Chapter 8

Regional perspectives on groundwater

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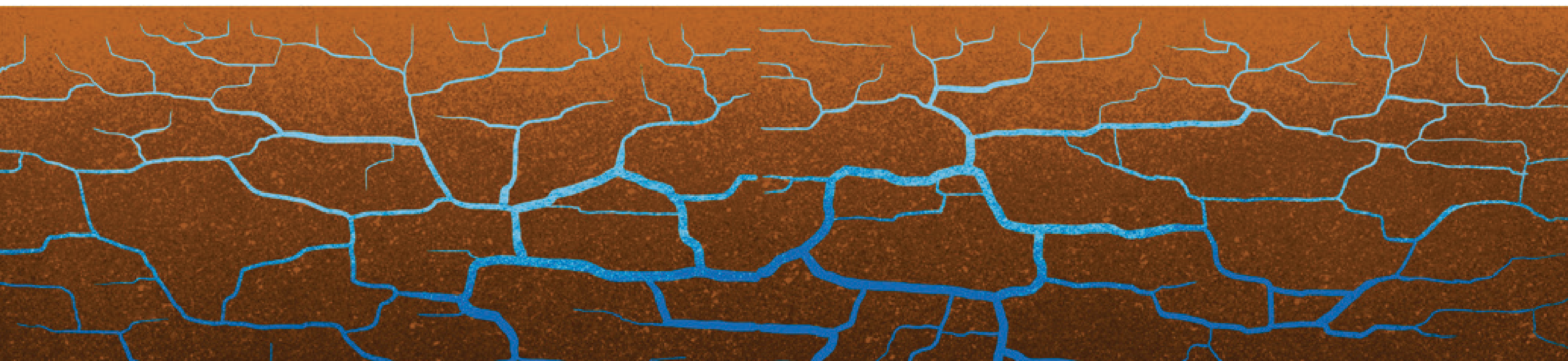


8.1 Sub-Saharan Africa

8.1.1 Introduction

About 400 million people in Sub-Saharan Africa do not have access to even basic water services. The majority of these people live in rural areas (WHO/UNICEF, 2021). Even cities, where household connections are more common, suffer from supply outages and unreliable flow due to high and increasing demand (Healy et al., 2020). Therefore, the overwhelming priority for most countries is to improve access, first to basic services and eventually to safely managed household supplies. However, climate change places a further pressure on available surface water resources, leading to recurrent water scarcity and droughts threatening the progress made so far (Taylor et al., 2013a). Extensive growth in water demand due to population growth and rapid urbanization adds to the pressure, and increases the need for an expansion in climate-resilient water services.

The development of groundwater has thus great potential to satisfy the need for rapidly increasing water supply across Sub-Saharan Africa, both for human survival as well as to promote economic development (Cobbing and Hiller, 2019). Groundwater, as the largest freshwater resource available, is highly reliable to support livelihoods, especially during extended periods of inadequate rainfall or dry spells, and could help to address issues of water scarcity and drought-related shocks (World Bank, 2018a; MacAllister et al., 2020). Groundwater development for drinking water through communal pumps and private household wells is well established in most countries, but development must go much further and faster. Use for irrigation and industry remains low except for some localized areas, like in South Africa, Zambia and Zimbabwe (Pavelic et al., 2012). Under a changing climate combined with economic growth, the biggest priority remains for countries to adopt best practices to develop and manage groundwater resources, in order to meet competing demands while recognizing the important role groundwater plays in sustaining freshwater ecosystems (Tuinhof et al., 2011). This section provides an overview of groundwater resources in Sub-Saharan Africa and the opportunities and challenges for utilizing this important resource.

8.1.2 Status of groundwater

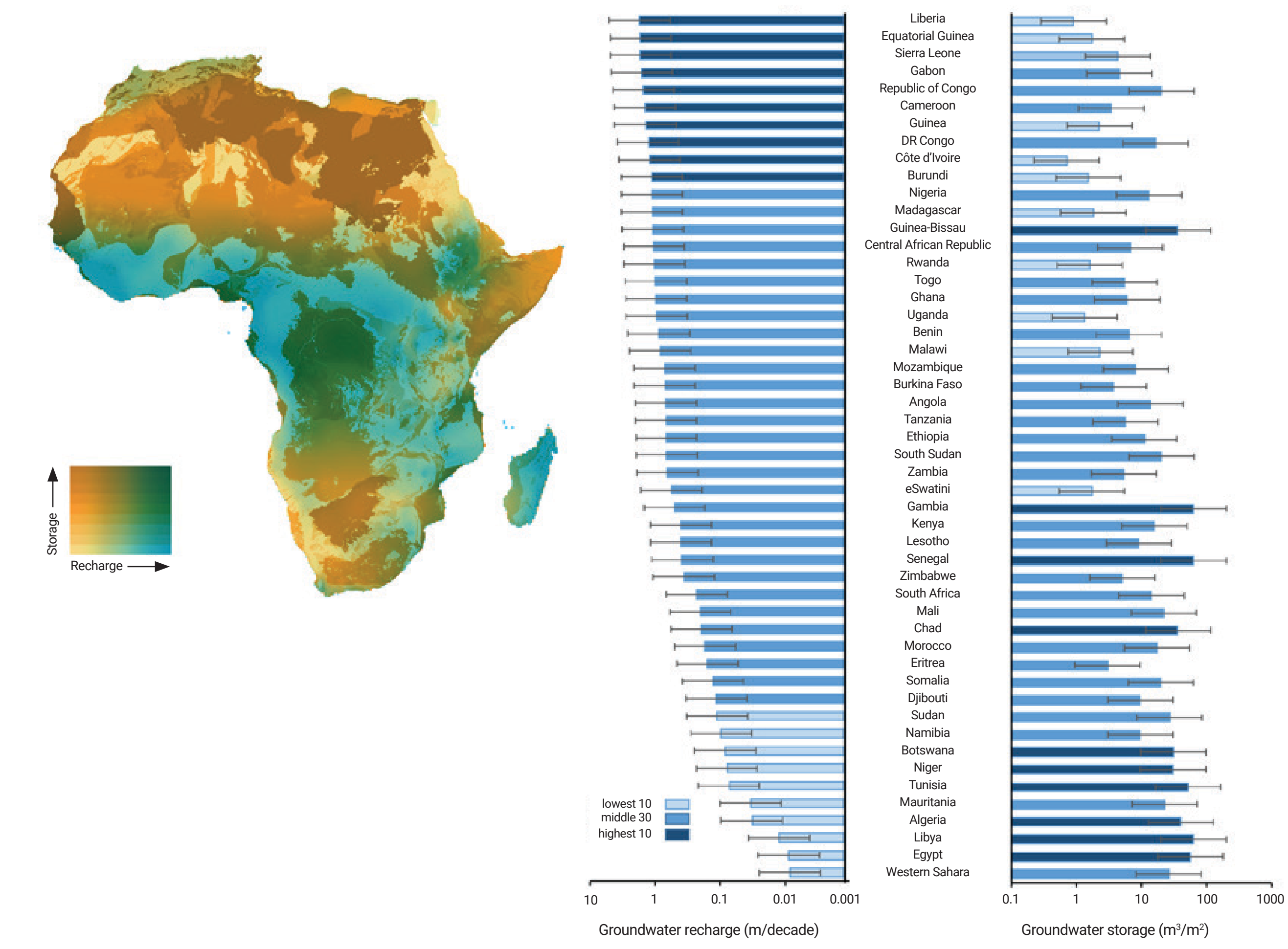
About 400 million people in Sub-Saharan Africa do not have access to even basic water services

Groundwater forms the basis of water supplies across much of Africa and its development is rising as demand for secure water increases (MacDonald et al., 2021). Groundwater resources in Africa are often considered as having the potential to bring about overall socio-economic transformation (Foster et al., 2012), to overcome current hydrologic variability (Grey and Sadoff, 2007) and to meet future demand. Recent studies call for the 'sleeping giant' of groundwater to be wakened (Cobbing and Hiller, 2019) through increased use of shallow groundwater for irrigation (Gowing et al., 2020) and through solar-powered groundwater development for irrigation and piped water schemes (Wu et al., 2017; Gaye and Tindimugaya, 2019).

The promise that groundwater holds is not just aspirational. Extensive hydrogeological investigation across the continent reveals that Africa possesses large groundwater resources. MacDonald et al. (2012), who produced the first quantitative groundwater map of Africa, estimated total groundwater storage in Africa to be 0.66 million km^3 (0.36–1.75 million km^3). Not all of this groundwater storage is available for abstraction, but the estimated volume is more than 100 times that of the estimated annual renewal of freshwater resources in Africa (MacDonald et al., 2012). Interestingly, with regard to climate change, Cuthbert et al. (2019a) concluded that future climate trends could affect Africa's surface water supplies but might not decrease groundwater resources due to the dependence of recharge on intense rainfall events, which are forecast to increase in the future. Therefore, groundwater is expected to be increasingly used as source of reliable water supply throughout Africa (Giordano, 2009; MacDonald and Calow, 2009). However, heterogeneity in recharge, aquifer storage and permeability will determine which subregions can benefit the most from groundwater. Aquifer storage and recharge determine the resilience of groundwater systems to climate change and thereby determine future water security. According to MacDonald et al. (2021, Figure 8.1, pp. 10–11), "*most African countries with little groundwater storage have high annual rainfall and therefore regular recharge. Conversely, many African countries with low rainfall, usually* *considered as water insecure, have considerable groundwater storage, which was mostly recharged millennia ago. […] Several countries, particularly, (but not exclusively) in North Africa have considerable water security when groundwater storage is taken into consideration. This storage provides a significant buffer before abstraction will impact the regional groundwater system*". However, current groundwater pumping will ultimately be at the expense of future generations. The economic, financial and environmental aspects of storage depletion should not be overlooked. Groundwater storage is generally low in West and Central Africa (Figure 8.1). In these subregions, the groundwater storage is replenished regularly and is a reliable source of water, although the limited storage capacity can mean that the countries in this area may be vulnerable to prolonged periods of drought.

Developing groundwater's potential to generate positive livelihood outcomes depends on many local and regional geophysical and governance challenges. One of the hydrogeological challenges is groundwater quality. Most of the groundwater storage is either fresh or brackish in nature. However, a considerable number of aquifers in arid and semi-arid areas as well as in coastal plains are impacted by geogenic contaminants such as salinity and fluoride (Idowu and Lasisi, 2020). Examples include the saltwater intrusion in coastal plains of North Africa spanning from Egypt to Tunisia. Groundwater in the East African Rift often has high concentrations of fluoride: a study in Ethiopia found that more than 40% of boreholes in the Ethiopia Rift valley has concentrations above the guidelines established by the World Health Organization (WHO) and therefore constitute a major risk to health (Tekle-Haimanot et al., 2006).

Figure 8.1 Groundwater resilience to climate change. High groundwater storage buffers against short-term changes in rainfall, and high average long-term groundwater recharge enable an aquifer to recover rapidly after drought.



Source: MacDonald et al. (2021, fig. 4, p. 7). Contains British Geological Survey material © UKRI 2021. Under the CC BY 3.0 IGO licence.

Anthropogenic groundwater quality deterioration is also on the rise, caused by factors such as mining activities (e.g. South Africa), poor irrigation practices (e.g. in the Nile Valley and the Senegal River basin) and urbanization (e.g. Nairobi, Accra, Maputo, etc.) (Lapworth et al., 2017). A recent survey across Ethiopia, Malawi and Uganda reveals that nearly 20% of water wells exceeded the WHO standard for bacteriological quality (Lapworth et al., 2020). Groundwater quality problems may be exacerbated by climate change and sea level rise, leading to increased salinization of groundwater systems through evaporative concentration or seawater intrusion. Recharge from intense rainfall events may also increase bacteriological contamination. Because of its diverse geologic setting, the 40,000 km-long coastal zones of Africa are comprised of a myriad of aquifer systems (Steyl and Dennis, 2010) with remarkable differences in the state of saltwater intrusion. Saltwater intrusion induced by overexploitation of coastal aquifers has led to salinity increase in a number of countries, including Egypt, Kenya, Libya, Tanzania and Tunisia, among others.

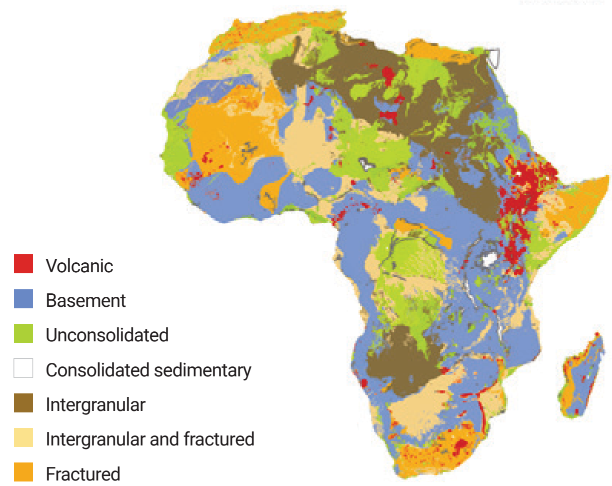
8.1.3 Availability and usage of groundwater resources for irrigation

Four broad aquifer classes underlie a large part of the Sub-Saharan area and are shown in Figure 8.2 (MacDonald et al., 2012):

1. *Volcanic rocks* – complex multi-layered aquifers underlying much of the Horn of Africa, with variable yields where groundwater generally occurs in fractures;
2. *Weathered crystalline basement* – an extensive but patchy shallow aquifer of low borehole yield, of about 1 l/s, and low storage potential;
3. *Major unconsolidated formations and minor alluvial deposits* – shallow unconsolidated aquifers providing moderate yields and often favourable recharge rates due to their connection to rivers; and
4. *Consolidated sedimentary rocks* – thicker aquifers of variable recharge but with prospects of higher yields at higher drilling costs.

Figure 8.2

The distribution of the main aquifer types in Africa



Source: MacDonald et al. (2012, fig. 4B, p. 6). Contains British Geological Survey material © UKRI 2012. Under the CC BY 3.0 IGO licence.

Current use of groundwater for irrigation is limited, partly due to the cost implications associated with groundwater exploration and construction, and difficulties in financing. According to Siebert et al. (2010), only 3–5% of total cultivated land in Sub-Saharan Africa is under irrigation, with the majority concentrated in three countries: Madagascar, South Africa and Sudan. Agriculture is, however, the main source of livelihood for many people. The agricultural sector accounts for about 30% of the gross domestic product (GDP) in Sub-Saharan Africa but employs about 65% of the population, the majority of whom are women (World Bank, 2018a), yet crops are produced almost entirely under rainfed conditions. Given the importance of the agricultural sector in Africa, any improvement in the sector has the potential of transforming the living conditions of the population. The development of groundwater could act as a catalyst for economic growth by increasing the extent of irrigated areas and therefore improving agricultural yields and crop diversity, and ultimately transforming the entire value chain (Schoengold and Zilberman, 2007).

8.1.4 Challenges related to groundwater exploitation

Despite the great potential for groundwater development in the Sub-Saharan region, several factors hamper an increased use of the resource. Most of these challenges are common across countries. The main governance challenge is to overcome inertia in the institutional setup. Up until the last decade, groundwater has received little attention from policy-makers. For instance, while South East Asian countries tapped their groundwater resources to transform agricultural activity in the 1970s and 80s, there was no such effort in Africa. Africa has also missed many other landmark global groundwater development trends. Globally, many countries started building groundwater databases and developing hydrogeological maps in the 1980s, but these are still rare in Africa. Regular monitoring of groundwater levels or quality, the first step to groundwater management, is restricted to only a few countries (IGRAC, 2020). There are few universities that teach groundwater as a subject, and few professional bodies for hydrogeologists or drillers. Data and information sharing is still in its infancy, despite the rapid growth and availability of data capturing tools. Regulatory frameworks to protect and safeguard groundwater at national levels are either weak or not enforced. There are signs that groundwater is beginning to be taken more seriously, possibly due to the realization of the major role that groundwater plays in achieving water supply targets. For example, several continental-, regional- and national-level initiatives have recently been established. These include, for example, the South African Development Community's (SADC) Groundwater Management Institute, and the Groundwater Desk Office and its associated groundwater programme within the African Ministerial Council on Water (AMCOW).

Finance continues to be a critical issue for developing groundwater resources. The funding gap between current spending and what is required to achieve Sustainable Development Goal (SDG) 6 is highest for Sub-Saharan Africa, where the achievement of universal water supply would require ten times the current level of investment of US$13.2 billion (Watts et al., 2021). A large proportion of this amount is required for operation, maintenance and rehabilitation of existing systems, which often fail to attract funding.

Qualified personnel with the capacity to conduct hydrogeological and geophysical studies is rare

Qualified personnel with the capacity to conduct hydrogeological and geophysical studies is rare. Therefore, work is often carried out by semi-skilled personnel, which often results in poor-quality construction or inappropriately sited boreholes, leading to long-term problems with functionality. For siting and constructing the higher-yielding boreholes required for large-scale irrigation or town supplies, the complex hydrogeological environment found in much of Africa demands considerable expertise, which – again – is difficult to find. The general lack of groundwater professionals impacts the staffing of institutions and of local and national government offices in many countries, hampering emerging initiatives to oversee effective groundwater monitoring, planning and development.

The nature of the groundwater resources can also be a challenge for groundwater development. Much of the continent is underlain by crystalline rock aquifers, which generally limits borehole yields to less than 1 l/s. Several countries in East Africa are underlain by volcanic rock aquifers, which have limited storage and complex flow paths (Figure 8.2). The large sedimentary aquifers of Northern Africa are generally located far from the point of need. Groundwater quality in the East African Rift can be a challenge due to the elevated fluoride levels, and the anthropogenic contamination in urban areas is often compounded by poor sanitation. Widespread contamination from nitrate or pesticides has not yet been identified, although this may follow the patterns observed in other parts of the world as agricultural practices intensify. Although still often cheaper to treat than surface water, costs for treating groundwater are likely to rise.

8.1.5 Case studies and best practices

There are many examples of groundwater development across Sub-Saharan Africa. Box 8.1 gives the example of Cape Town and the measures the city took to ensure that the taps continued to flow. Historically, Cape Town depended on surface water sources to meet its water needs. However, increase in population coupled with climate change caused a water shortage crisis, and groundwater became part of the solution.

Box 8.1 Cape Town water supply crisis

Cape Town is South Africa's second-largest city with a population of about 3.7 million people. Six reservoirs in the mountains around Cape Town supply most of the city's water, storing a combined maximum of about 900 million m^3. Beginning in 2015, a severe drought reduced the volumes stored in these reservoirs to critical levels. Without good rains in 2018, there was a real possibility of a 'Day Zero', when the city's taps would run dry.

Cape Town responded to the crisis in several ways. Leaks in the system were reduced to about 17%, half of the national average. Campaigns and water restrictions halved total water use in the city to about 200 million m^3/year. Temporary desalination plants and emergency groundwater bolstered the supply (with 6 million m^3/year and 55 million m^3/year, respectively). Stand-alone boreholes were drilled at schools, hospitals and other important locations to reduce their vulnerability to Day Zero.

Source: Adapted from World Bank (2018a, Box 6, p. 34).

In 1990, the Nairobi City Council closed down wells used to supply water to the city when surface water supply from the Tana River (with a capacity of 520 Ml/day) was commissioned. However, in 2002, supply mains failure (due to a landslide), coupled with persistent high leakages and fiscal losses from the distribution system, meant that the demand from the city could no longer be met and water availability was reduced to below 200 Ml/day. As a result, many boreholes were drilled and capacity increased to about 300 Ml/day. As such, this (mainly) private drilling has managed to mitigate a water supply crisis (Tuinhof et al., 2011).

Another tool used in the region is the Managed Artificial Recharge (MAR) of aquifers, which involves landscape modification or infrastructure development to enhance water infiltration into the ground for use during dry periods (see Box 7.1 and Section 11.5). An example of this technology is its adoption in Windhoek (Box 8.2).

8.1.6 Opportunities and responses from the region

The further development of groundwater in Sub-Saharan Africa is not currently limited by a lack of groundwater, but rather by a lack of investment

It is clear that opportunities exist in Sub-Saharan Africa for the increased development of groundwater resources to meet the growing demand caused by population and economic growth, rapid urbanization, and the increasing demands of irrigation. As climate change continues to affect precipitation patterns, causing increasing pressure on the existing surface water resources, groundwater offers the buffering capacity to protect against these uncertainties and provide a more reliable water supply. The conjunctive use of groundwater and surface water offers considerable potential, with groundwater supplies adding resilience and capacity to existing surface water resources, especially in rapidly growing cities (Jacobsen et al., 2013).

