemical qualities decrease. In addition, the need for freshwater increases steadily with future population growth, agricultural as well as industrial development, and generally higher living standards. Our principal aim in this chapter is to provide an overview of global water resources. Among the various storage compartments, groundwater currently represents the most plausible water resource for human use, as it is comparatively accessible at low costs and often requires only little or no further treatment. Thus, focus will be put on its quantification and expected future pressures on this valuable resource, including protection and water management. Methods of detection and quantification are outlined in Appendix 2.

Comparison of Global Water Estimates

The variety of methodological approaches and the diversity of input parameters allow only rough estimates, such as the above-mentioned 1300–1500 million km^3 of globally available water. Ocean water represents about 96–97.5% of this total water volume. The remaining 2.5–4%, or 35–50 million km^3, is attributable to freshwater resources that can be subdivided into ice and snow (~ 2–3% of globally available water) as well as surface water and groundwater (~ 0.5–1%). The volumes of water stored in the atmosphere amount to only 0.013 km^3, thus making up only 0.033% of the global freshwater stocks. The estimates of volumes attributed to each of the freshwater storage compartments differ considerably, depending on the source of data and methods of estimation.

Figure 16.1 (Kanae, this volume) presents a merged annual global water balance based on UNEP (2002a) and Seiler and Gat (2007). The figure also shows an annual global precipitation of 0.5 million km^3 yr^{-1}, with almost 80% attributed to precipitation that occurs over the oceans (0.39 million km^3 yr^{-1}). Evapotranspiration from the land surface is set to 0.07 million km^3 yr^{-1}. Assuming a steady state system, the difference between continental precipitation and continental evapotranspiration (0.11–0.07 million km^3 yr^{-1}) makes up the global runoff from continents (0.04 million km^3 yr^{-1}). It can be subdivided into surface runoff (estimated as 55% or 0.022 million km^3 yr^{-1}) (Seiler and Gat 2007) and subsurface or groundwater discharge into the oceans (estimated as 45% or 0.018 million km^3 yr^{-1}). The sum of groundwater and surface water discharge to the oceans (0.04 million km^3 yr^{-1}) makes up the difference between evaporation from the oceans (0.43 million km^3 yr^{-1}) and precipitation over the oceans (0.39 million km^3 yr^{-1}). The latter closes the cycle of the global water balance. These numbers roughly match the figures by Kanae (this volume)

Table 12.1 provides various estimates for fluxes such as global precipitation, evapotranspiration, surface and subsurface runoff, and available stocks. It shows that numbers of precipitation over the oceans generated by UNEP (2008) and Seiler and Gat (2007) differ by 15–25% from those provided by

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Table 12.1 Selected estimates of the fluxes and stocks within the global water balance. Numbers are given in million km^3 yr^{-1} for fluxes and in million km^3 for stocks.

	Precipitation oceans	Precipitation continents	Evapotranspiration oceans	Evapotranspiration continents	Surface and groundwater runoff from continents	Groundwater runoff from continents	Ocean volume	Average water content in atmosphere	Water in the form of ice	Continental groundwater stocks
1	0.4	0.1	0.4	0.06	0.04	—	1400	0.01	48	15.3
2	0.32	0.1	0.35	0.07	0.04	—	1320	0.013	29.2	8.35
3	0.359	0.122	0.384	0.097	—	—	—	—	—	—
4	0.385	0.111	0.425	0.071	0.04	—	1350	0.0155	27.8	8
5	0.391	0.111	0.437	0.066	0.076	0.030	1338	0.013	24.1	23.4
6	0.46	0.11	0.5	0.065	0.045	0.018	1351	0.013	27	8
7	0.46	0.119	0.5	0.074	0.045	0.002	1365	—	32.9	23.4
8										4
9										6
10										8.2
11										8.34
12										10
13										10.55
14										23.4
15										23.4