However, the increasing development of groundwater may threaten the ecosystem service that groundwater provides as baseflow to rivers and aquatic ecosystems. Already, baseflow has been shown to reduce in Nairobi, where groundwater has been extensively developed (Oiro et al., 2020), and groundwater discharge to rivers from abandoned mines has caused extensive contamination in South Africa (Ochieng et al., 2010). Transboundary aquifers also require particularly management, but in many circumstances, they promote joint working and understanding, rather than causing conflict.

Box 8.2 Windhoek's Managed Artificial Recharge (MAR) scheme

Windhoek (Namibia's capital) receives annual rainfall of 360 mm, making it one of the driest capital cities on Earth. In the early 1990s, Windhoek's existing water sources (three dams and a groundwater wellfield) began to struggle to meet growing water demands. Studies showed that new sources of water, such as desalinated seawater that would have to be pumped from the coast, were far away and would be costly to develop.

City planners responded with an innovative set of solutions: during times of surplus, treated water was stored underground in aquifers, so that it was protected from evaporation and could be used during times of shortage. Windhoek also began to reuse a proportion of its wastewater, treating it to drinking water standards at a new treatment plant. Other strategies employed included demand management, aimed at identifying leaks, restricting garden watering and increasing public awareness. Windhoek then began to operate a 'dual pipe' water supply in some areas: semi-purified sewage from an old water treatment plant was distributed to sports fields, parks and cemeteries for irrigation, further saving potable water. Windhoek's MAR scheme and other water management actions have proved far less expensive than other water supply solutions, and made Windhoek a world leader in the sustainable use of reclaimed water, and in MAR.

Source: Adapted from World Bank (2018a, Box 7, p. 36).

The further development of groundwater in Sub-Saharan Africa is not currently limited by a lack of groundwater, but rather by a lack of investment. There is a pressing need to find ways to unlock the potential of groundwater, in order to help develop sustainable livelihoods and achieve equitable growth. This involves investments in infrastructure, institutions, trained professionals and knowledge of the resource.

Technological advancements (such as Earth observation, renewable energy and advanced drilling methods) can support the development of groundwater, but must be accompanied by a strong professional groundwater community, to get the best from the technologies.

Historically, investments in groundwater were viewed less favourably than surface water schemes, since much of the infrastructure was invisible and therefore thought more subject to corruption. However, studies in Sub-Saharan Africa have shown that groundwater development does not suffer disproportionately from corruption (Plummer, 2012). Investments to promote safer and more efficient construction standards will be necessary to improve the functionality of water points. Investments in the institutions required to manage groundwater are also necessary to ensure that future developments do not threaten the sustainability of the resource.

8.2 Europe and North America

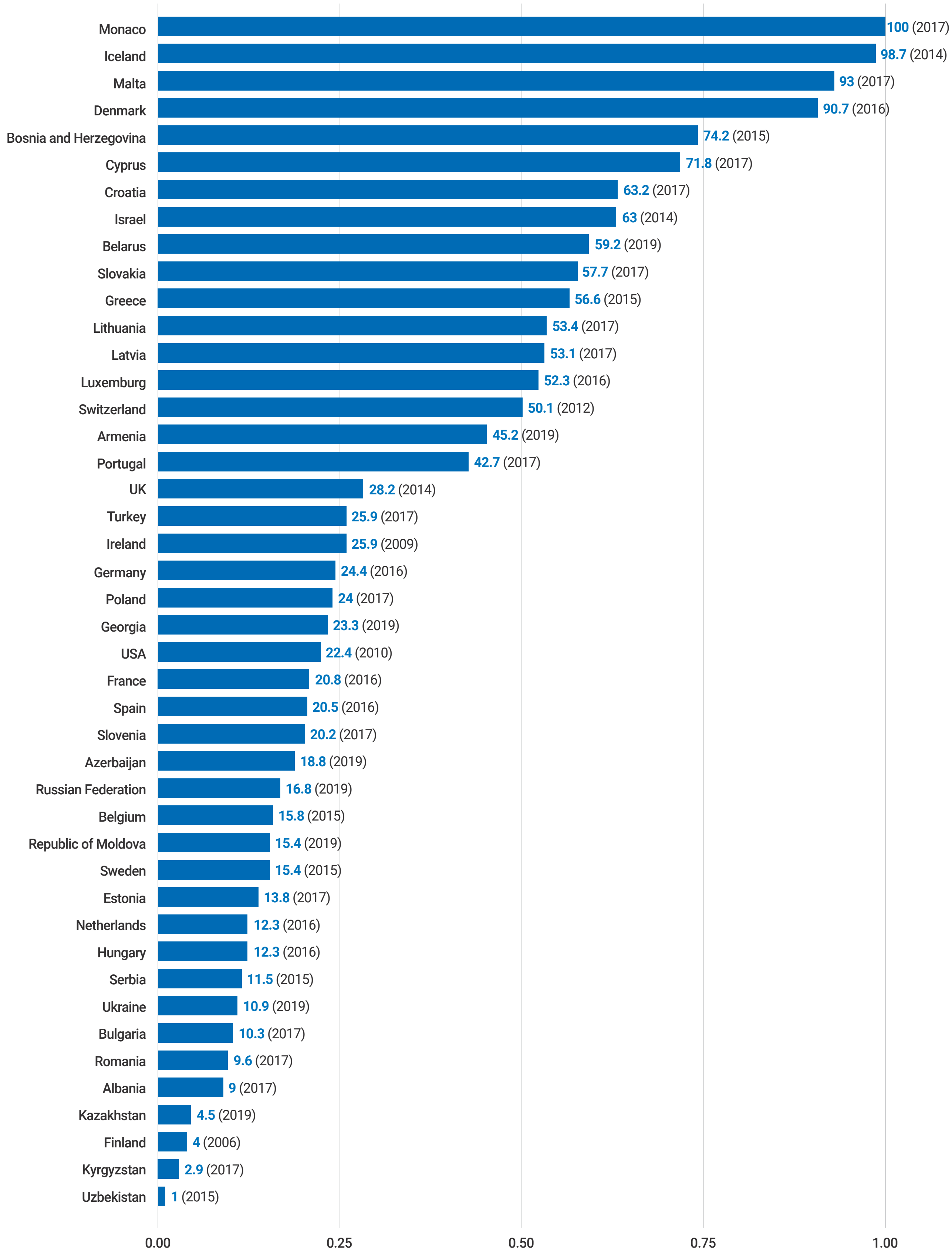
The characteristics of groundwater resources and their availability vary between and within pan-Europe and North America, reflecting the differences in geology and hydrology (see the Prologue, Figure 6). This chapter briefly describes groundwater abstraction in the different subregions, the particularities of governance in each, and a few pressing challenges specific to groundwater (e.g. pollution).

8.2.1 Abstraction and use of groundwater resources

The share that groundwater makes up of the total withdrawal of freshwater varies greatly per country across pan-Europe and North America, ranging from 1 to 100% (Figure 8.3).

In 2017, 24% of total water abstraction in the area of the European Union, Iceland, Liechtenstein, Norway, Switzerland and Turkey was from groundwater (EEA, 2019). Groundwater makes up an important source of household water: some 75% of the European Union's (EU) inhabitants depend on groundwater for their water supply (European Commission, 2008). For the purposes of industry and agriculture (irrigation), groundwater is also important.

Figure 8.3 Fresh groundwater abstracted as a percentage of total (gross) freshwater abstracted in selected countries (latest year available)



Source: UNSD, based on data from Eurostat, OECD and the UNSD Environment Questionnaire.

In the USA, the abstraction of fresh groundwater in 2015 was estimated to amount to 311.5 million m³/day, about 8% more than in 2010 (Dieter et al., 2018), while total freshwater withdrawals have been trending downward since 2005. In Canada, 30.3% of the population relies on groundwater for municipal, domestic and rural use (Government of Canada, 2013).

8.2.2 Evolving management and governance of groundwater

Table 8.1 provides an indicative overview of some regional integration aspects of groundwater governance in the subregions discussed in this chapter.

Table 8.1 Some general characteristics of groundwater governance for each subregion, from a regional integration perspective (indicative only)

Subregion	European Union (EU)	Eastern Europe, Caucasus and Central Asia	North America
Level of regional integration and consistency of approaches to groundwater governance	The Water Framework Directive (WFD) and the Groundwater Directive incorporate an integrated approach to surface water and groundwater. Regional harmonization and policy coherence are fostered by the EU Common Implementation Strategy, including its Working Group on Groundwater.	Historically, the area had a common approach, which has diversified over time within the countries. Groundwater commonly falls under different authorities than surface water. There is some uptake, progressively, of the WFD approach (groundwater bodies etc.) in the neighbourhood of the EU.	Decentralization: Individual (federated) states (USA) and provinces and territories (Canada) play a key role in groundwater management. There are significant differences between the states of the USA in terms of groundwater policy, also regarding linking to surface waters.

The environmental objectives of the EU Water Framework Directive (WFD), which has since the year 2000 provided a regional legal framework in water policy, oblige the EU Member States to prevent deterioration of good status and protect, enhance and restore good groundwater status, involving consideration of both quantitative and chemical status (Box 8.3).

The EU Water Framework Directive has contributed to harmonizing approaches to delineating and assessing groundwater bodies

The WFD requires identifying and characterizing groundwater bodies and – in conjunction with monitoring data – to assess the impacts of human pressures on groundwater. It also addresses the risks of failing to meet environmental objectives, and establishes measures for achieving and keeping good quantitative and chemical status. The WFD has contributed to harmonizing approaches to delineating and assessing groundwater bodies (GWBs), also in the EU's neighbourhood (Box 8.4).

In a number of countries of Eastern Europe, the Caucasus and Central Asia, the principle of integrated management of surface water and groundwater has been until recently missing in water laws. Better protection was needed as, for example, licensing of abstraction was insufficiently used and monitored (UNECE, 2011). In many of these countries, groundwater monitoring and assessment degraded after the break-up of the Soviet Union, even if some countries maintain a strong scientific-technical tradition. Georgia is a case in point: there were no centralized monitoring activities from 1990 to 2013, and since 2013 monitoring stations have been gradually added or reactivated, with different projects' support (EUWI+, 2020). Frequent political and administrative changes have in many cases resulted in fragmentation, and groundwater monitoring and assessment is still commonly separated from overall water management.

In the USA, there have also been substantial changes in groundwater governance, and there are significant differences between the individual states' legal frameworks for groundwater, including in how the hydrologic connection between surface water and groundwater is reflected (Megdal et al., 2014). Most legal frameworks treat water quantity and quality separately, with separate state agencies in charge (Gerlak at al., 2013). In California, the Sustainable Groundwater Management Act (California Department of Water Resources, 2014) introduced a state-wide groundwater governance framework that established local Groundwater Sustainability Agencies. These have frontline responsibility for developing and implementing regulatory

Box 8.3 Quantitative and chemical status of groundwater bodies in the European Union

During the second cycle of River Basin Management Plans (2016–2021) in the EU, the status of groundwater bodies was assessed (EEA, 2018a; see Figure below), showing that a good chemical status has been achieved for 74% of groundwater bodies (GWBs, a management unit), while good quantitative status had been achieved for 89% of the groundwater bodies (EEA, 2019). For a good quantitative status, the available groundwater resource should not be reduced by abstraction, but also impacts on linked surface water or groundwater-dependent terrestrial ecosystems, among others, should be avoided.

Quantitative and chemical status of groundwater bodies

Note: (*): Regional average; AT (Austria), BE (Belgium), BG (Bulgaria), CY (Cyprus), CZ (Czech Republic), DE (Germany), DK (Denmark), EE (Estonia), ES (Spain), FI (Finland), FR (France), GR (Greece), HR (Croatia), HU (Hungary), IE (Ireland), IT (Italy), LT (Lithuania), LU (Luxembourg), LV (Latvia), MT (Malta), NT (The Netherlands), NO (Norway), PL (Poland), PT (Portugal), RO (Romania), SE (Sweden), SI (Slovenia), SK (Slovakia) and UK (United Kingdom).

Source: EEA (2018a), based on data reported by the EU Member States under the Water Framework Directive.

Box 8.4 Challenging transition from hydrogeological assessment to accounting for human pressures

The European Union Water Initiative Plus for Eastern Partnership Countries (EUWI+, 2016–2021) supported the implementation of the Water Framework Directive (WFD) integrated management principles to surface water and groundwater in the Eastern Partnership countries Armenia, Azerbaijan, Belarus, Georgia, Republic of Moldova and Ukraine. In particular for groundwater, it was a challenging change, switching from the earlier, traditional approach focusing at individual local problems and describing the hydrogeological situation and the chemistry of groundwater only, to a more holistic perspective of delineating groundwater bodies (GWBs, the WFD management units) and also considering the relevant human pressures and their impacts on groundwater quantity and chemistry. With the support of EUWI+, in total 117 groundwater bodies were delineated (including 42 transboundary ones). Cooperation between Belarus and Ukraine, both taking steps to apply the WFD, to identify transboundary GWBs (Lyuta et al., 2021) demonstrates the process and underlines the need to harmonize across borders.

controls concerning groundwater management (Kiparsky at al., 2017). In Canada, the Constitution defines that provinces and territories have primary legal jurisdiction over water and groundwater, while the federal Government has powers to manage groundwater on federal lands, including national parks (Rivera, 2014).

For the 42 countries sharing waters in Europe and Northern America, legal and institutional frameworks for transboundary cooperation increasingly cover aquifers

For the 42 countries sharing waters in Europe and Northern America, legal and institutional frameworks for transboundary cooperation increasingly cover aquifers. Out of the 36 countries sharing transboundary aquifers in the region, 24 have reported that operational arrangements cover 70% or more of their transboundary aquifer area (UNECE/UNESCO, 2021). The institutional and legal frameworks, notably the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, have strengthened cooperation in the region (Lipponen and Chilton, 2018).

8.2.3 Groundwater-related challenges and opportunities

Three challenges that either affect groundwater resources, and therefore the uses and socio-economic activities that depend on them, or in which groundwater is part of the solution, are illustrated with examples below: climate change and water scarcity, groundwater-dependent ecosystems and, lastly, pollution, including emerging pollutants.

Climate change and water scarcity

States across the region are grappling with the challenge of dealing with water abstraction pressures, further aggravated by climate change, and groundwater is a crucial resource in this regard, providing some possible solutions.

In 2015, during the summer months, 33% of the population in the region covering the European Union as well as Liechtenstein, Norway and Switzerland was exposed to water stress conditions[27] (EEA, 2019). The EU member States are exchanging information on good practices to deal with water abstraction pressures, taking into account climate change. A guidance document on MAR is under development in the EU.

The measures foreseen by the Government of Kazakhstan (2018) aim to reduce water scarcity, both at the national and regional levels, allocate transboundary water resources, use groundwater efficiently and sustainably, build new infrastructure, increase the forest cover of catchment areas, and implement environmental releases.

In the USA, declining groundwater levels and conflicts between users are among the top common priorities for groundwater governance that state agency officials have identified (along with water quality and contamination) (Megdal et al., 2014; Petersen-Perlman et al., 2018).

[27] As defined here, 'water stress' occurs when the percentage of water use against renewable freshwater resources in a given time and place (in this example at river basin level) exceeds 20%.

Water marketing has been studied in the USA as a means to provide a financial incentive for groundwater right holders to invest in water conservation in order to make a profit on the unused water or on the transfer to other users. In the state of Arizona, decreased water availability has led to the use of effluent as an alternative source, while statutory changes authorize long-term tradable storage credits through aquifer recharge from the Colorado River water or effluent (Bernat et al., 2020).

Groundwater-dependent ecosystems

In the EU, the River Basin Management Plan cycle ending in 2021 shows that the linkage between groundwater and its associated aquatic ecosystems and groundwater-dependent terrestrial ecosystems is increasingly considered by the Member States. This serves to better identify such ecosystems, to further consider quantity and quality aspects, and to continue establishing appropriate groundwater threshold values derived from ecosystem needs. Progress is supported by technical reports (e.g. European Commission, 2011, 2014a, 2015).

In many countries of Europe, groundwater is principally used for drinking water, which underscores the need to control water quality for potential health risks

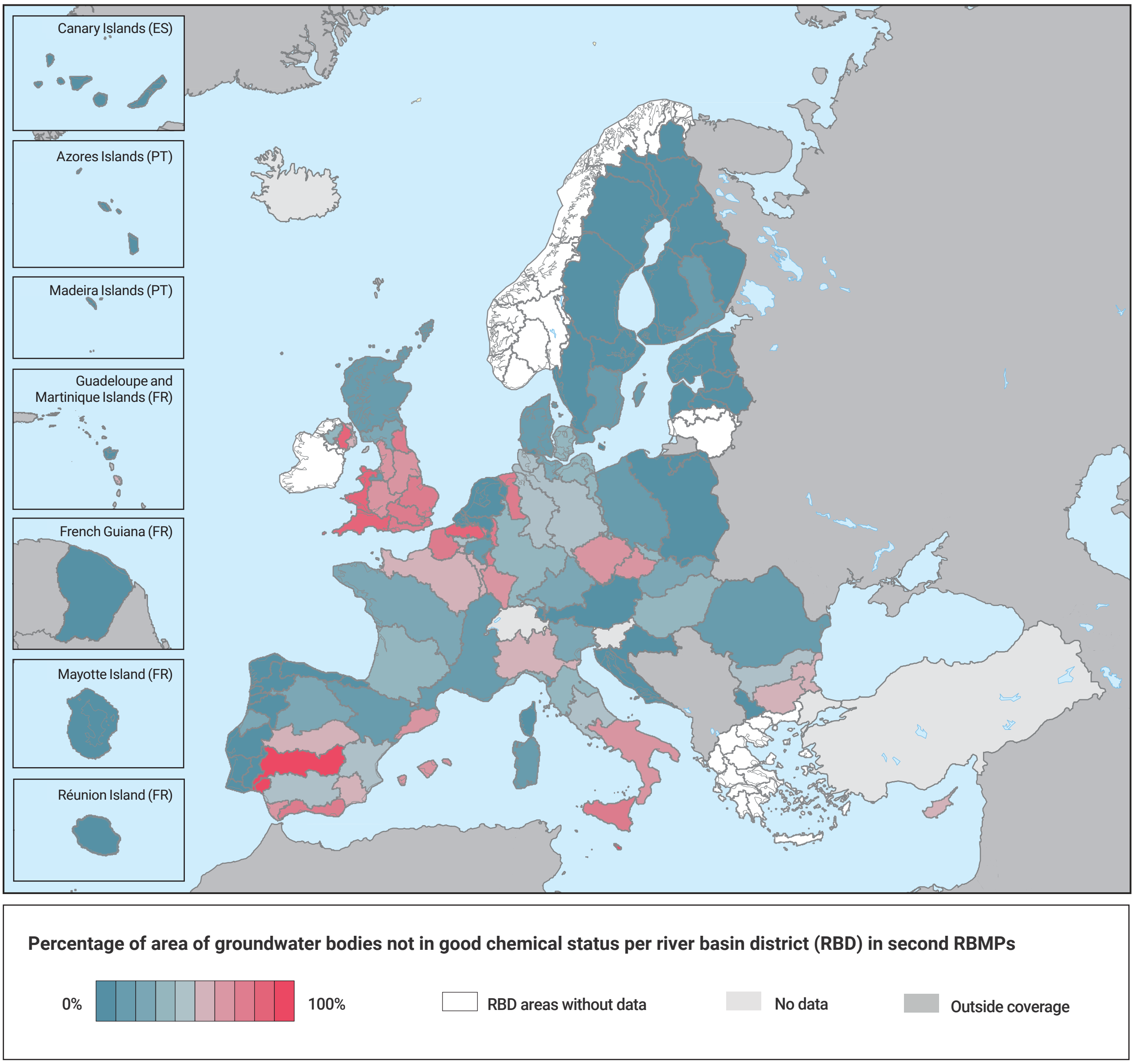
MAR provides ways to take advantage of subsurface storage in aquifers for variable flows (see Box 7.1 and Section 11.5). Environmental non-governmental organizations (NGOs) quantify groundwater recharge to local aquifers, as well as its ecosystem benefits and flood risk reduction, which helps create partnerships with multiple benefits. In California, farmers can receive monetary compensation for recharging groundwater in the early fall when water is particularly scarce. Such controlled flooding practices also provide critical temporary wetland habitats for shorebirds migrating along the Pacific Flyway, which often have nowhere to stop over on long migrations (The Nature Conservancy, n.d.). Further experience from the USA shows that water funds have allowed to protect green space in and around local communities and, in the case of the Edwards Aquifer in Texas which supplies the city of San Antonio, to improve quality of the water that is recharging aquifers (The Nature Conservancy, 2019).