[1] Berner and Berner (1996); [2] Van der Leeden (1975); [3] Marcinek et al. (1996); [4] Mook and de Vries (2000); [5] Oki and Kanae. (2006); [6] Seiler and Gat (2007); [7] UNEP (2008); [8] Lvovitch (1970); [9] Nace (1971); [10] Jones (1997); [11] Schwartz and Zhang (2003); [12] UNESCO (2003); [13] Shiklomanov (1996); [14] Gleick (1993); [15] Shiklomanov and Rodda (2003)

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others. Also the values of precipitation and evaporation over the ocean provided by van der Leeden (1975) are more than 25% lower than the others. Such estimates of fluxes over the ocean vary considerably because they are often based on few measurements and have been constructed with the help of models. On the other hand, the numbers for subsurface runoff presented by Oki and Kanae (2006) are double when compared to Seiler and Gat (2007), and estimates of water stocks in the form of ice and snow by Berner and Berner (1996) are 1.8 times higher than most others. Differences may originate from difficulties to determine storage of water in the atmosphere due to its short residence times. Also note that surface runoff is mostly known from the largest rivers that have gauging stations. Most of these are summarized, for example, in the Global Runoff Data Centre (GRDC 2008). Smaller rivers, which in sum discharge considerable amounts of water to the oceans, are often not taken into account.

Estimates of global saline and fresh groundwater stocks differ greatly, with the lowest value of 4 million and the highest of 23.4 million km^3. Thus, the total magnitude of variance reaches 585%. This is due to large uncertainties in volumetric evaluations of subsurface waters, which are only visible at piezometers, and wells or through high-resolution geophysical techniques, which often only apply to small scales. In addition, groundwater discharge to surface waters, particularly from coastal aquifers to the oceans, is only vaguely quantified, and on large scales the numbers are often calculated by difference between continental recharge via precipitation and discharge via rivers. While groundwater is likely present in Earth's crust to depths of several kilometers, it can be considered to be useable only to a few hundred meters below the surface. Beyond this depth, efforts for abstraction render groundwater use uneconomic in most cases, while salinities increase as well. Exact critical depths for groundwater use are often difficult to determine, and pore spaces of aquifers often remain poorly quantified. In addition, the depth to which groundwater is abstracted often depends on the urgency to supply water. For instance, in arid regions (e.g., Saudi Arabia and northern Africa), wells can reach depths of several thousand meters or more.

Most of the global water cycle is controlled by natural factors such as evaporation, transpiration, precipitation, and runoff. Nevertheless, human activities may cause yet unknown influences on global and regional water balances. Globally, humans may influence water stocks and fluxes through climate change; regionally their impact may be through reshaping waterways (e.g., damming, river channeling, subsurface constructions), groundwater abstraction, irrigation, or by re-injecting water to aquifers. The reduction of water quality through pollution may further influence useable water stocks. To date, these factors of the global water balance are difficult to quantify, but there are numerous examples for human influences on water quality and quantity (Diamond 2005). Such impacts are expected to grow with increasing world population and the growing water demands that are associated with technological and societal developments. Therefore the anthropogenic causes and effects

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on the water balance require much attention in the future. This is particularly important for groundwater with its smaller capabilities of re-naturation, due to slow flows and long memory effects, and its expected rapid increase of use.

Groundwater and Its Position in Global Water Balance

Next to food production, groundwater often serves as an important source for drinking water supply (Struckmeier et al. 2005). In some cases, groundwater is of limited use for human consumption and needs additional pretreatment measures and techniques, such as sanitation, filtration, and desalinization. Without such measures, untreated water may still be of use for industrial applications (Arad and Olshina 1984).