Groundwater quality, pollutants and health risks

The pollutants that most commonly cause poor chemical status in the EU are nitrates as well as pesticides. While pollutants from agriculture dominate (and this problem is not limited to Europe), industrial chemicals and substances related to mining also lead to chemical groundwater pollution in several river basin districts (Figure 8.4 – EEA, 2018b). More information is needed concerning 'new' (or 'emerging') pollutants in groundwater. A process of establishing a 'Watch List' for substances in groundwater started in line with EU Directive 2014/80/EU (amending the Groundwater Directive, 2006/118/EC, under the WFD umbrella) to both "*increase the availability of monitoring data on substances posing a risk or potential risk to bodies of groundwater, and to facilitate the identification of substances, including emerging pollutants, for which groundwater quality standards or threshold values should be set*" (European Commission, 2014b). So far, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS) and non-relevant pesticide metabolites have been considered.

In many countries of Europe, groundwater is principally used for drinking water, which underscores the need to control water quality for potential health risks. Such efforts are supported by reporting on the national targets that were set by countries in the framework of the UNECE/WHO Protocol on Water and Health (UNECE/WHO, 2019). Reflecting a more widely emerging issue, the Netherlands reported the management of new substances, such as pharmaceuticals, microplastics and nanoparticles among the challenges of concern to groundwater, along with surface water (OECD, 2019a). In one study in the USA, at least one hormonal or pharmaceutical compound was detected in 6% of 844 groundwater sites used for public supply, suggesting that the aquifers had limited vulnerability to contamination by these compounds (Bexfield at al., 2019). However, some of these emerging organic pollutants and their metabolites may pose a threat to groundwater bodies, possibly for decades under certain conditions, due to long residence times (Lapworth et al., 2012).

Figure 8.4 Percentage of area of groundwater bodies 'not in good chemical status' per river basin district



Source: Adapted from EEA (2018b, map 4.1, p. 51).

In Eastern Europe and the Caucasus, a limited scope of monitoring (substances and/or frequency) and/or the restrictive way it has been laid down in legislation is sometimes hindering the application of a risk-based, cost-efficient monitoring approach (surveillance and operational monitoring).[28]

8.2.4 Responses to groundwater challenges

The diverse legal and governance systems result in different solutions being deployed in the European Union, Eastern pan-Europe (Eastern Europe, Caucasus and Central Asia) and North America (Table 8.2). In addition to the need for collaboration among different water users in a given region, there is an increasing awareness of the transboundary nature of many groundwater resources, and, therefore, of the need for interjurisdictional cooperation (see Chapter 12).

[28] UBA (unpublished).

Table 8.2
Selected governance and/or management responses to groundwater challenges in each subregion (indicative only)

European Union (EU)	Eastern Europe, Caucasus and Central Asia	North America
Improving the quantitative and chemical status of groundwater in the overall objective of the framework of River Basin Management Plans. Harmonizing approaches across the EU. Improving policy coherence (supported by cross-cutting strategies like the EU Action Plan *"Towards a Zero Pollution Ambition for Air, Water and Soil – Building a Healthier Planet for Healthier People"*).	Implementing technical solutions to groundwater (e.g. modernizing water infrastructure and improving efficiency). Strengthening environmental protection, including that of groundwater resources.	USA: Market-based mechanisms and incentivizing. Water markets, reallocation of water rights or storage credits. Partnerships between conservation organizations and economic sectors for multi-benefit projects.

Like groundwater quantity, groundwater quality concerns are paramount. Studies and research from the region have revealed groundwater quality problems, including due to emerging pollutants. In order to have cost-effective and sustainable monitoring in the long term, some priorities have to be set to strike a balance between having sufficient coverage of monitoring but also adequate attention to specific pollutants. Groundwater monitoring and expertise is commonly held by specialized institutions, while the implementation of the water policy instruments (for example WFD, as indicated in Table 8.1) calls for cooperation between institutions. Indeed, many pressures and drivers are the same for ground- and surface water. Integrated policies and efforts to ensure coherence are being developed.

8.3 Latin America and the Caribbean

8.3.1 Introduction

In Latin America and the Caribbean, groundwater represents a relevant water source as it discharges approximately 3,700 km³/year into the region's rivers (Campuzano et al., 2014). This translates into 10,200 m³ per capita/year of renewable groundwater resources, representing just over a third of the average per capita water endowment per year in the region. In addition, due to the relative abundance of surface water and the limited level of groundwater use, less than 30% of the freshwater abstracted comes from groundwater sources. For the countries that do rely on groundwater, approximately half of the extraction is used for irrigation, a third is for domestic use and the rest is for industrial use (Aguilar-Barajas et al., 2015). Reliance on groundwater supplies is likely to increase in coming years due to population growth, urbanization and climate change, among other factors.

In arid and semi-arid zones, groundwater represents a key and strategic resource (Espindola et al., 2020; UNESCO, 2007). This is particularly the case in the so-called Dry Corridor of Central America as well as in Mexico City, among other areas. However, throughout the region there are shortcomings in groundwater's protection and monitoring, giving way to its intensive exploitation and/or contamination, ultimately endangering its sustainability (Campuzano et al., 2014) as well as the water access of the most vulnerable populations, who depend on these groundwater sources for their drinking water supply (WWAP, 2019). See Figure 8.5 for an overview of the groundwater resources and recharge levels in the region.

8.3.2 Main groundwater uses

In northern and central Mexico, northeast Brazil, the coasts of Peru and Chile, and the pre-Andean zone of Argentina, groundwater is mainly used for irrigating crops in the most arid areas (Foster and Garduño, 2009). Groundwater and the subsoil that contains it play an important role in the water supply systems of most Latin American cities, and not only in those where groundwater is the main source of supply (e.g. León, Lima, Mexico

City, Natal, San José and São Paulo, among several others[29]). In countries like Costa Rica and Mexico, groundwater supplies 70% of households in urban areas, and practically sustains all domestic demand in rural areas. It also represents 50% of the water used by the industrial sector (Campuzano et al., 2014). In other countries, aquifers are hardly exploited due to lack of information and other factors (UNESCO, 2007). The mining industry in the region also uses groundwater intensively and competes over it with the agricultural and domestic sectors. In Chile, for instance, 63% of the water used by the mining sector comes from groundwater. Groundwater use in mining represents an important risk of aquifer pollution, which can occur if there are wastewater leakages (Ruz et al., 2020).

Groundwater and the subsoil that contains it play an important role in the water supply systems of most Latin American cities, and not only in those where groundwater is the main source of supply

8.3.3 Groundwater management challenges

Several countries, including parts of Argentina, Brazil, Mexico, Paraguay and Peru face significant overexploitation and contamination of their groundwater. Mexico has tried multiple approaches[30] to improve the management of its overexploited aquifers (Arroyo et al., 2015). Throughout the region, the most common groundwater quality problems are associated with unwanted elements of natural origin (mainly arsenic and fluoride), anthropogenic pollutants (nitrates, faecal pollutants, pesticides), various compounds of industrial origin (mining by-products, organochlorine solvents, hydrocarbons, phenolic compounds, etc.), and emerging pollutants, such as cosmetics, antibiotics, hormones and nanomaterials. For example, in Bolivia, the quality of groundwater is being threatened by industrial, agricultural and domestic pollution, while in Honduras, the high demand for water in urban areas threatens the future availability of this resource (Ruz et al., 2020).

The above-mentioned challenges result in an increase in the number of conflicts over access to and use of water in the region. These conflicts are frequently related to water management decisions across different users, and/or land access conflicts,[31] or revolve around the impacts of activities concerning mineral ores and the extraction of building materials, fossil fuels, climate justice or energy projects. It is estimated that the number of conflicts related to groundwater pollution and depletion that started between 2000 and 2019 is more than four times higher than those started between 1980 and 1999 (ICTA-UAB, n.d.).

8.3.4 Challenges specific to Small Island Developing States (SIDS) and other coastal areas

In the Caribbean, where surface water tends to be relatively scarce, groundwater represents about 50% of the water abstracted. Countries such as the Bahamas, Barbados and Jamaica rely heavily on groundwater resources as their main source of water supplies. In Barbados, groundwater even represents 90% of the total supply, in Jamaica this is estimated at 84%, and in Saint Kitts and Nevis it is around 70%. However, in Grenada, Dominica and Saint Lucia groundwater is hardly utilized, which illustrates the variability across the Caribbean. Overexploitation of aquifers, saline intrusion and pollution pose major threats to groundwater resources in this subregion, turning them into unsustainable sources. "*A major challenge facing water resource managers as well as service providers is the difficulty associated with being able to determine the safe yields of aquifers and to undertake regular assessments of the yield-demand balance. Often the required hydrogeological data, the models and the skilled personnel are all in short supply*" (Cashman, 2014, p. 1192).

In Belize, as well as in many other coastal areas of the region experiencing rapid urban growth, the effects of saline intrusion threaten groundwater quality (Campuzano et al., 2014; IGRAC, 2014; Ruz et al., 2020). In addition, climate change and variability, particularly the increased frequency and intensity of hurricanes, also pose greater threats to Caribbean SIDS, due to

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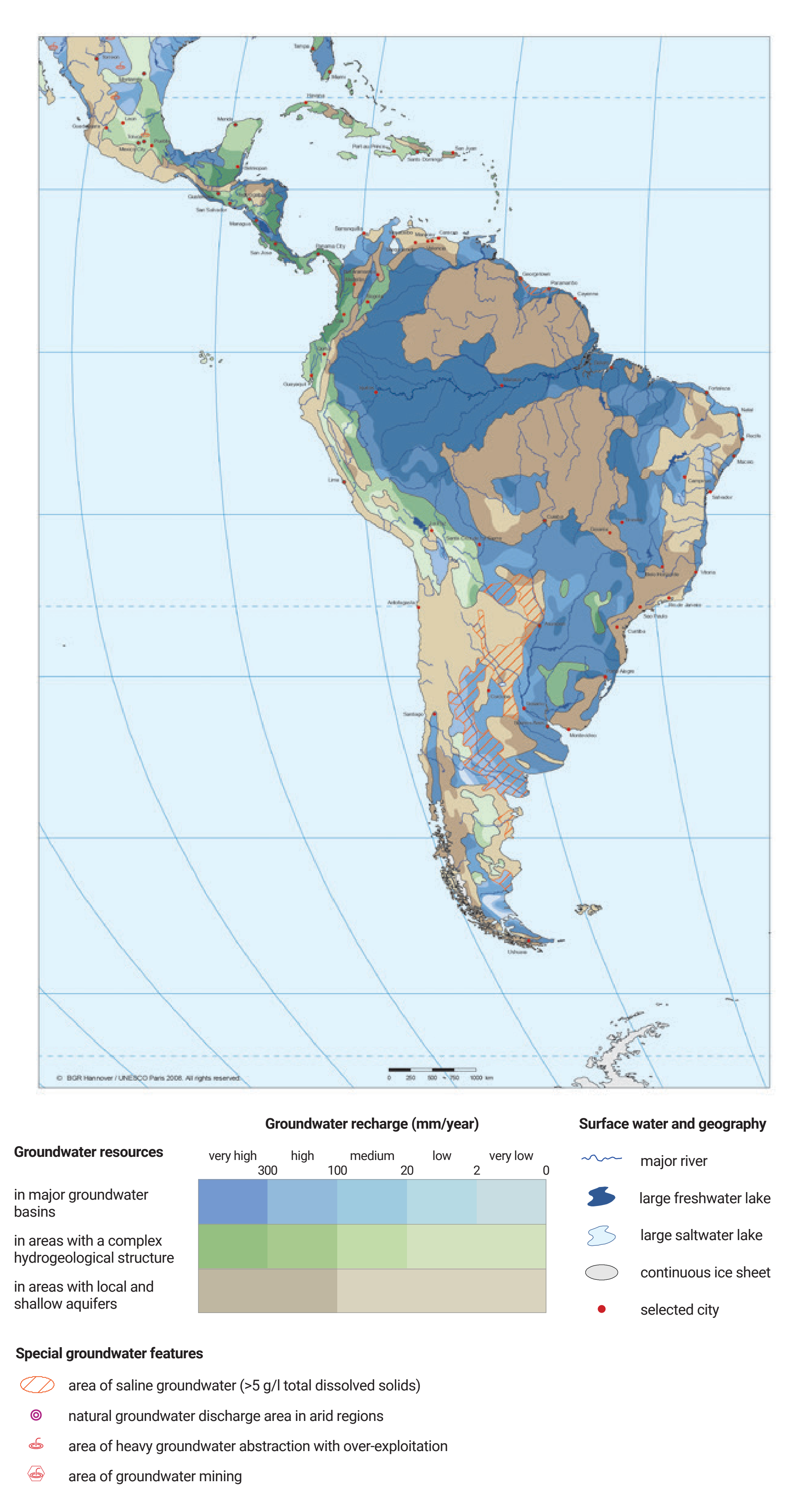
29 In Buenos Aires, where the use of groundwater has decreased significantly as a result of 'surface water imports', sanitary and drainage problems began to occur in several large areas (Foster and Garduño, 2009).

30 Efforts to collect and analyse information, the use of planning and modelling tools, policy-oriented programmes to reduce the overdistribution of water rights, and elimination of rural electricity subsidies.

31 Forests, agriculture, fisheries and livestock management.

Figure 8.5

Recharge rate in main groundwater systems of Latin America and the Caribbean



Source: BGR/UNESCO (2008).

storm surge and well infiltration. Freeport, the capital of the island Grand Bahama, presents an example in case. The town is totally supplied by groundwater. In 2019, the passage of Hurricane Dorian caused storm surges that flooded the main wellfields of the island, salinizing its waters to brackish levels. Although elevated salinity values do not cause immediate health problems, even if ingested, brackish water is very unpleasant to consume (Chaves, 2019).

8.3.5 Monitoring, management and governance

In Latin America and the Caribbean, monitoring networks vary in modality. Some countries have national monitoring programmes, such as Brazil, Chile, Colombia, Costa Rica, El Salvador, Mexico, Peru and Venezuela. Others have local networks, like Argentina, while Bolivia, Paraguay and Uruguay monitor aquifers of specific interest (i.e. the Pura-Purani, Patiño and Raigón aquifers – Ruz et al., 2020). Besides enhanced coverage, frequency and continuity of monitoring tools and systems, the sustainable management of groundwater resources also requires technical knowledge, institutional changes, legal and economic instruments, and social participation. In this respect, a formal system of groundwater usage concessions and rights can directly contribute to the rational allocation, and in some cases to the reallocation of groundwater. Charging groundwater extraction fees can be also an important demand management tool, but it requires a transparent and accepted common basis for quantifying water extraction and use (Foster and Garduño, 2009). Finally, it is also important that information from surface waters be crossed with groundwater, as both resources are often interdependent.

Through the Internationally Shared Aquifer Resources Management (ISARM) Americas programme (UNESCO, 2007; UNESCO/OAS, 2010), 52 transboundary aquifer systems with different degrees of knowledge have been identified in the region.

The Amazon Aquifer System underlies an area estimated to cover 3.95 million km² (OTCA, 2018). The Brazilian National Water Agency (ANA) conducted studies to expand the hydrogeological knowledge of the Amazon Aquifer System in Brazil (SAAB), the largest in the country and one of the largest in the world. The SAAB consists of Cretaceous to Cenozoic sediments of a sandy, silty and clayey nature that cover the hydrogeological provinces of the Amazon and Orinoco. It is part of a transboundary aquifer system that underlies parts of Bolivia, Brazil, Colombia, Ecuador, Peru and Venezuela. In Brazil, it has an area of 2 million km² in the states of Acre, Amapá, Amazonas, Pará, Rondônia and Roraima, with an estimated permanent reserve of 124,000 km³, located in the sedimentary basins of Marajó, Amazonas, Solimões and Acre. The Brazilian states of Pará and Amapá, frequently affected by droughts, rely on this source for 79% and 64% of their freshwater withdrawals respectively (UNESCO, 2007; UNESCO/OAS, 2010; Hu et al., 2017).

The Guarani Aquifer System (GAS) is a transboundary aquifer shared by four countries in Latin America: Argentina, Brazil, Paraguay and Uruguay. The GAS covers an estimated area of 1.09 million km² (OAS, 2009). In regional terms, from the replenishment zones (GAS outcrop areas) to the discharge zones, GAS groundwater tends to flow from north to south, accompanying the orientation of the Paraná Sedimentary Basin. In 80% of the area, the GAS is confined by basaltic rocks, with old to very old water (from 4,000 to >100,000 years – Sindico et al., 2018). The exploitation of groundwater has been intense in some areas, due to the expansion of economic activities and the pollution of surface waters, as well as periodic droughts. Some 80% of the groundwater that is pumped up is used for public water supply, 15% for industrial processes and 5% by geothermal spas (Foster and Garduño, 2009). One of the main features of the GAS is its governance arrangement (Box 8.5).

Another important aquifer is the Pantanal Transboundary Aquifer System, located in the Paraguay River basin. The estimated area of the aquifer is approximately 141,500 km² (102,000 km² in Brazil, 21,500 km² in Bolivia, 18,000 km² in Paraguay) (UNESCO/OAS, 2010). This aquifer system stands out for its key role in the maintenance of the Pantanal ecosystems, the natural regulation of the rainfall regime, and the water supplies of local communities and indigenous populations. Because it is an unconfined aquifer, it is vulnerable to pollution, mainly related to agricultural and livestock activities (García, 2015). In the last decade, it has been

Box 8.5 The Guarani Aquifer Agreement (GAA)

In 2010, the four countries sharing the GAA (Argentina, Brazil, Paraguay and Uruguay) decided to negotiate a treaty (the first of its kind) focusing on the management of the Guarani Aquifer, which is also notable given the absence of serious conflicts over the natural resource (Villar and Costa Ribeiro, 2011). The negotiations went on for a decade and the Agreement on the Guarani Aquifer was ratified by all parties and entered into force on November 26, 2020. The GAA sets out a transboundary aquifer governance framework. It contains the general rules of international law applicable to transboundary water resources (both surface and groundwater). Countries are sovereign but are at the same time committed to cooperate and to not cause significant harm to neighbouring states (GAA, art. 6). Countries will see to use the aquifer rationally, sustainably and equitably (GAA, art. 4). The exact meaning of these concepts will be a weighing-and-balancing exercise based on several factors. While these are not listed in the GAA, they can be found in the emerging international legal framework applicable to transboundary aquifers (United Nations, 1997, art. 6; and ILC, 2008, art. 5). Other management practices are included in the treaty, such as the exchange of information and activities that may affect the aquifer (GAA, art. 8). Of particular importance is the commitment to inform other states if a planned activity may have a transboundary impact (GAA, art. 9). A further provision that is worth highlighting is the reference to critical transboundary areas (GAA, art. 14), which may warrant particular joint attention.

Note: The GAA (2020) is available at: www.internationalwaterlaw.org/documents/regionaldocs/Guarani_Aquifer_Agreement-English.pdf.

threatened by excessive sedimentation in the rivers and in wetlands, caused by accelerated erosion due to deforestation in the highlands and soy plantations. This sedimentation reduces the infiltration and the consequent recharge capacity (UNESCO, 2007).

The importance of aquifers for the region´s ecosystems, social development and economic activities will only further increase in the near future due to climate change and its impacts on the water cycle

In 2006, the ISARM-Americas identified a transboundary aquifer called *Esquipulas-Ocotepeque-Citalá*, located in the tri-national Trifinio area shared by El Salvador, Guatemala and Honduras. The Governance of Groundwater in Transboundary Aquifers (GGRETA) project, aimed at acquiring experience in good governance and management of groundwater, took this aquifer as a demonstration project. In its research on the aquifer, all the available information about the transboundary aquifer was compiled, ordered, analysed, prioritized and systematized, resulting in the identification of information gaps. This study has shown that what was originally supposed to be a single aquifer is, in fact, composed of two aquifers (the Esquipulas and the Ocotepeque-Citalá aquifers) in the valley floor of the upper Lempa River basin. These two aquifers maintain their transboundary character. The Esquipulas Aquifer is shared trilaterally and the Ocotepeque-Citalá system is shared bilaterally by El Salvador and Honduras. In this context, there is growing pressure for adequate monitoring and governance agreements. An additional innovative feature of the GGRETA project is that it incorporates a gender perspective in monitoring, evaluation, and reporting on water. Sex-disaggregated indicators include: male/female perceptions on the adequacy of the current water availability in quality and quantity; male/female perceptions of gender equality in household decisions on water, sanitation and hygiene (WASH); and the presence of women in cooperatives and industries related to water (UNESCO, 2016).

To conclude, sovereign states with both national and transboundary aquifers will require frameworks that help ensure the sustainable use of groundwater resources. In the case of transboundary settings, the latter may require the development and maintenance of supranational institutions, but that alone does not ensure an equitable and sustainable use (see Chapter 12). Similarly, national institutions require both information and authority to foster sustainable usage. The region needs to move towards political processes that harmonize decision-making, monitoring and groundwater management both nationally and internationally. The importance of aquifers for the region´s ecosystems, social development and economic activities will only further increase in the near future due to climate change and its impacts on the water cycle. While regional groundwater resources remain relatively abundant, there is an urgent need for improved management and governance to ensure their sustainable usage. Thus, research, fieldwork and monitoring are expected to close existing knowledge gaps and provide a stronger basis for informed and coordinated decision-making.

8.4 Asia and the Pacific

8.4.1 Overall hydrogeological setting

Asia and the Pacific is the largest region in the world in terms of both area (28 million km²) and population (4.7 billion). Groundwater serves as an important source of freshwater supply and has played a key role in the region's socio-economic development. However, the unsustainable abstraction of groundwater resources, coupled with the impacts of climate change, have led to aquifer depletion and increased water scarcity in a number of areas. Additionally, groundwater quality is under threat due to a variety of anthropogenic and geogenic drivers that further contribute to water stress in the region.

The occurrence of groundwater resources varies across the region due to its various geological settings. Sedimentary aquifers, mainly composed of floodplain alluvial deposits, run along large rivers such as the Ganges, Mekong and Yangtze, and provide favourable conditions for groundwater productivity. In the mountainous regions of Central and Northern Asia, groundwater generally occurs in aquifers made of jointed hard rocks. Although the inland arid areas of Central Asia receive little precipitation and have high evaporative conditions, the thawing of snow and glaciers in the high mountains provide essential groundwater recharge. Aquifers composed of carbonate rock are widely distributed in Southeast Asia, developed karst systems composed of stratified limestone can be found in southern China and parts of the Indochinese peninsula, and aquifers under the Circum-Pacific islands are composed of Quaternary volcanic rock (Lee et al., 2018b; Villholth, 2013b). Figure 8.6 illustrates the region's groundwater resources and recharge.

8.4.2 Groundwater significance

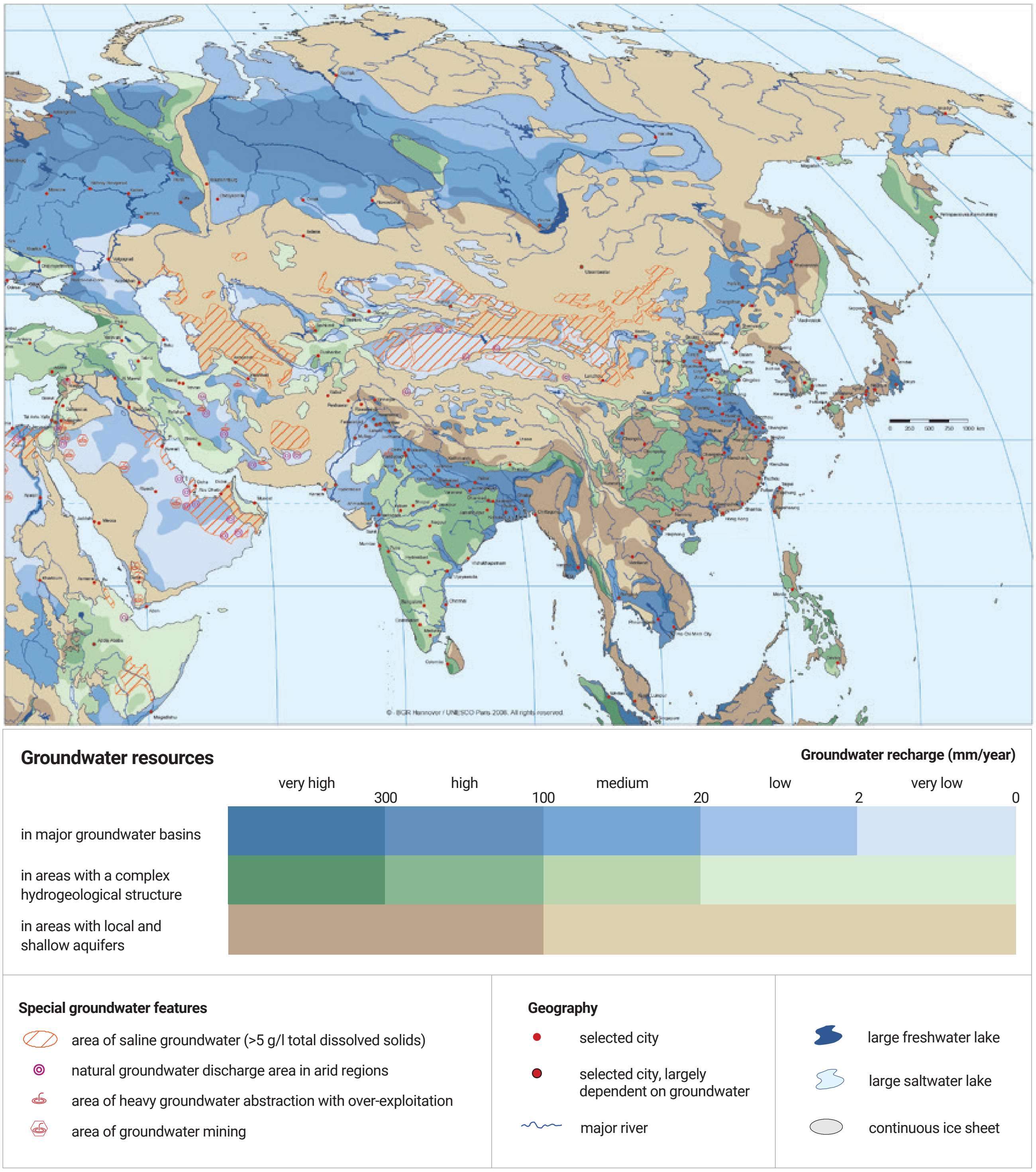
Groundwater serves as an important source of freshwater supply and has played a key role in the region's socio-economic development

The Asia-Pacific region is the largest groundwater abstractor in the world, containing seven out of the ten largest groundwater-extracting countries: Bangladesh, China, India, Indonesia, Iran, Pakistan and Turkey (see Table 5.1). These countries alone account for roughly 60% of the world's total groundwater withdrawal (Aquastat, n.d.). The critical driver of groundwater development in the region is rising demand for water due to growing populations, rapid economic development and improving living standards. Utilization of groundwater resources has provided numerous benefits for irrigation, industrial activity, domestic use, drought resilience and livelihood enhancement. These socio-economic benefits have been particularly crucial for the agricultural sector – a sector that is key to economic development in many developing countries in the region, and that accounts for an estimated 82% of total water withdrawals (Aquastat, n.d.). Rapid growth of groundwater irrigation, particularly in the North China Plain and South Asia between 1970 and 1995, was the main driver of the agrarian boom in the region (Shah et al., 2003). Serving as a critical resource for irrigation, groundwater contributes towards food security and poverty alleviation. The region's dependence on groundwater is associated with the increase in food productivity or the lack of surface water supply. For instance, from 1960 to 2015, India's population nearly doubled and along with it, the country's food production index increased by 330% (Lee et al., 2018b). While irrigated agriculture's dependence on groundwater is evident throughout South Asia and China, the industrial and municipal sectors are also major users of groundwater in urban centres (Kataoka and Shivakoti, 2013). Groundwater is also the preferred source of water for drinking and irrigational needs in South Asia, as surface water channels were historically used as pathways for domestic and industrial waste, making it unfit for consumption (Mukherjee, 2018). Additionally, aquifers provide high buffering capacities against climate variations, which help to stabilize water supply during peak drought seasons.

8.4.2 Challenges

Groundwater is abundant across most of the Asia-Pacific region, but yet, groundwater depletion has led to concerns over the sustainability of groundwater usage in different areas across Central Asia, China, South Asia and certain urban centres in Southeast Asia (Jia et al., 2019; Kataoka and Shivakoti, 2013; Lee et al., 2018b; Mukherjee, 2018). Severe depletion threatens food production, livelihoods and industrial water supplies, and causes land subsidence, seawater intrusion and ecological damage. Climate change also impacts

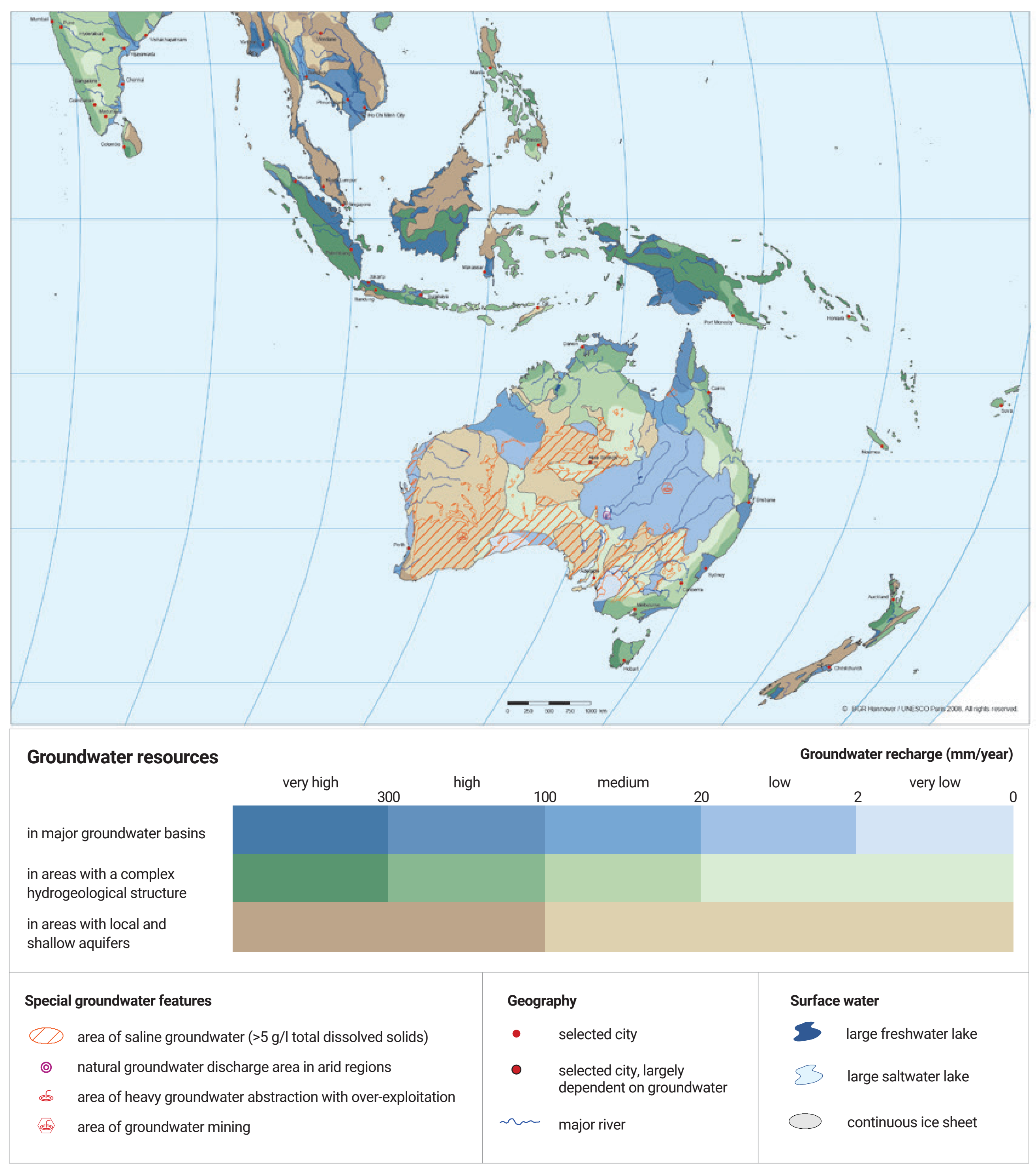
Figure 8.6 Groundwater resources of Asia and Australia & Oceania



Source: BGR/UNESCO (2008).

precipitation variability in the region, further exacerbating pressure on groundwater resources, particularly in areas with semi-arid to arid climates and on Pacific SIDS, where groundwater forms the only reliable source of freshwater but is threatened by rising sea levels (Ashfaq et al., 2009; Asoka et al., 2017; Bouchet et al., 2019; Dixon-Jain et al., 2014). Furthermore, as groundwater extraction is expected to increase in the future due to intensified water demand from economic and household activities, while groundwater recharge will diminish due to climatic variations, the risk of water shortages is also expected to increase (Hofmann et al., 2015).

Figure 8.6 Groundwater resources of Asia and Australia & Oceania (cont'd)



Besides groundwater depletion, groundwater contamination from both anthropogenic and geogenic processes is an additional problem of equal concern, as water that is unfit for consumption also contributes to water stress in the region (Hirji et al., 2017; MacDonald et al., 2016). The mobilization of geogenic contaminants such as arsenic (Indo-Gangetic basin aquifer, Red River delta, Mekong River delta), fluoride (Pacific islands, southern peninsular India, Sri Lanka, central and western China) and uranium (China, India) poses significant health risks to people across the region (Coyte et al., 2018; Hara, 2006; Ministry of Environment of Japan/ IGES, 2018; Le Luu, 2019; Mukherjee, 2018). Anthropogenic contaminants in groundwater, such as heavy metals (i.e. cadmium, chromium, lead, mercury), coliform, salinity and emerging contaminants[32] are an increasing problem (Lapworth et al., 2018; Sui et al., 2015) as rapid urbanization, seawater intrusion, intensive agriculture and industrial activity continue to increase in the Asia-Pacific region. Additionally, disinfection by-products (DBPs) require attention as chlorinating groundwater with halides and dissolved organic carbon (DOC) may promote the formation of toxic DBPs in drinking water (Coyte et al., 2019).

Rapid economic and population growth compounded with poor planning and inadequate governance has resulted in overexploitation and water quality degradation in certain areas, threatening the lives and livelihoods of populations that depend on this vital resource (Kataoka and Shivakoti, 2013; Lall et al., 2020; Shah et al., 2003). For instance, the Kharaa River basin in Mongolia is an area undergoing important economic and industrial development – with positive economic benefits derived from mining, agriculture, animal husbandry and tourism – but these activities, combined with accelerating urbanization, contribute to increasing groundwater pollution (Hofmann et al., 2010, 2015).

Pollution associated with the overuse of agricultural chemicals has been shown to affect groundwater quality well below the surface. In the North China Plain, nitrates have been detected at 24 metres in depth (Chen et al., 2005).

Improved groundwater governance, with popular support and enforcement capacity, is urgently needed

It is therefore critical that continued development and utilization of groundwater must be done in a sustainable manner, in order to reduce the pressure on these resources. While management practices and institutional, legal and regulatory systems to address groundwater issues exist throughout the Asia-Pacific region, groundwater governance is met with challenges due to its unrestricted open access in many countries across the region (Kataoka and Shivakoti, 2013). Thus, improved groundwater governance, with popular support and enforcement capacity, is urgently needed. Problems with groundwater depletion, land subsidence and groundwater contamination require urgent action and transboundary cooperation, in order to mitigate current negative trends and to ensure future water security in the region.

8.4.4 Responses

Groundwater systems and the activities that rely on them are complex. Therefore, proper understanding of an aquifer's hydrogeological conditions, water demand, and social and economic needs are necessary for effective policy-making. While there is no one-size-fits-all solution for the various challenges groundwater systems may face, there are a number of actions and pathways that national governments can take to address these issues. Below are three examples of actions taken by governments to address their groundwater challenges.

Groundwater recharge in Rajasthan (India)

Rajasthan, India's most arid state, is prone to frequent droughts and highly dependent on groundwater for both irrigation and drinking needs. With erratic rainfall, overexploitation of groundwater and the highest evaporation losses in the country, agricultural communities in the region face increasing challenges in meeting their water needs. In 2016, the government of Rajasthan launched *Mukhyamantri Jal Swavlamban Abhiyan* (MJSA), a programme to help rural communities become self-reliant in meeting water needs. Focusing on MAR (see Box 7.1 and Section 11.5), the programme constructed irrigation tanks, dams, trenches and other water harvesting structures to capture runoff. The programme also promoted water conservation through micro-irrigation and improved the watershed by planting trees in barren wastelands and developing pastures. Interim results after two monsoons showed that out of 21 non-desert districts, 16 districts saw an increase of groundwater levels by an average of 1.4 m. Internal impact assessments also reported that participating villages reduced water transportation (i.e. water tankers) by 56% compared to non-participating villages (Verma and Shah, 2019).

[32] Emerging contaminants consist of pharmaceuticals, pesticides, industrial chemicals, microplastics, surfactants and personal care products.

Groundwater depletion interventions in the North China Plain

The North China Plain has one of the lowest water resources availability per capita in both China and the world. Rapid economic development over the past 40 years was sustained by groundwater exploitation, resulting in severe groundwater level decline limiting further development in the region. In recent years, multiple water management plans have been implemented to address this issue. Actions include harvesting rainwater, diverting river water from the south, promoting water-saving irrigation technologies, subsidizing drought-resistant crops and 'Grain for Green' projects.[33] As a result of these and other measures, the rate of groundwater decline appears to have been reduced in Beijing and part of Hebei province (Shao et al., 2017; Xu et al., 2018; Zhao et al., 2020).

Kiribati's adaptation programme

The Republic of Kiribati is mainly comprised of low-lying atoll islands with a total area of 726 km², located in the central and western Pacific Ocean. Kiribati is one of the smallest and most remote, geographically dispersed and climate change-vulnerable countries in the world. The country is subject to frequent, prolonged droughts while rising sea levels significantly threaten the country's freshwater supply (rainwater and shallow unconfined groundwater). Throughout the country, clean, safe drinking water is mainly sourced from thin, fresh groundwater lenses floating on denser seawater within the aquifer. Due to the fragile nature of these lenses, if the balance of the lenses is disturbed due to droughts or over-abstraction, the groundwater becomes brackish and unfit for drinking and irrigation. From 2011 to 2018, the Government of Kiribati made several efforts to build the country's resilience to climate change at the national, island and community levels, with support and contributions from development partners.

Scaling up measures from the previous two pilot phases, Phase III of the Kiribati Adaptation Program (KAP)[34] implemented a holistic approach that included:

- improving water use and management by installing rainwater harvesting systems, in addition to groundwater abstraction systems utilizing horizontal infiltration pipes placed at shallow depths to abstract water within the freshwater lens;
- reducing water leakages and waste in existing systems;
- protecting water reserves;
- improving long-term planning for local-level water management;
- protecting against coastal erosion by investing in protection, such as seawalls and mangrove planting; and
- strengthening government and community capacity to manage the impacts of climate change and natural hazards through a national Coastal Management Policy, in addition to locally managed Adaptation Plans.

Evaluation reports indicate that through the project, the number of people with access to improved water sources rose from the baseline of 5,000 (from 2017) to 12,780, exceeding the project's original end target of 11,000 people by 116%. Rehabilitation efforts for existing water systems detected and eliminated water losses of 645 m³/day and combined engineering and nature-based measures provided 1.87 km of coastal erosion protection (World Bank, 2019).

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[33] Officially known as the Conversion of Cropland to Forest Program (CCFP), the programme pays farmers to plant trees on their land and provides degraded land to rural families to restore.