Groundwater represents 96–97% of easily accessible freshwater (Seiler and Gat 2007). About 53% of the entire continental surface (excluding Antarctica) is underlain by aquifers with major groundwater resources (Struckmeier and Richts 2008). The remaining 47% contain minor occurrences of groundwater, predominantly entrapped in the upper subsurface compartments (Struckmeier et al. 2005). Groundwater flow and recharge depends on hydrogeological characteristics of the surface and subsurface, climatic and atmospheric processes, and water regimes of lakes, streams, rivers, and wetlands (Freeze and Cherry 1979). The quantification of groundwater availability, flow, and recharge is possible with the help of direct measurements, which are carried out predominantly on local scales. These can lead to models on regional scales; however, the generation of accurate numbers of groundwater volumes on regional and continental scales remains challenging for several reasons (Balek 1989; Seiler and Gat 2007):

- Uncertainties in estimates of the volume of pore space in subsurface.
- Limited availability and reliability of data on recharge, runoff, and groundwater levels. This is especially true in countries that do not have sufficient resources for measurement networks.
- Difficulties in determining the groundwater table distance from the surface over larger areas and its long-term and annual variance.
- Unknown quantities and directions of flow of groundwater–surface water exchange, particularly for marine and coastal systems.
- Limited information on long-term effects of human impact on groundwater.
- Unknown volumes of groundwater with limited usability and/or access entrapped in deep aquifers and under ocean floors.

Although about 60% of global groundwater resources are stored at depths greater than 1 km (Arnell 2002), the useable part of the continental groundwater is predominantly represented by water in more shallow aquifers. The closer to the surface, the more useable but more vulnerable the groundwater becomes.

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The average depth of abstraction is less than 100 m below ground but can reach several thousand meters for deep and confined aquifers. Shallow groundwater usually has “modern meteoric origin”; it is formed as a result of rainfall with subsequent infiltration (i.e., groundwater recharge). Modeling studies show that today shallow continental groundwaters receive approximately 85% of the total recharge, whereas the remaining 15% of precipitation may reach deep groundwater (Seiler and Gat 2007). Due to the regular recharge by rainfall events, continental shallow groundwater has relatively short mean turnover times, from weeks to decades (Nace 1971). This residence time depends on the remoteness of the recharge area from the location of groundwater discharge (i.e., springs, rivers, lakes, wetlands, and the ocean). Estimates of the average velocity of shallow groundwater movement toward the discharge are on the order of several meters per day or slower, depending on the aquifer and type of solution (Seiler and Gat 2007). By contrast, mean transport times of deep groundwater vary between centuries and thousands of years, with average velocities of a few meters or even millimeters per year or less. For instance, large-scale numerical models by Lemieux et al. (2008) showed that deep groundwater dynamics in North America are still affected by Pleistocene glaciations (> 10,000 years ago).

Groundwater volumes and fluxes are also influenced by human activities such as abstraction, fundament measures, and channeling of rivers. During recent decades, humans have caused drastic changes in global water balances through the generation of considerable volumes of wastewater, heavy abstraction of water resources, and manipulations with soil and vegetation (Falkenmark et al. 1999). The consequences are often irreversible for centuries. Excessive abstraction of groundwater, for example, has caused depletion of aquifer systems in regions of Australia, India, China, Latin America, and Northern Africa (Diamond 2005) and has, in turn, often resulted in unpredictable inflows of groundwater from neighboring aquifers. Such growing anthropogenic pressures are likely to affect groundwater even more in the future. Areas of particularly high anthropogenic pressures are urbanized and agricultural regions. These areas deserve particular attention for sustainable water management.

In arid climates, nonrenewable groundwater constitutes a significant share of water resources and is often the only source of water. Increased demands of water for agricultural and industrial purposes in these areas render the issue of nonrenewable groundwater usage even more acute. Here, alternative principles of sustainable groundwater management need to be developed to avoid conflicts on the basis of the future water supply and to ensure preservation of nonrenewable groundwater from rapid depletion (Foster and Loucks 2006).

The regional distribution of groundwater and its recharge strongly depends on climatic factors. Precipitation provides water that further recharges groundwater through infiltration, whereas evapotranspiration reduces the volumes of the recharge. High evapotranspiration rates in arid climates can prevent groundwater recharge or even withdraw some water from groundwater stocks

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via capillary forces or deep-rooted plants that reach the groundwater table. On the other hand, porosities and transmissivities of the unsaturated zone define how much water infiltrates and how much becomes overland and interflow. Generally, regions with moderate and humid climates have higher rates of groundwater recharge and produce more overland flow. Conversely, areas with moderate precipitation volumes of less than 200 mm yr^{-1} occupy approximately 15% of Earth's continental surface. Often, evapotranspiration in such arid climates accounts for up to 97% of the precipitated water. In contrast, values for evapotranspiration in humid climates, such as Western Europe, return up to 62% of the overall precipitation to the atmosphere.