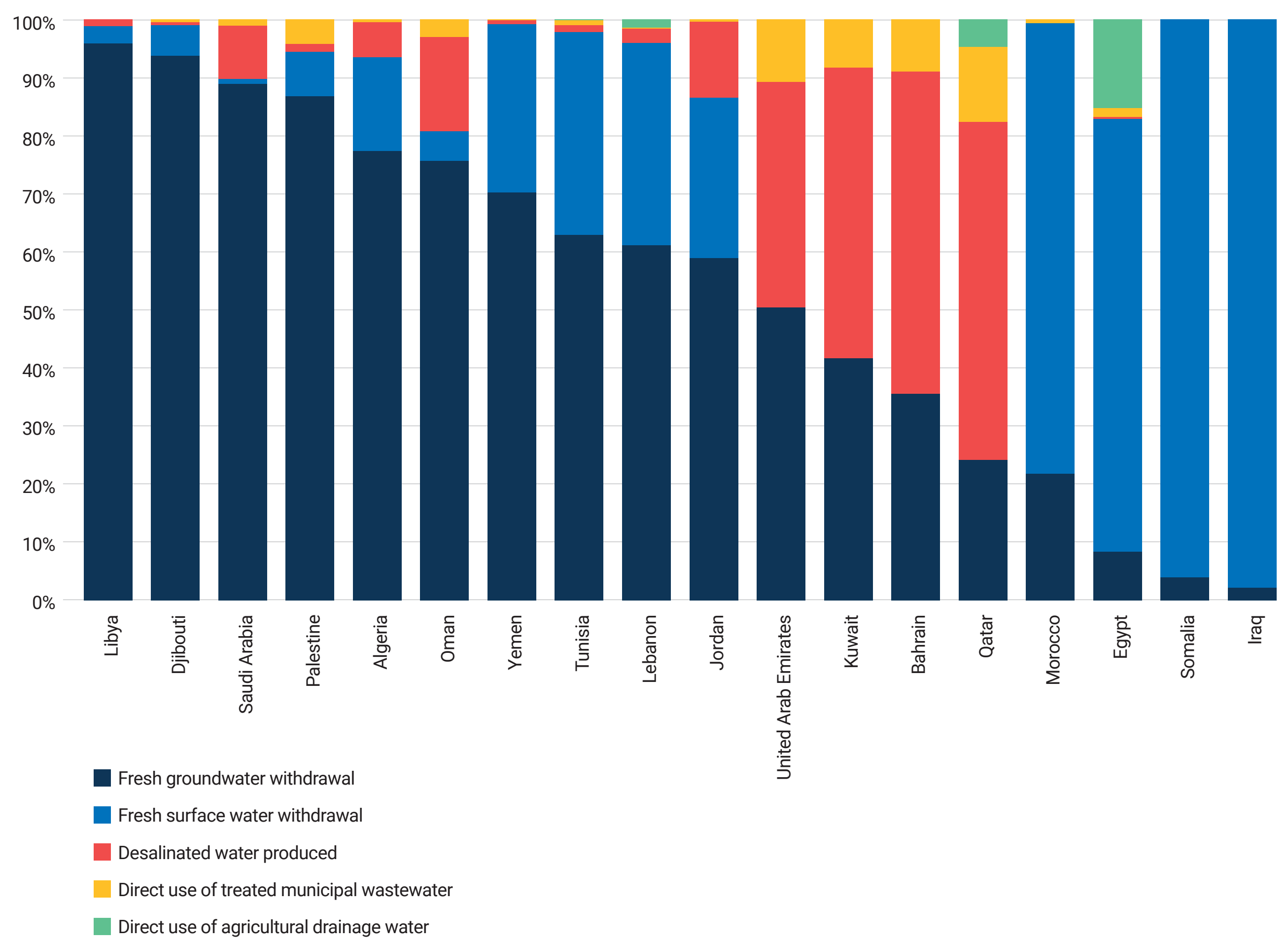
[34] projects.worldbank.org/en/projects-operations/project-detail/P112615.

8.5 The Arab region

8.5.1 Regional setting

The Arab region is one of the most water-scarce regions in the world. In 2020, 19 out of 22 Arab states fall below the threshold for renewable water scarcity of 1,000 m³ per capita/year, with 13 states situated below the absolute water scarcity threshold of 500 m³ per capita/year (UNDESA, 2020; Aquastat, n.d.). It is expected that by the year 2050, 17 Arab countries will be below the absolute water scarcity threshold (UNDESA, 2020; Aquastat, n.d.). This has pushed countries to draw upon other conventional and non-conventional water resources to meet their freshwater needs. Groundwater is the most relied-upon water source in at least 11 of the 22 Arab states and accounts for more than 80% of the freshwater withdrawals in Libya, Djibouti, Saudi Arabia and Palestine (Figure 8.7) (Aquastat, n.d.).

Figure 8.7 Origin of water withdrawal in selected Arab states by source



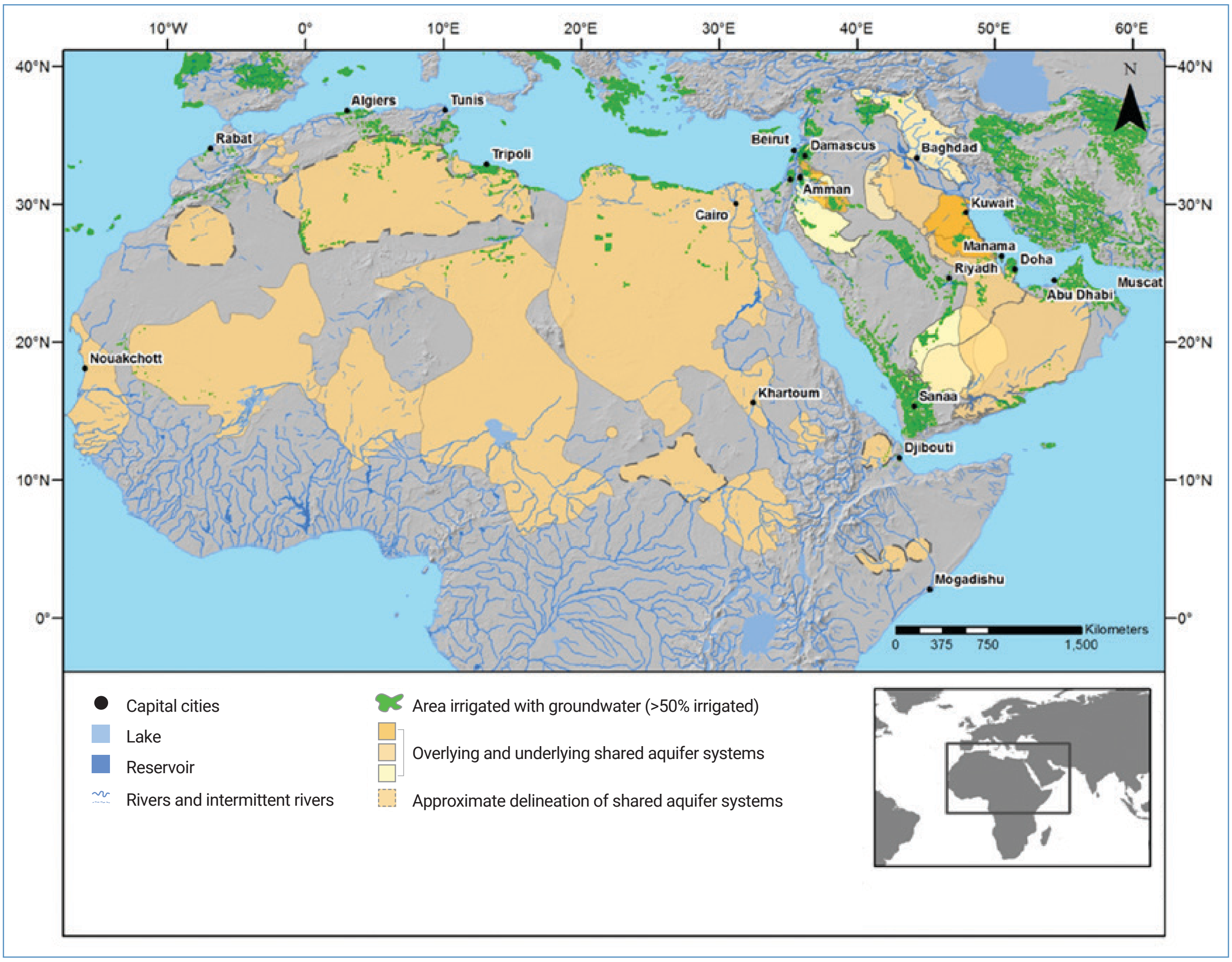
Note: Not all data are for the same year. The latest data available for each country are used.

Source: Based on data from Aquastat (n.d.), Al-Zubari and Alajjawi (2020) (for Kuwait), and Abd-El-Mooty et al. (2016) (for Iraq).

Groundwater in the region also tends to extend over large geographic areas and across political boundaries. Most groundwater resources in the region are non-renewable, and must be managed with a view to the fact that they are a finite resource. However, monitoring groundwater extraction remains difficult, despite the emergence of new technologies. This complicates the management of groundwater, particularly in a transboundary context. All Arab states except for the Comoros draw upon one or more transboundary groundwater resource, with 42 transboundary aquifer systems covering almost 58% of the Arab region's area (Figure 8.8). The Nubian Sandstone aquifer has an area of 2.17 million km² with a storage of 373,000 billion m³ shared between Chad, Egypt, Libya and Sudan (Bakhbakhi, 2006).

Close cooperation is needed to ensure that transboundary aquifers are properly managed. Unfortunately, only very few cases of groundwater cooperation exist in the region. Jordan and Saudi Arabia signed an agreement of cooperation on the Al-Disi/Saq-Ram aquifer in 2015, aiming to ensure proper management, utilization and sustainability of the groundwater, under the supervision of a joint technical committee.[35] Cooperation on the transboundary Nubian aquifer, which is shared by Chad, Egypt, Libya and Sudan, is pursued through a Joint Authority tasked with the study and development of the groundwater. Cooperation and data exchange in the North Western Sahara Aquifer System (NWSAS) shared by Algeria, Libya and Tunisia is facilitated through a consultation mechanism hosted by the Sahara and Sahel Observatory (OSS) (UNESCWA, 2019).

Figure 8.8 Transboundary aquifer systems in the Arab region



Source: UNESCWA (2015, Map 2, p. 33). © UNESCWA.

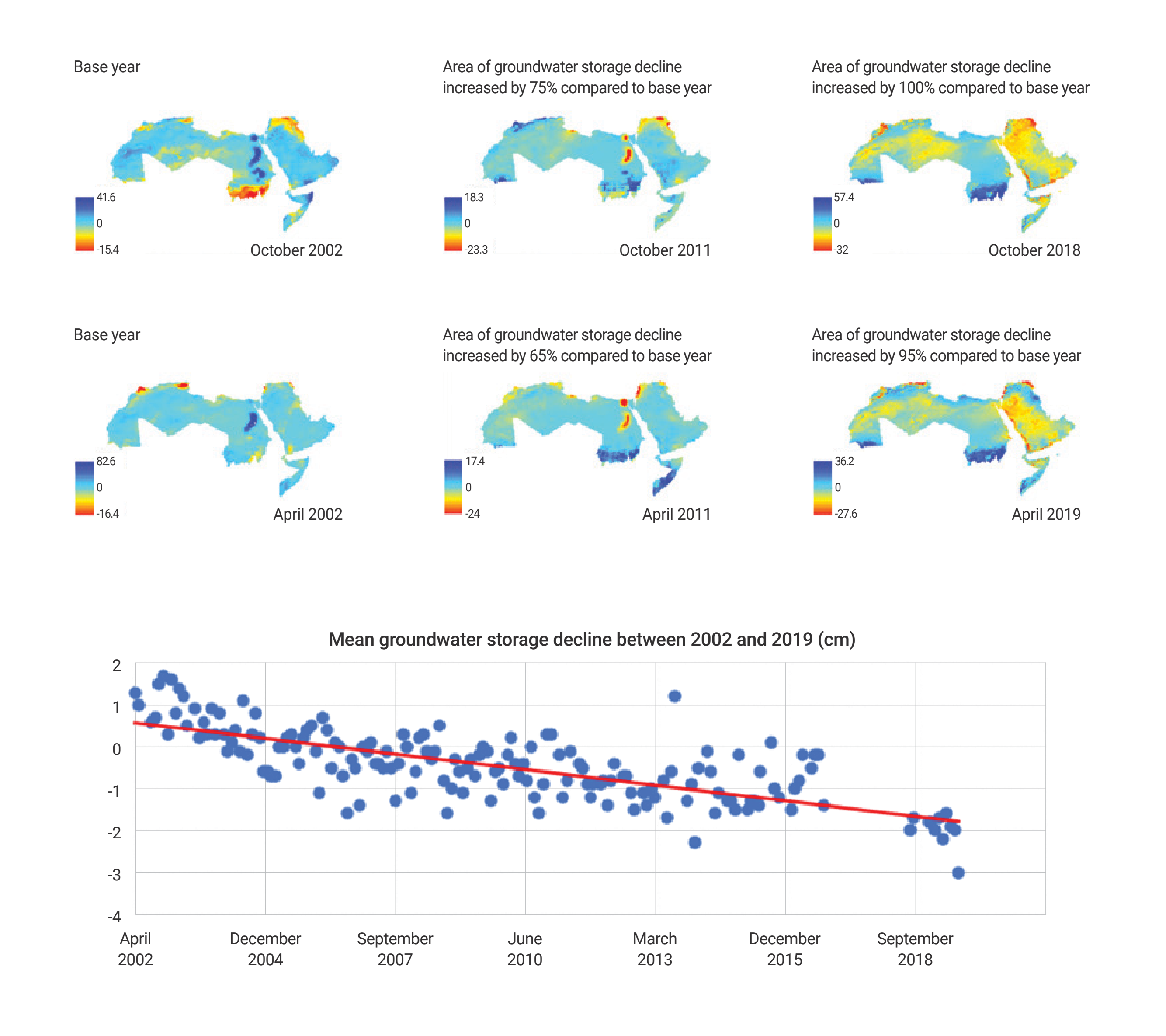
8.5.2 Groundwater-related challenges

Population growth, socio-economic development and climate change are increasing groundwater stress and threatening the water security in the region. The over-extraction of groundwater in many parts of the region has led to groundwater table declines, especially in highly populated and agricultural areas. This is especially alarming as groundwater is the primary source of water for vulnerable groups that are not formally connected or have access

35 Agreement between the Government of the Hashemite Kingdom of Jordan and the Government of the Kingdom of Saudi Arabia for the Management and Utilization of the Ground Waters in the Al-Sag/Al-Disi Layer, 30 April 2015, https://internationalwaterlaw.org/documents/regionaldocs/Disi_Aquifer_Agreement-English2015.pdf.

to public sources of water. Analysis from Gravity Recovery and Climate Experiment (GRACE) mission data has confirmed an overall declining trend in groundwater storage in the Arab region. In fact, groundwater storage anomalies from the mean (2004–2009) show that the area undergoing a decline in groundwater storage had increased by 75% in October 2011 and by 100% in October 2018 when compared to October 2002, whereas it had increased by 65% in April 2011 and by 95% in April 2019 when compared to April 2002 (Figure 8.9). This depicts not only the significant decreasing trend in groundwater storage between 2002 and 2019 (Figure 8.9 – graph), but also highlights the seasonal variability effect on groundwater storage combined with the excessive groundwater withdrawals in the dry period. Furthermore, depletion of groundwater in aquifers and specifically in aquifers with non-renewable groundwater resources has been estimated at 317% of the renewable volume in the Member States of the Gulf Cooperation Council (Al-Zubari et al., 2017).

Figure 8.9 Change in groundwater storage (liquid water equivalent thickness) in the Arab region between 2002 and 2019 using GRACE mission data (in cm)



Source: Compiled by UNESCWA, based on McStraw (2020) and on GRACE 2.0 (n.d.).

Another major stress that threatens the availability of good-quality fresh groundwater is contamination. Unsustainable agricultural practices, as well as industries and urbanization, are significantly impacting groundwater quality. Groundwater salinity is the most frequently observed groundwater quality problem observed in coastal cities where over-abstraction results in seawater intrusion. For example, the Umm er Radhuma-Dammam aquifer system has brackish to saline water in its coastal area that includes parts of Bahrain, Kuwait, Qatar, Saudi Arabia and the United Arab Emirates (UAE), with a Total Dissolved Solids (TDS) value higher than 1 g/l (UNESCWA/BGR, 2013).

Growing awareness of the increased importance of and dependency on groundwater has led some Arab countries to seek new ways to managing this vital resource

Climate change is further affecting groundwater availability through decreased aquifer recharge and a decline in surface water availability, leading to increased pumping. Drawing upon regional climate modelling projections to inform hydrogeological modelling, the United Nations Economic and Social Commission for West Asia (UNESCWA) found that the groundwater table of the Ben Tadla aquifer in Morocco is expected to decrease from between 10 m to more than 25 m under different climate scenarios between 2020 and 2100, leaving some aquifer areas completely dry (UNESCWA, forthcoming).

Groundwater governance limitations in the Arab region complicate the response to these challenges. A regional diagnostic report on groundwater governance in the region noted inadequate or lacking groundwater policies and legislations, combined with inadequate political will for their implementation. Other governance challenges include limited funding, weak institutions and coordination, weak monitoring systems, and lack of information, resulting in poor understanding of groundwater systems (Al-Zubari, 2014).

8.5.3 Innovations

Growing awareness of the increased importance of and dependency on groundwater has led some Arab countries to seek new ways to managing this vital resource. In Morocco, aquifer contracts have been introduced as a new participatory groundwater management measure to enhance sustainability based on local needs (see Box 8.6). Traditional knowledge also continues to be applied, such as *aflaj*, which are ancient tunnels used to convey water by gravity for irrigation – mostly from groundwater sources. In Oman, more than 3,000 functional *aflaj* conveyors continue to supply water for agriculture. Communal practices and traditional arrangements also support the fair distribution of water to stakeholders from one generation to the next (Ministry of Regional Municipalities, Environment & Water Resources of Sultanate of Oman, 2006).

Many Arab countries are also increasingly pursuing MAR (see Box 7.1 and Section 11.5) to offset groundwater depletion and improve groundwater quality. For example, in Tunisia, treated wastewater has been released to an infiltration basin for MAR in the Korba aquifer since 2008. The results showed some improvement in terms of groundwater salinity, but clogging lowered the effectiveness of this method (Jarraya-Horriche et al., 2020). In Qatar, three types of MAR are being implemented. The first one consists of recharge through wells located in depression areas where rainwater accumulates naturally; this is implemented in non-urban areas to recharge the groundwater basins. The second type uses recycled water, mainly treated wastewater, to recharge deep boreholes in the Doha basin. The third type collects and treats urban stormwater and mixes it with shallow groundwater to recharge deep wells in the Doha aquifer in order to reduce salinity (Al-Muraikhi and Shamrukh, 2017). The UAE started pursuing work on MAR in 2001, with the Nizwa project in Sharjah as the first example of successful Aquifer Storage and Recovery (ASR) for an unconfined aquifer in the UAE (Sharjah Electricity and Water Authority, 2015). Abu Dhabi then became home to the world's largest ASR initiative (see Box 8.7), using desalinated water to recharge a desert dune sand aquifer near the Liwa oasis. The water stored here can be recovered under emergency conditions (Stuyfzand et al., 2017). In Oman, Saudi Arabia and the UAE, check dams built on riverbeds to divert runoff and recharge aquifers remain the most commonly practiced MAR approach in the region.

Box 8.6 Morocco aquifer contracts

Morocco is facing increasing water insecurity, which has contributed to unsustainable groundwater use. In response, in 2006 the government adopted a new management approach that issues aquifer contracts to all groundwater consumers in a designated aquifer region. Under this participatory framework, agreements are forged among local stakeholders, including governmental organizations, public institutions, agricultural water users' associations and research institutions, to identify needs and secure mutual benefits in order to improve groundwater management and availability. This was in direct departure from centralized management arrangements administered at the national level.

The use of aquifer contracts was first piloted in the Souss Massa-Draa River basin, which includes three aquifers. The Souss aquifer contract signed between the government and the concerned stakeholders in 2006 sets jointly defined general water use goals, but with a particular focus on groundwater, and includes a listing of the agreed-upon necessary activities that need to be accomplished in order to achieve these goals. Local stakeholders have a shared responsibility for the sustainability of the groundwater, which represents an incentive for the implementation and development of the aquifer contract.

The Souss aquifer contract resulted in the signing of the Framework Agreement for the Protection and Development of Water Resources in the Souss-Massa Basin, which was followed by six additional Specific Partnership Agreements agreed to by local stakeholders. These outlined specific goals and activities inspired by the Framework Agreement (Closas and Villholth, 2016).

This aquifer contract approach is the first in the Arab region and shows the opportunities presented by decentralization and the integration of local water users in participatory decision-making processes. However, in order to translate this participatory approach into concrete results, more needs to be done in ensuring inclusivity of small farmers, including women and marginalized groups, not to mention harmonization of policies across sectors.

Other countries are still testing artificial recharge approaches or are implementing them at a smaller scale. For instance, Kuwait has been studying and piloting ASR on the Dammam and the Kuwait group aquifers since the 1980s, using desalinated water and treated wastewater (Al-Rukaibi, 2010). In Bahrain, a recent study identified six optimal sites to apply MAR through rainwater harvesting (Kadhem and Zubari, 2020). In Lebanon, preliminary assessments were completed for 22 sites using natural water sources (rivers and springs), and ten sites using treated wastewater, in order to recharge 12 groundwater basins that are either being depleted or contaminated with seawater. The technique for recharge was mainly injection through wells, because of its suitability in a karstic environment and its cost-effectiveness (UNDP/Ministry of Energy and Water of Lebanon, 2014).

The importance of groundwater for the Arab region's water security under a changing climate demands improved governance through innovative management approaches, enhanced use of technologies, dedicated funding for better understanding of the resource, and heightened regional cooperation.

Box 8.7 MAR application in Abu Dhabi

The Liwa project in the United Arab Emirates was launched in 2004 and is the largest MAR project in the world. Aquifer Storage and Recovery (ASR) is applied, which consists of infiltrating desalinated water into a desert dune sand aquifer and recovering the water under emergency conditions, without treatment. The recharge process started in 2015 and the aquifer reached full capacity in 2017.

The Liwa ASR system is not typical, as ASR usually only consists of wells. Instead, this application is comprised of three underground recharge basins, which are each surrounded by 105 recovery wells. The aim is to infiltrate 26,500 m^3/day of desalinated water for 824 days with a concentration of total dissolved solids (TDS) below 250 ppm, and to be able to recover the water at a rate of 170,280 m^3/day for 90 days with a TDS of approximately 400 ppm in case of emergencies. The tested recovery efficiency ranges between 60 and 85%, and demonstrated the ability of MAR to reduce disaster risks and support the emergency response.

Source: Stuyfzand et al. (2017).

Chapter 9

Building and updating the knowledge base

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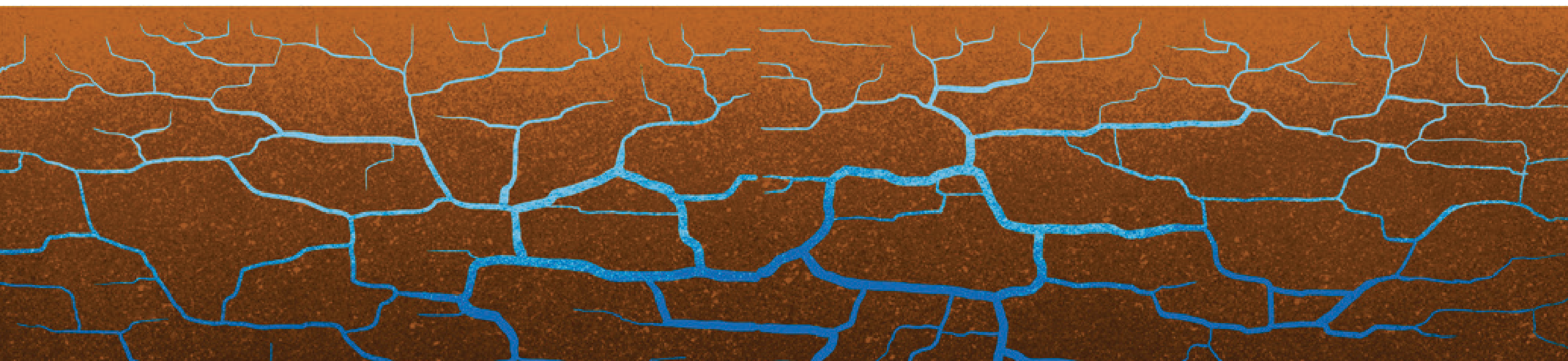


9.1 Introduction

A sound groundwater knowledge base is essential for efficient and sustainable decision-making. Since emerging as a science in the 19th century, hydrogeology has relied on a set of methods and tools aimed at assessing groundwater resources at different scales, and across various environmental and societal settings.

Groundwater data obtained through regular monitoring allow for the identification of trends and patterns in groundwater systems, which is indispensable for modelling/simulating current processes, or for predicting possible future conditions by means of scenario analysis. Outcomes of model calculations should always be accompanied by uncertainty analyses. Collected data and generated information need to be shared with all those who rely on groundwater or are engaged in its management. Moreover, building the knowledge base and applying it in the field or at the management decision-making level require adequate training of groundwater specialists.

A sound groundwater knowledge base is essential for efficient and sustainable decision-making

While groundwater assessments require sufficient and reliable data, their acquisition can often be challenging. However, significant progress in the field of hydrogeology has enabled a broad understanding of aquifer properties and of the physical and chemical principles governing groundwater flow and contaminant transport. In parallel, various methods and tools for data acquisition and analysis have been developed (e.g. aquifer testing, geophysics, hydrological and hydrochemical surveying, numerical modelling). Although there are still scientific questions that warrant additional attention, research is advancing fast, pushing forward the horizons of hydrogeology and, by adopting an interdisciplinary approach, bridging gaps with other disciplines such as environmental sciences, sociology, health care, economics, law and politics. In addition, increasing attention is being paid to strengthening the cooperation among various stakeholders via transdisciplinary approaches like socio-hydrogeology (Re, 2015; Hynds et al., 2018). Scientific knowledge in hydrogeology and the methods and tools available are sufficient to address most groundwater management issues, like siting wells, optimizing abstraction and predicting its effects at the local and regional scale, preventing contamination, etc. The challenge lies more with the scarcity of reliable data for area-specific groundwater assessments and scenario analyses, especially in low-income countries, and with the limited dissemination of data, information and knowledge among researchers, practitioners and decision-makers.

9.2 Studying groundwater: characterization and assessment

Since all aquifers and their boundary conditions are unique, there is always a need for groundwater assessments at field level to enable informed policies and management of groundwater resources. Groundwater studies that are limited to the physical groundwater systems, where only aquifer characteristics (including inputs and outputs) are considered, are ranked here under the category *hydrogeological characterization*. Studies that include other aspects, be they environmental (e.g. groundwater-dependent ecosystems), socio-economic (e.g. gender aspects and costs of water supply), legal (e.g. regulations) and/or institutional (e.g. capacity, authorization), are described here as *groundwater system assessments*. Groundwater system assessments at the regional/continental/global scale are primarily based on the aggregation and upscaling of local assessments.

9.2.1 Hydrogeological characterization

Hydrogeological characterization encompasses the estimation of aquifer parameters and variables, including the extent of the aquifer (e.g. depth, thickness) and its hydrogeological properties (hydraulic conductivity, storativity, etc.). The variables are about input (recharge), output (discharge) and the state of the aquifer. The recharge comes chiefly from precipitation (and also from surface water inflows), whereas discharge takes place via springs and baseflow to surface water, evapotranspiration (in shallow aquifers), and through abstraction wells. The main variables depicting the state of the aquifer are groundwater levels, and groundwater quality variables such as water temperature, pH and electrical conductivity (an indirect measure of salinity). Table 9.1 provides a listing of parameters frequently included in groundwater quality monitoring.

Table 9.1

Parameters frequently included in groundwater quality monitoring

Basic care parameters	
EC	Electrical conductivity
pH	Acidity
T	Temperature
NO_3	Nitrate
Cl	Chloride
Supplementary parameters at lower frequency	
Ca, Mg, Na, K	Major cations
Cl, HCO_3, SO_4	Major anions
TDS	Total dissolved solids
Microbiological monitoring of drinking water sources	
FC	Faecal coliforms
FS	Faecal streptococci
E Coli	Escherichia coli
Supplementary parameters (required in specific hydrogeological settings)	
F	Fluoride
Fe	Soluble iron
As	Soluble arsenic
Mn	Soluble manganese
U	Soluble uranium
P	Orthophosphate
NH_4	Ammonium
Additional parameters (if specific agricultural or industrial pressures identified)	
Specific pesticides	Heavy metals
Selected volatile organics	Certain emerging contaminants
Selected hydrocarbons	

Source: Adapted from IAH (2017, p. 6).

Because the subsurface is usually made of different geological units with different hydraulic properties, groundwater can have a range of physical and chemical properties at different locations and at different depths. As groundwater recharge and discharge are complex processes that vary in space and time, reliable numerical estimates can only be made on the basis of detailed field observations.

However, direct observations of groundwater and the subsurface are limited mostly to wells and springs, where only a few data can be measured, such as groundwater level, well yield, spring discharge and groundwater quality. Other data are estimated via indirect methods, including pumping tests, geophysics, dye tracing, recharge estimation methods and numerical modelling. These estimates come with some degree of uncertainty, and different estimation methods can yield a range of different outcomes. This applies even for the estimation of a major variable like groundwater recharge (Scanlon et al., 2002; Healy, 2010; Walker et al., 2019). Estimates of hydraulic parameters like hydraulic conductivity or storativity can differ by an order of magnitude depending on the pumping tests and interpretation methods used. Furthermore, some variables and parameters are rarely quantified in the field through direct or indirect methods: they are instead extrapolated based on common values available in published literature. Dispersivity, for instance, a parameter controlling solute transport processes, is usually inferred from the lithology and the scale of the solute transport process (Schulze-Makuch, 2005).

Because point data measured or estimated in the field have a limited spatial representativity, they need to be carefully interpolated, using continuous and/or supplementary information (e.g. remote sensing, geophysics) whenever possible. The quality of field investigation is crucial for an assessment, and additional field work/verification is often recommended. Hydrogeological maps and accompanying cross-sessions (Figure 9.1) are a necessary part of any aquifer characterization.

Due to the diversity and complexity of its processes, it is often difficult to recognize the role of groundwater and adequately incorporate it into decision-making processes

In addition to hydrogeological data, hydrogeological characterization requires other data relating to the water cycle (e.g. meteorological data, surface water data, land cover). It is also crucial to collect data on groundwater abstractions. In jurisdictions where new boreholes or wells are required to be registered, such regulations can allow public authorities to control groundwater abstractions. Most well registration forms indicate where groundwater is being pumped, by whom, for what purpose and in what amount. Sometimes, as in the case of boreholes equipped with high-yielding pumps, well owners need to pay a fee or apply for a license, which is a further way of controlling groundwater abstractions, while constituting a source of revenue for the authorities in charge of groundwater management. The registration of new boreholes provides another opportunity to collect significant groundwater data from well owners or drillers, including stratigraphic logs, information on groundwater quality and water levels after completion of the borehole, as well as well test data. Enforcing the registration and licensing of wells can be challenging, and locating illegal wells is often difficult and time-consuming. As a result, there are many illegal wells, especially in developing countries, where data are often not collected and abstraction may be uncontrolled.

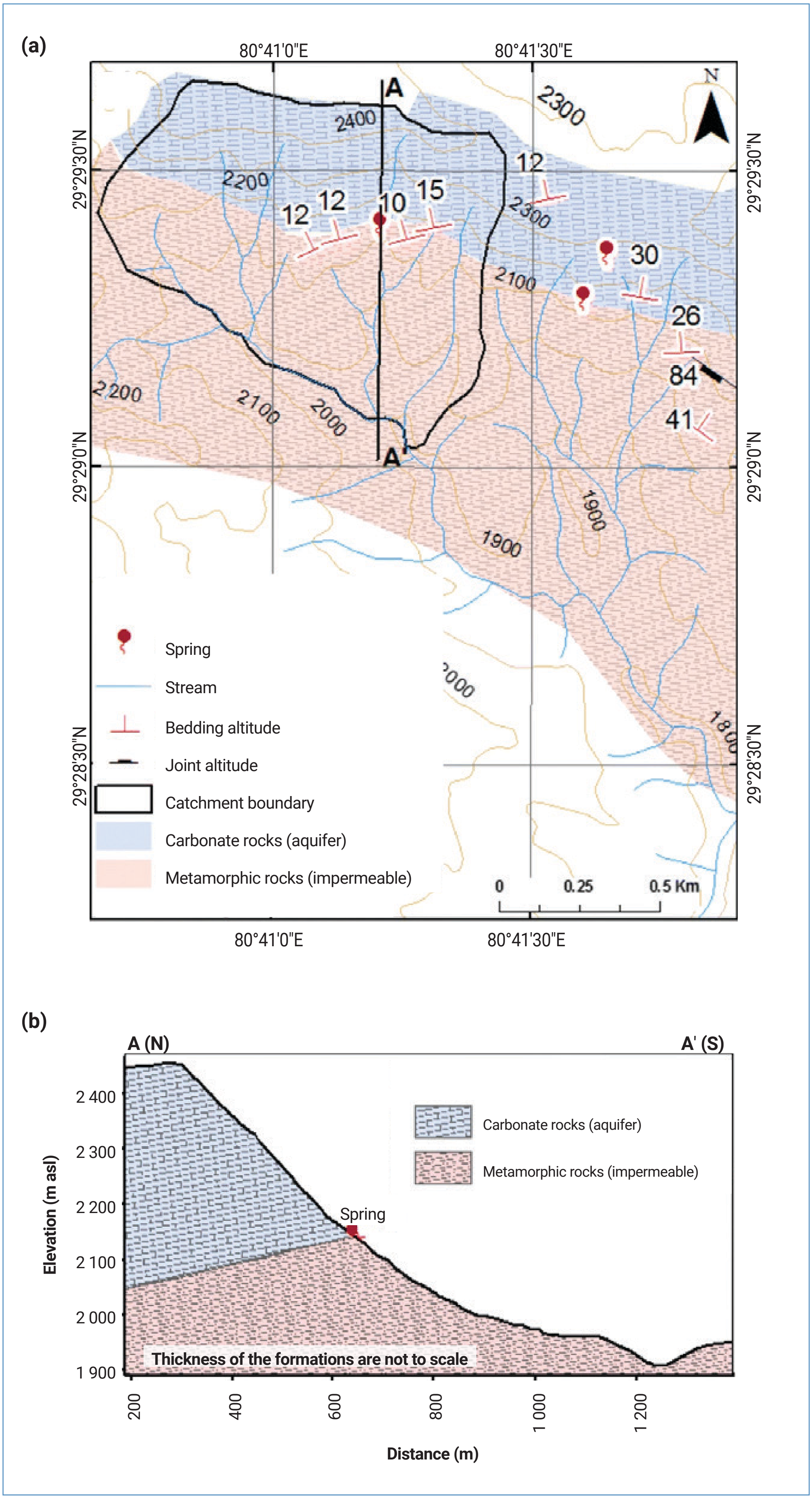
9.2.2 Groundwater system assessment

As highlighted in previous chapters, groundwater plays an important role in a variety of environmental and societal aspects and processes, from wetlands to food production, and from health and sanitation to combatting climate change. Due to the diversity and complexity of its processes, it is often difficult to recognize the role of groundwater and adequately incorporate it into decision-making processes. Therefore, groundwater systems need to be assessed in the context of relevant societal and/or environmental issues, in an interdisciplinary fashion, by complementing hydrogeological characterization with environmental, socio-economic and perhaps policy/institutional analyses. Next to provisioning services (i.e. water supply to households, agriculture and industry), groundwater also provides regulatory (e.g. aquifer buffering capacity), sociocultural (e.g. thermal baths) and supporting services (e.g. land subsidence prevention) (see Figure 1.3). All these aspects need to be taken into consideration when assessing groundwater systems.

Data required for an interdisciplinary assessment are very diverse and come from different sources. Some sociological data relevant for interdisciplinary assessments (such as gender considerations in connection with water supply) can be collected in the field from well owners and groundwater users, together with hydrogeological data. The engagement of local communities during groundwater assessments promotes the subsequent adoption of groundwater management measures that fit their needs, which turns out to be key for the sustainability of such measures. This approach is promoted by the socio-hydrogeology network[36] of the International Association of Hydrogeologists (IAH) (see also Re, 2015).

[36] For more information, see: sociohydrogeo.iah.org.

Figure 9.1
An example of a hydrogeological map and a cross-section



Source: Adapted from Matheswaran et al. (2019, fig. 2, p. 2186).

9.3 Groundwater monitoring

9.3.1 In-situ monitoring

Groundwater needs to be monitored over time in terms of quantity and quality, in order to learn about the behaviour and state of aquifers, and to identify possible negative changes such as over-abstraction, reduced recharge (including climate change effects) and pollution. Groundwater levels, as indicators of the quantitative status of the groundwater system, are monitored in wells (Figure 9.2), manually or with automatic recorders (data loggers). Additionally, loggers can be equipped with sensors that allow for a telemetric transmission of data to a database. Groundwater recharge is usually estimated, while several components of groundwater discharge (well abstraction, spring discharge, river baseflows) can in principle be monitored, using different methods and devices.

Groundwater quality monitoring involves sampling wells and springs. Because the chemistry of a groundwater sample can change quickly once groundwater reaches the surface, certain unstable parameters (such as pH and water temperature) need to be measured on the spot (wellhead or spring), while the full analyses are normally carried out on samples brought to a laboratory. Where laboratories are not available locally, field kits can be used.

Groundwater monitoring programmes need to be planned according to well-defined objectives, which determine what parameters must be monitored (Table 9.1), how, where and how often. The objectives of national monitoring programmes are usually to provide data about the long-term state and trends of groundwater, and inputs for water policy planning (IGRAC, 2020). A groundwater quality monitoring programme seeks to assess natural or anthropogenic changes in water chemistry and microbiology. Other objectives could be to investigate specific pollution issues, or a targeted study area. Detailed local-scale monitoring of spring flows and groundwater levels is especially important for groundwater-dependent ecosystems.

In many countries, groundwater monitoring is the responsibility of public institutions such as water ministries and environmental protection agencies (IGRAC, 2020), although other organizations, like water companies and research institutes, might have their own monitoring

Figure 9.2

Modern piezometer with a data logger and an explanation for the public (National Park De Alde Feanen, Province of Friesland, the Netherlands)

Photo: Claudia Ruz Vargas.

programmes. However, many low-income countries have very limited or no monitoring networks in operation (SADC-GMI/IGRAC/IGS, 2019a; IGRAC, 2020), mainly due to the costs of developing, operating and maintaining such networks.

Groundwater monitoring programmes need to be planned according to well-defined objectives, which determine what parameters must be monitored how, where and how often

Groundwater monitoring is challenging due to the hidden and three-dimensional nature of groundwater flow, the usually long travel time of groundwater and the complexity of contaminant transport. Separate observation boreholes (Figure 9.3) or clusters of piezometers within one borehole at different depths may be required as water levels and hydraulic gradients may vary between (and within) aquifers (Misstear et al., 2017). The location of the monitoring wells plays an important role too. Groundwater samples need to be taken at specific locations and depths due to the (often) complex hydrogeology; moreover, nearby pollution sources or the construction methods adopted for the monitoring boreholes may strongly influence the results obtained. In addition, the frequency of observation needs to be well defined according to the monitoring objectives and the assumed time series characteristics of the monitored variable. Groundwater levels should be recorded at sufficiently frequent intervals to identify seasonal variations and long-term trends arising from changing abstraction patterns or climate variations. Sampling frequency will also depend on the groundwater flow system and the land use pressures on groundwater quality. Highly vulnerable aquifers that provide services to people and the environment need to be monitored more frequently. For all these reasons, groundwater monitoring programmes should be defined carefully and be based on solid hydrogeological knowledge, including a sufficiently detailed conceptual model of the aquifer under consideration.

Although often relatively expensive, monitoring is a wise investment: identifying problems at an early stage can be highly cost-effective (Kim and Kim, 2019), allowing mitigation measures to be introduced before serious deterioration of the resource takes place.

Figure 9.3

Cluster of boreholes for monitoring water levels at different depths (overburden, shallow and deep bedrock) at a site in eastern Ireland

Photo: Bruce Misstear.