While discharge from open water toward groundwater is possible (Lerner et al. 1990; Trémolières et al. 1994), one can assume that groundwater generally feeds rivers, lakes, streams, and wetlands via baseflow that moves toward these morphologically lower structures. Such baseflow is often the only source of river recharge in arid climates (Struckmeier et al. 2005). Note that the quantity of groundwater which discharges directly into the ocean has not been well quantified to date (Dragoni and Sukhija 2008; Moore et al. 2008).

Struckmeier et al. (2005) have estimated annual global groundwater abstraction between 600–700 km^3 for 2001. Although this number corresponds only to about 15% of total global freshwater consumption, it makes groundwater the most mined environmental resource compared to other commodities such as gravel, coal, or oil (Zektser and Everett 2004). Often, excessive groundwater removal occurs in regions where replenishment is poor. For instance, Falkenmark (2007) found that up to 25% of India's harvests rely on aquifers from which annual groundwater abstraction exceeds recharge. Nevertheless, some of these abstracted volumes are not lost but are instead recycled to groundwater. Depending on the evapotranspirative capacity of plants, the infiltration capacity of the soil, and the irrigation method, up to about half of the water used for irrigation can be assumed to infiltrate back to the groundwater. In contrast, for drinking, household, and industrial water, one can assume that most of the used water is discharged to surface water systems.

Water Quality

Many urbanized areas in the world rely on groundwater abstraction to secure their water supply. As a result, the magnitude of groundwater withdrawals has often reached critical values in and around cities (Potter and Colman 2003). The largest cities of the world (e.g., Mexico City, Bangkok, Beijing, and Shanghai) have caused decreases of groundwater levels that reach 10–50 m (Foster et al. 1998). Often, this affects the quality of the water. For instance, leaking sewer systems and use of pesticides and fertilizers in green zones put additional pressures on subsurface waters in and around cities as well as in agricultural areas. This demonstrates that overexploitation of water often runs parallel with

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pollution. Shallow groundwater is particularly susceptible to contamination. Although soils, rocks, and minerals in the subsurface zone above and below the groundwater table may filter out, retain, or degrade many of the pollutants, more soluble compounds (e.g., pesticides, nitrate) may reach groundwater wells. In addition, floods may cause groundwater pollution through, for instance, the mobilization of the contents of septic tanks or contaminated areas near rivers. Groundwater contamination may, however, also occur naturally if aquifer materials have high concentrations of, for instance, arsenic, boron, or selenium. Table 12.2 lists the major sources of groundwater contamination.

The major components of groundwater quality deterioration are represented by a wide range of microbes, viruses, heavy metals, organo-metallic compounds, organic pollutants, and fertilizers (Fetter 1999). Furthermore, groundwater salinization is a widespread problem, particularly in arid regions and areas with intensive agriculture or downstream of dams. In addition, in many coastal zones, excessive groundwater abstraction has caused seawater intrusions that further reduce the quality of groundwater (Shannon et al. 2008). As a result, seawater that entered coastal aquifers compromises their use for drinking water. This situation has worsened after irrigation mobilized fertilizers and pesticides into the groundwater. Similar examples can be found elsewhere, especially in countries where few resources are available for planning sustainable water management and agriculture (Diamond 2005). To counteract such problems, artificial recharge is applied for restoring aquifers. However, care must be taken to ensure that groundwater levels do not approach the surface, as this enables excessive evaporation and may eventually render soils saline. Nonetheless, numerous examples of successful artificial groundwater recharge with pretreated rainwater exist, for instance, in India, Israel, Germany, Sweden, and the Netherlands (Fairless 2008).