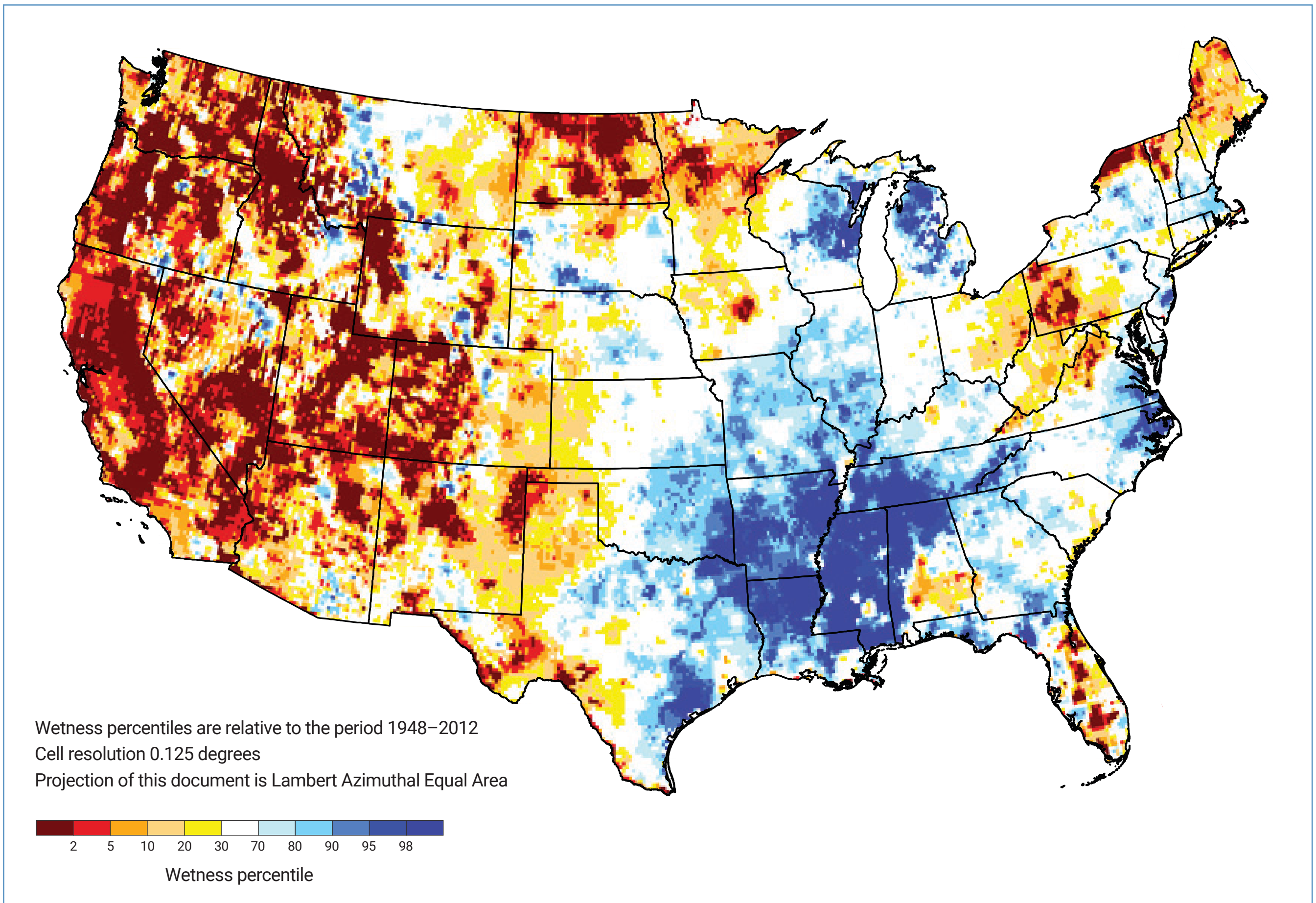
Remote sensing techniques have also been used by the scientific community to improve the monitoring and estimation of groundwater resources

Conventional monitoring programmes can be augmented by citizen science initiatives, where volunteers take additional measurements/samples.[37] Manual sampling can be supported with new technologies, such as smartphone apps for data collection, which make paper forms obsolete and hence decrease errors in data handling. Citizen science goes beyond just taking measurements: engagement of the public (e.g. via semi-structured interviews) and capacity-building for in-situ measurements can help ensure the integration of local know-how into hydrogeological assessments (Re, 2015). In doing so, one-way communication from the scientific community towards the civil society can be avoided. Although mainly applied to surface water so far, citizen science is gradually finding its way to groundwater applications as well, including through projects in Lebanon (Baalbaki et al., 2019) and India (Maheshwari et al., 2014).

9.3.2 Remote sensing

Remote sensing (airborne and satellite observations) is widely used to study and predict hydrological processes. Since changes in surface water bodies can be detected directly from remote observations, remote sensing has found a broad application in hydrological science and the management of rivers and lakes. Remote sensing techniques have also been used by the scientific community to improve the monitoring and estimation of groundwater resources (Güntner et al., 2007; Scanlon et al., 2002, 2012b; and Shamsudduha et al., 2017). Notably, the outcomes of the Gravity Recovery and Climate Experiment (GRACE) have shown potential as an additional source of information on groundwater storage changes and used in combination with models to generate various outputs, such as drought indicators (Figure 9.4).

Figure 9.4 GRACE-based shallow groundwater drought indicator for the USA



Source: NASA/NDMC (2021).

[37] See, for example, the experiences of the MARVI project: www.marvi.org.in.

The primary scientific objective of GRACE is to measure variations in the Earth's gravity field. These measurements can be used to derive total water storage change (ΔTWS) on Earth (Rodell et al., 2018). By subtracting from ΔTWS the change of volume of water stored in the other terrestrial components of the water cycle (namely soil moisture, rivers, lakes and reservoirs, ice and glaciers) for the same period, groundwater storage change (ΔGWS) can be estimated.

The main limitation of applying GRACE is the coarse resolution of satellite-derived data. Also, as ΔGWS is computed indirectly, it can include accumulated errors from the other water components considered, some of which are estimated by modelling.[38] Despite these limitations, the approach has been used and combined with other data sources in order to improve the accuracy of groundwater storage change estimations. The ongoing Global Gravity-based Groundwater Product (G3P) project[39] will provide a global, consistent and freely accessible data set on ΔGWS.

Although satellites do not give direct indications of groundwater quality, they can provide information on land use and geology, which can be related to groundwater quality and vulnerability to pollution. Moreover, remote sensing results can be used as additional variables to support predictive modelling. For instance, predictions of certain contaminants can be derived from information about anthropogenic activities, such as soil salinity problems arising from intensive irrigation (WWQA, 2021; UNEP, 2020). Also, information about land subsidence collected through remote sensing (e.g. using an interferometric synthetic-aperture radar – InSAR) can be linked to groundwater level change and groundwater mining.

Historical data about groundwater system variables (e.g. groundwater levels or salinity), acquired through monitoring, are used to identify trends and patterns in aquifer behaviour

9.4 Scenario analysis and uncertainty of predictions

Historical data about groundwater system variables (e.g. groundwater levels or salinity), acquired through monitoring, are used to identify trends and patterns in aquifer behaviour. This information is indispensable when attempting to forecast the change in groundwater quantity and quality in the future. This forecasting is often carried out through a scenario analysis using numerical models, where outcomes of various possible inputs or interventions in groundwater system are tested and analysed.

Both deterministic and stochastic (probabilistic) numerical models are used for a scenario analysis. A deterministic model is based on a hydrogeological conceptual model, being a simplification of a usually complex subsurface environment and simulating the flow and transport through that environment. A stochastic model looks primarily at the variables (input, state and output), developing various algorithms (through 'machine learning') to simulate the processes that connect them. Stochastic models are widely used in surface water hydrology because of data availability and the fast response times of the system. These advantages, along with the complexity of hydrogeological environments, are the two main reasons for using stochastic models in modelling of karst groundwater systems.

Deterministic numerical models, based on physical and chemical properties of the environment, are powerful tools to simulate and predict an aquifer's state under various scenarios. Yet, it must be emphasized that models are a simplification of the real world, and that they come with a certain level of uncertainty, which depends on several factors, including the number and the complexity of physical and chemical processes simulated, the heterogeneity of the subsurface, the quality and quantity of input data, and the model's calibration. This uncertainty can be significant, and should therefore always be assessed and communicated before using any model output. With the advances in computational capabilities and algorithms, it is possible (and highly recommended) to carry out uncertainty analyses, whereby the level of confidence of model predictions can be estimated.

[38] A recent study by Shamsudduha and Taylor (2020) showed that the range of uncertainty of GRACE-derived estimates of ΔGWS for 37 aquifer systems varies from 36% to 219%.

[39] For more information, see: www.g3p.eu.

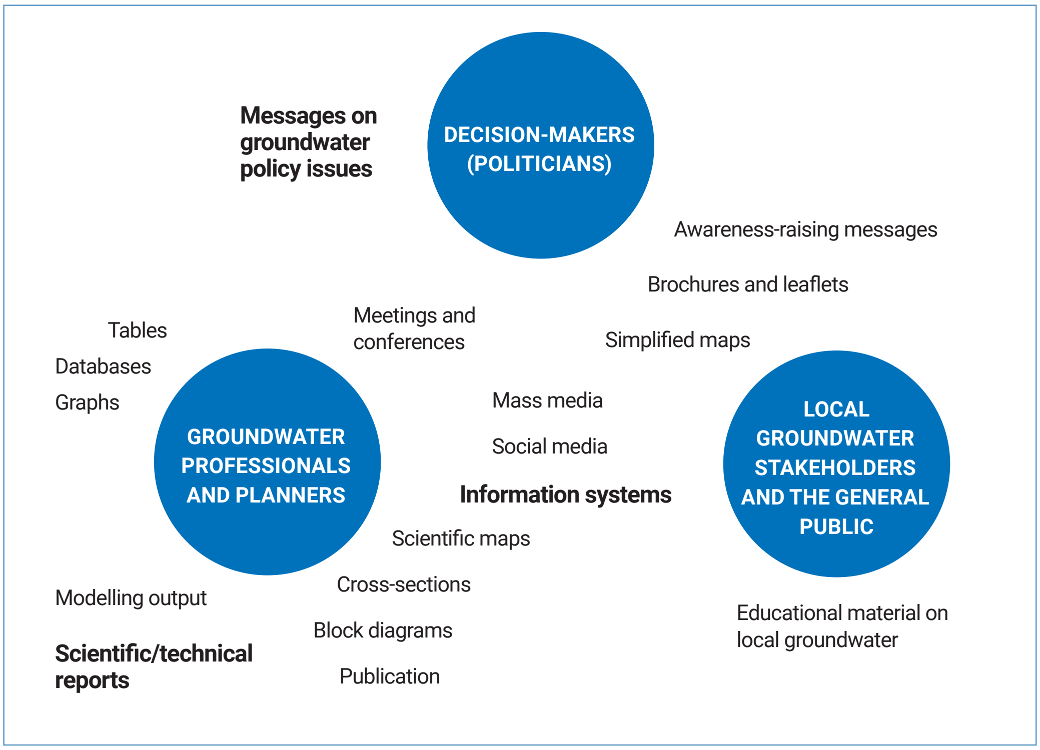
Regardless of which models are used, a scenario analysis requires a good understanding of the anthropogenic and environmental driving forces impacting groundwater systems, and the ways in which they can evolve. Groundwater models nowadays are also used as a component in much more complex hydro-economic modelling frameworks, where scenario analyses encompass the outcomes of various models, addressing a diversity of topics and issues.

9.5 Sharing the knowledge base and building capacities

Benefits of data and information are multiplied if they are shared among communities and organizations which are, or might be, involved in groundwater use, protection, development and management, or in their financing. Awareness of the state of groundwater is the first requirement for managing this resource efficiently and sustainably. The range of communities and organizations having an interest in groundwater is broad, and each of them has different information needs, at different scales, ranging from local aquifers to aquifer systems, and from river or lake basins to other geographical units such as countries, subregions or continents. Hence, there is a need for aggregation of groundwater information and knowledge at the regional, national and global scales in order to understand the role and impact of groundwater in the context of interlinked societal and environmental challenges. Climate change impacts (e.g. droughts, sea level rise), food production and trade, conflicts, and migrations are just some examples of processes and issues that require consistent groundwater policy at multiple levels. Accordingly, groundwater information needs to be adequately tailored for specific audiences. As illustrated in Figure 9.5, this can be in the form of scientific reports, information systems, social media postings, brochures and conference presentations, among others (Re and Misstear, 2018).

Figure 9.5

Selected forms of presenting groundwater data and information, in relation to envisaged users



Source: Van der Gun (2018, fig. 10.4, p. 207).

While information-sharing has long been promoted (e.g. in Principle 10 of the Rio Declaration, 1992), the importance of data-sharing and open data has also been recognized (e.g. through the INSPIRE Directive in the EU, 2007). Nevertheless, the sharing of data and information is often deficient, especially in low-income countries. Data might be difficult to access and not freely available (SADC-GMI/IGRAC/IGS, 2019a). This is due to technical challenges (gaps in data collection, outdated databases and limited information technology capacities), but sometimes there is also a reluctance to share 'sensitive' data, or to share it for free. Groundwater data collected with public funds should be freely accessible.

Also, private companies should disclose relevant data and information concerning subsurface water-related parameters that would improve the assessment and management of groundwater. For example, geophysical and borehole data acquired during oil and gas exploration could improve knowledge of aquifer extent and parameters. Furthermore, mining companies are increasingly disclosing their water use (Northey et al., 2019). Large international beverage and bottled water producers risk negative publicity if they are associated with the depletion and/or pollution of aquifers in situations where no clarity exists about the state of the aquifer and related pressures, impacts and trends. This should motivate companies to assess their risks, to use groundwater in an evidence-based, sustainable manner, and ultimately to share their water-related data.

Private companies should disclose relevant data and information concerning subsurface water-related parameters that would improve the assessment and management of groundwater

Moreover, if they want to grow sustainably, companies need to act beyond the site operations and help improve water governance aquifer-wide. This is recognized by some leading companies and is referred to as water stewardship. A CDP enquiry found that 64% of the reporting companies lowered or maintained their water withdrawals in a year-over-year comparison between 2019 and 2020. Yet, the participation of reporting companies is still low, and the monitoring of wastewater discharge is far from sufficient. A growing number of companies are incorporating water issues into their long-term business objectives, strategies and financial planning. Despite this, the examples of capital investments that have already been made to reduce use of potable water and risks of pollution are much less numerous. Regular monitoring and disclosure of groundwater use, thorough environmental risk assessments, and active water stewardship are the main parameters to distinguish between greenwashing and the responsible and ethical management of a company (IGRAC, 2016). The CEO Water Mandate is set up to address global water challenges through corporate water stewardship, in partnership with the United Nations, governments, civil society organizations and other stakeholders.[40]

Advocacy for open data is growing and online infrastructure is being developed to support the sharing of groundwater data and information. Also, the number of national and international portals with access to groundwater data and information is steadily growing. Some international examples are: the Southern African Development Community (SADC) Groundwater Information Portal, the Africa Groundwater Atlas and Literature Archive (developed by the British Geological Survey) and the Global Groundwater Information System (GGIS) developed by the International Groundwater Resources Assessment Centre (IGRAC – Figure 9.6).

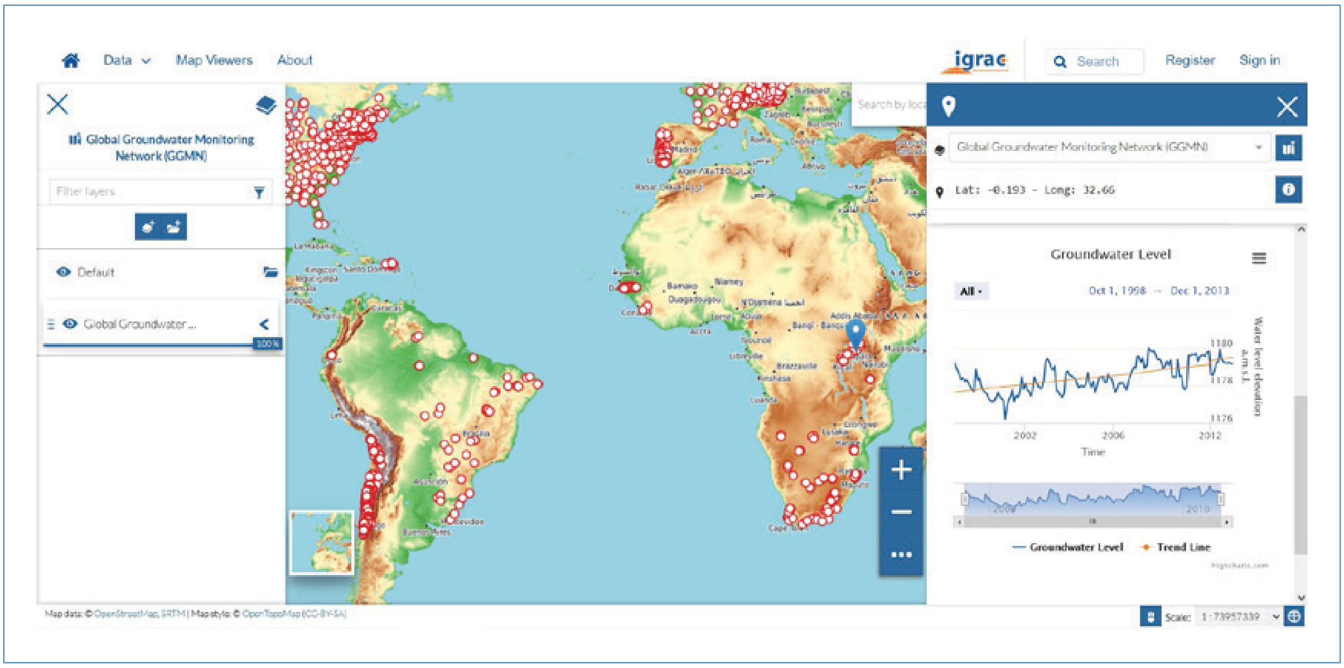
The dissemination of scientific data about groundwater increasingly occurs in open-access publications, including journal papers, textbooks and manuals. A notable initiative is the so-called Groundwater Project,[41] which is promoting free access to groundwater knowledge, through online books and other educational materials. It is important to share scientific knowledge with all, particularly in low-income countries where the price of books and subscriptions to scientific journals can be a barrier to accessing scientific information.

Given the increasing relevance of groundwater resources in the context of global change, groundwater specialists should not only add to the knowledge base, but also help in developing policies and participate in decision-making. However, their potential contribution is often not recognized (Gleeson et al., 2020b; Gorelick and Zheng, 2015). Organizations engaged in

[40] For more information about the CEO Water Mandate, see: https://ceowatermandate.org.

[41] For more information, see: gw-project.org.

Figure 9.6 Global Groundwater Information System (GGIS)



Source: IGRAC (n.d.).

groundwater management, such as water companies, water, sanitation and hygiene (WASH) agencies, river basin organizations, and environmental agencies would benefit from engaging hydrogeologists in the development of their activities.

In many low- and middle-income countries, hydrogeological capacity is missing, even when groundwater makes up the largest part of their managed water resources

In many low- and middle-income countries, hydrogeological capacity is missing, even when groundwater makes up the largest part of their managed water resources (Foster, 2020). This lack of capacity often comprises both human capacity as well as institutional capacity (Abdolvand et al., 2015; Albrecht et al., 2017). Weak institutional groundwater governance and management, in turn, undermine associated water security (United Nations, 2018). Well-founded capacity-building schemes are, therefore, an essential building block to move from a vicious circle of groundwater overexploitation and environmental degradation to a virtuous circle of creating local groundwater champions who eventually foster sustainable management practices and strengthen institutional capacity (Ortigara et al., 2018; Jadeja et al., 2018; Taylor et al., 2012b). Accordingly, Target 6a of the Sustainable Development Goals (SDGs) identifies international cooperation and capacity-building as key factors for achieving sustainable water resources management.

To ensure that capacity-building measures have an impact that lasts, respective activities should be target group-specific, provide interdisciplinary perspectives, allow for feedback from trainees and involve success verification mechanisms (Re and Misstear, 2018; Ferrero et al., 2019). Exemplary frameworks that foster institutional capacity-building include binational communal partnerships or governmental cooperation agreements involving relevant specialist agencies. This can also encompass the creation of national or regional centres of excellence in the recipient country. Achieving institutional success through hydrogeological capacity-building usually requires an enduring effort, which should be complemented with development programmes that allow for emerging local groundwater champions to bring their expertise to bear. At a smaller scale, the formation of human capacity can be reinforced by, for example, bilateral academic exchange programmes or postgraduate training opportunities.