Summary and Conclusions

To date, global freshwater resources and fluxes have not been clearly quantified, and large differences exist between various published estimates. This complicates future projections of natural water stocks and compromises local and large-scale planning of water resources. Such planning is crucial when accepting that global water demands will increase. Such increases can be expected due to higher rates of irrigation, industrial, and household uses of water commensurate with growing populations and societal developments. Therefore, factors such as climate change and growing anthropogenic influences on water quantity and quality need to be taken into account. These include large-scale reservoirs, re-channeling of streams, expansion of urban centers as well as chemical and microbial loading from landfills, sewerage, agriculture, industry, and households.

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Table 12.2 Major anthropogenic sources of groundwater contamination, modified after Fetter (1988).

Origin	Anthropogenic Groundwater Contamination Sources			
	Municipal	*Industrial*	*Agricultural*	*Individual*
Surface or near surface	Air pollution	Air pollution	Air pollution	Air pollution
	Landfills	Landfills	Fertilizers	Garbage
		Industrial sites		
	Urban runoff	Open pits	Pesticides	Detergents
	Public transport	Chemicals spills	Chemicals spills	Cleaners
	Storage facilities	Storage facilities	Livestock waste	Motor oil
Below surface	Landfills	Pipes	Wells	Wells
	Sewage systems	Underground storage	Underground storage	Septic systems
	—	Mines	—	—

Large gaps in the reliability of predictions about the availability freshwater attach more importance to the comparatively stable and huge groundwater reservoir in the subsurface of our continents. Groundwater plays an important role because it is often the principal supply for drinking water, agriculture, and industry. Recognition of demand and quality deteriorations is particularly important for groundwater because it has only limited capacities for re-naturation due to slow flow rates and long memory effects. This renders aquifers fundamental, but also sensible and often uncertain resources of freshwater. In addition, regions of intensive groundwater use are also often the ones that severely compromise groundwater quality through urban or agricultural influences, causing double pressure on water resources in regions where water is most needed. Such double pressures are particularly critical in areas with excessive groundwater abstractions and poor or missing groundwater management.

We also know that by mass groundwater remains the most mined resource compared to oil, gravel, and other mineral and metal resources. Despite this unique status, the numbers on available useable groundwater quantities, particularly on large scales, remain uncertain. This does not mean that surface waters and moisture stored in the atmosphere have higher priorities; they are just easier to access and thus availability of data about their quantities is generally better. Thus, more investigations are needed of the dynamics, quality management, and treatment of groundwater on local and larger scales. The most accurate results of groundwater stocks and recharge can be generated at local scales and thus should be further combined to produce global estimates and used for calibrating large-scale models. Groundwater quantity and quality evaluations remain challenging due to costs of high-resolution monitoring via piezometers and wells or other geophysical and geo-electric methods or satellite monitoring and GIS with systematic and international use of data. Even with currently available and advanced future investigation methods, we have to accept that

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it will hardly be possible to establish an exact picture of the entire subsurface situation. This includes the risk that poor definition of groundwater resources may lead to their overexploitation. If better quantification of groundwater is a necessity, detailed research is needed to understand the interactions between the ground- and surface water, particularly with the ocean.

Of course, groundwater is not the only source of freshwater. Other promising methods to reduce pressures on water stocks include further development of desalination, artificial groundwater recharge, new economic use of water (e.g., drip irrigation practices), and storage of water masses in aquifers rather than surface water structures. Although the latter storage form does not enable the generation of hydropower, it would prevent destruction of ecosystems through damming, reduce evaporative losses, and prevent salinization of soils if the groundwater levels are deep enough below the land surface.

Acknowledgments

This work was supported by a grant from the Ministry of Science, Research and the Arts of Baden-Wuertemberg (AZ33-7533.18-15-02/80) to Johannes Barth and Peter Grathwohl. This work was also partially undertaken within the European Integrated Project AquaTerra (GOCE 505428). The project has received research funding from the Community's Sixth Framework Programme.

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