Chapter 10

Groundwater policy and planning

UNDP

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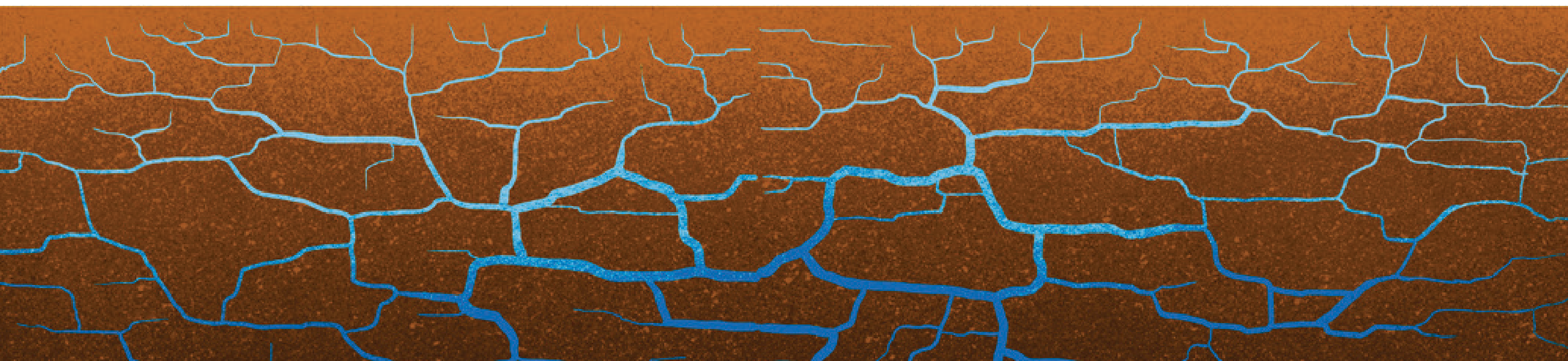
* Commissioned through Water Governance Facility, hosted by SIWI

** Ask for Water GmbH on behalf of the Rural Water Supply Network



Groundwater policy defines objectives, ambitions and priorities for managing groundwater resources, for the benefit of society. Planning translates policy into programmes of action. Both are often part of a wider water resource policy and planning framework, but the specific challenges pertaining to groundwater have traditionally received less attention than surface water.

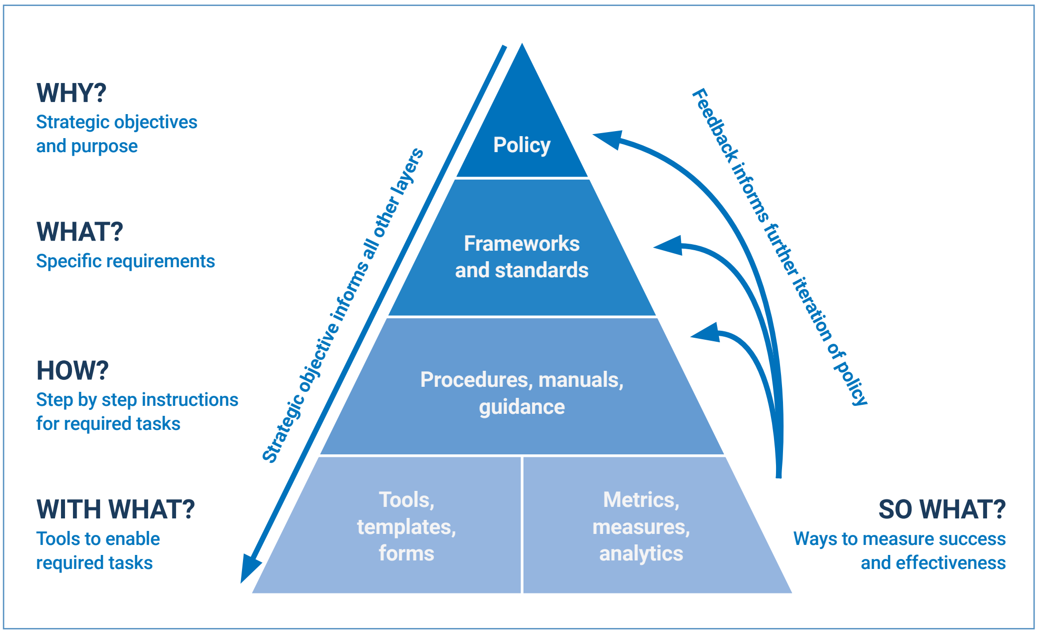
The terms 'policy,' 'strategy' and 'plans' are used interchangeably in many countries and contexts.

10.1 Groundwater policy

Policy seeks to represent values and ideas deemed to be in the public interest. Through broadly formulated statements, a policy document sets strategic objectives, establishes why they are important, and sets specific requirements to guide the course of action for present and future decisions (Torjman, 2005; De Sousa and Berrocal Capdevila, 2019). Figure 10.1 indicates how policy relates to specific requirements (What?); procedures, manuals and guidance (How?); and enabling tools (With what?), illustrating how to translate the policy into action (De Sousa and Berrocal Capdevila, 2019; Smith, 2003).

Figure 10.1

What is Policy? A model from the State of New South Wales (Australia)



Source: De Sousa and Berrocal Capdevila (2019).

In a national context, 'policy-makers' are normally a publicly elected or designated body with mandate to frame the policy and its scope. Federal states often have groundwater policies at the national and at the state level. The policy can be intended primarily for, and relate to the mandates of, authorities, organizations, jurisdictions and non-governmental organizations.

Federal states often have groundwater policies at the national and at the state level

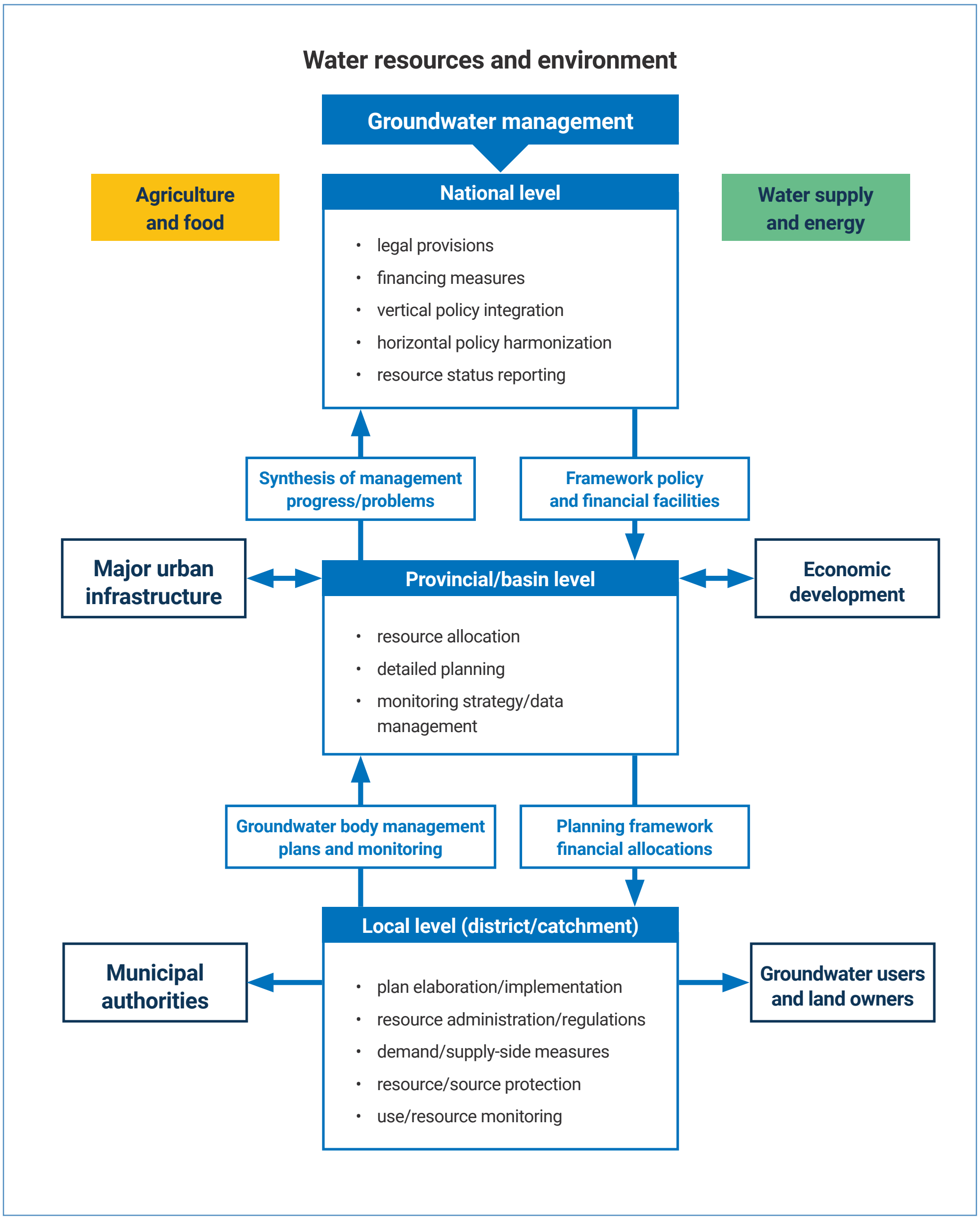
Developing policy requires making choices about the most appropriate means to a desired end. Economic principles (see Figure 13.1) can be used to guide choices, assigning value to groundwater resources (Smith et al., 2016). Instrumental, intrinsic and relational values and principles are also of essence to uphold environmental ethics, human needs, and cultural and historical values (see Figure 2.1 and United Nations, 2021).

The first step is to determine a national 'groundwater management vision' that is embedded within a national vision for water resources, in dialogue with actors ranging from local groundwater users and technicians to scientists, policy-makers and investors, for catalysing and managing the changes needed (Smith et al., 2016) – such as in South Africa (Republic of South Africa, 2010). Groundwater policy should be contingent on the legal status and nature of ownership of groundwater (public or private), of the water users, the interrelated surface water features, and land use in aquifer recharge areas (Foster and Chilton, 2018). It also should provide for integrated decision-making for groundwater resources and aquifer systems, and connect to other sectors and domains of society beyond the water sector – such as socio-economic development, gender equality and poverty alleviation, food and energy, ecosystems, climate change, and human health.

Figure 10.2 illustrates a generic institutional structure, showing how policy-making can enable vertical and horizontal integration and linkages to related sectors. The choices and the structure sit in a wider policy context where international guidelines and treaties can set outer frames. Recommendations of the Groundwater Governance Project (2016c), rules laid down in the European Union Groundwater Directive (European Parliament/Council, 2006), as well as the Model Provisions on Transboundary Groundwaters (UNECE, 2014) under the UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE, 1992) and the Draft Articles on the Law of Transboundary Aquifers (ILC, 2008; see Chapter 12) can also guide and influence policy-setting.

Figure 10.2

Institutional structure for groundwater policy development



Source: Foster and Chilton (2018, fig. 4.4, p. 87).

A (ground)water policy includes fundamental standards and basic guiding principles. Sustainability, efficiency, equity, the precautionary principle, the polluter pays principle, conjunctive management, demand and supply and maintenance management, and integrated water resource management (IWRM) are critical to inform future decisions (Smith et al., 2016). To ensure that indigenous communities' interests are addressed, for instance when concessions are given to groundwater resource developers, the principle of free, prior and informed consent – a component of the United Nations Declaration on the Rights of Indigenous Peoples (UNGA, 2007) – is also essential. Procedural elements may call for participation, transparency, accountability, non-discrimination and universality, the rule of law, anti-corruption, and subsidiarity. The participatory approach emphasizes that women play a central part in the provision, management and safeguarding of water, as stressed in the Dublin Principles (ICWE, 1992). An updated set of principles for valuing water has been proposed by the High-Level Panel on Water (2018), and these principles have been further elaborated in the *World Water Development Report 2021: Valuing Water* (United Nations, 2021). Procedural principles are also fundamental for the human rights-based approach.

The participatory approach emphasizes that women play a central part in the provision, management and safeguarding of water

The General Comment No. 15 on the right to water recommends that priority in the allocation of water must be given to personal and domestic uses (CESCR, 2002). Drinking water is therefore prioritized over other sectors, for instance in South Africa (Republic of South Africa, 2010). Following policy-making, it may be useful to frame such policy in law, based on human rights terms, thereby elevating drinking water from 'needs' to 'rights' (Mechlem, 2016).

All too often, the adoption of a groundwater policy is primarily focused on the utilization of groundwater after abstraction. This is far removed from sound management of *the aquifer*, which requires attention to land use, replenishment, protection, and implementation of measures that aim at preserving the multiple groundwater system services and functions (see Chapter 1). The aquifers, acting as the 'hosts' of the groundwater, and the very sources of various (ground) waters are distinct but interconnected, and need to be managed by targeted, yet complementary measures that provide for conjunctive use (Eckstein, 2017; Puri and Villholt, 2021).

10.2 Examples of groundwater policies

The Indian National Water Policy of 2012 states that groundwater "*needs to be managed as a community resource held, by the state, under public trust doctrine to achieve food security, livelihood, and equitable and sustainable development for all.*" (Ministry of Water Resources of India, 2012, p. 4). Regardless, the extraction of groundwater generally continues without strict regulation or enforcement (Pandit and Biswas, 2019), where powerful interests scarcely affected by the imposed government disincentives are reluctant to reduce their profitable groundwater use. Many states and union territories cover groundwater in their water policies; for instance, in Karnataka – a State that faces severe agrarian distress and acute shortage of domestic water – the over-exploitation of aquifers is now widely recognized, as is the interlinked groundwater–energy nexus (Kelkar Khambete, 2020). A stumbling block to realizing policy ambitions is the data bias in official statistics. Dry wells, for example, carry critical information about groundwater stress that is missed when data are filtered. This gap undermines policy interventions and resource allocation, as noted in the neighbouring State of Tamil Nadu (Hora et al., 2019).

In Australia, after decades of focusing primarily on surface water, the federal government as well as the States, territories and river basin authorities now pay more attention to groundwater. An example is the updated New South Wales (NSW) government's 20-year strategy (NSW Government, 2021). This document shows a high degree of horizontal integration, with groundwater linked to all the sectors depending on, and impacting, the resource.

10.3 Groundwater management planning

A groundwater (management) plan translates policy into a budgeted/financed programme of action and can provide a blueprint for its implementation.

Strategic planning identifies and defines actions that are likely to contribute to achieving the stipulated policy ambitions and goals, in particular for priority aquifer systems (Box 10.1). It can also serve to involve stakeholders in the process. Strategic plans are developed to promote rational, effective and fair water management and decision-making in relation to the resources and users of main concern. Planning considers uncertainty in a changing environment to address known future problems as well as those that cannot be predicted. This requires IWRM and linkages to all relevant policy sectors.

Box 10.1 Action points for the process of planning priority aquifers

Elaborating and implementing groundwater management plans for priority aquifers is the ultimate test of adequacy for governance provisions, and involves the following stepwise sequence of actions in each adaptive management cycle:

- identification and characterization of groundwater management units;
- assessment of resource status, opportunities and risks;
- reaching consensus on required aquifer services and plan objectives;
- drawing up the management strategy (including specific measures, monitoring needs and associated finance); and
- planning implementation over a specified period, with systematic monitoring, review of effectiveness, and adjustment of the next cycle.

Source: Groundwater Governance Project (2016c, p. 86).

A groundwater (management) plan translates policy into a budgeted/financed programme of action and can provide a blueprint for its implementation

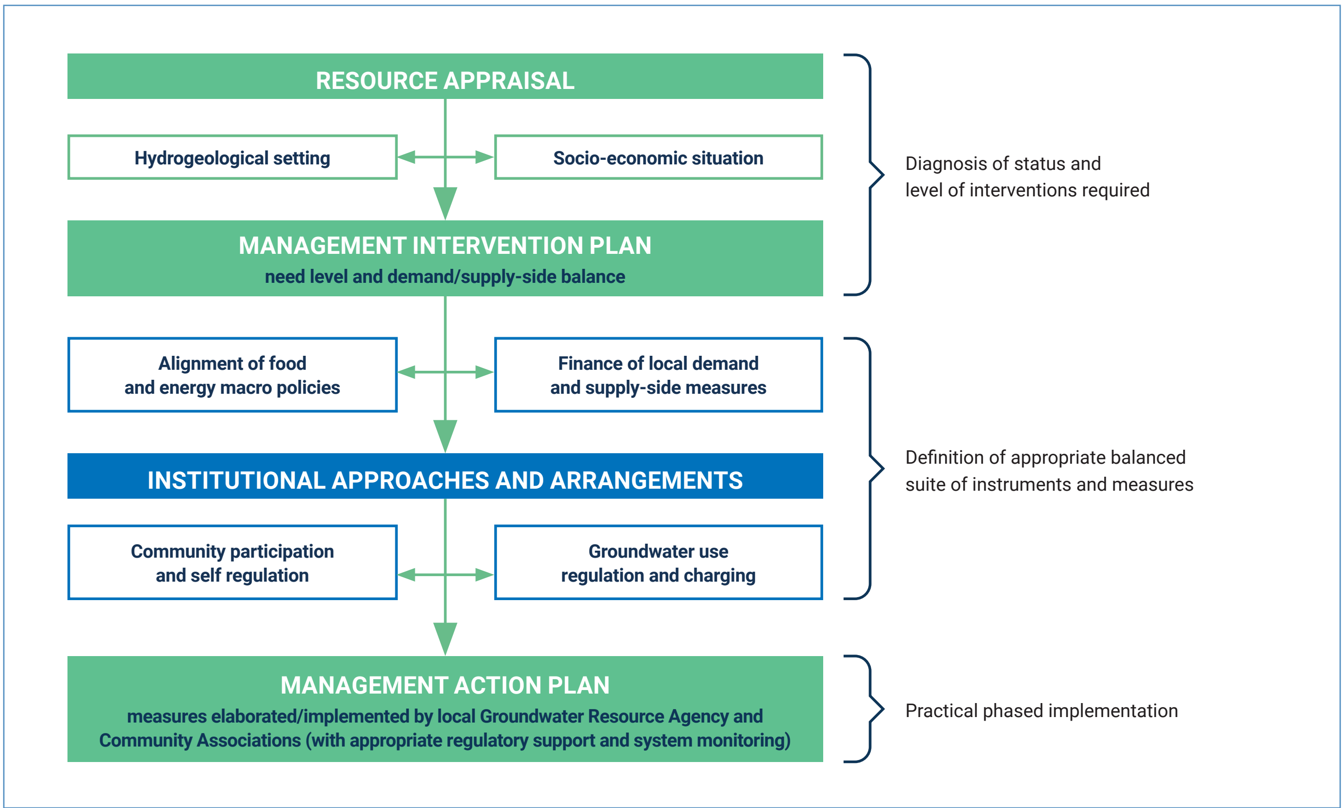
Operational management planning specifies the interventions and other activities to be carried out at field level, including their timing. It deals with subjects such as water supply infrastructure, reforestation projects and artificial aquifer recharge, as well as non-technical measures linked to legal and policy requirements, guidelines and related matters including who should be involved and at what phase. Operational plans go more into detail than strategic ones and usually cover only one policy sector, or only part of a sector, but acknowledge where they need to liaise.

In groundwater systems with little development stress, plans designed to monitor the aquifers for impacts without specific control mechanism would be appropriate. In contrast, in regions with intense usage competition or with historical or anticipated water shortages, plans detailing control measures would be important for preventing and managing risks of overexploitation (White et al., 2016).

Plans can be developed to specifically address issues such as flood risks caused by raised groundwater levels, typically following prolonged rain. Alternatively, the focus may be on avoiding depletion, seawater intrusion and land subsidence, and/or on protecting vulnerable groundwater-related ecosystems. Digitalization – including technologies for monitoring groundwater quality and aquifer systems in real time – offers efficiency gains and optimization through data collection and analysis, of importance at each stage of groundwater management planning (ITU, 2010). For instance, in arid regions, where a unified methodology for evaluation and decision-making is often restricted, a strategic approach for aquifer management planning may have to be based on a risk model (Şen et al., 2013).

The main components of groundwater plans include: inventorying, diagnosing and characterizing the aquifer systems or parts thereof (the 'management units'); evaluating and prioritizing the importance of the system to socio-economic development and ecosystems; assessing pressures on the system; and involving and consulting stakeholders (Foster and Chilton, 2018). Additional components include the specification of interventions and other management measures, and the expected impacts of such measures. All of these are central to 'adaptive management', which is needed to confront the joint challenges of global change and scientific uncertainty around complex groundwater resources and aquifers. Planning for conjunctive management of surface water and groundwater is critical to diversify water sourcing and to increase resilience (Grönwall and Oduro-Kwarteng, 2018). Additional aspects are shown in Figure 10.3.

Figure 10.3 Stages and factors in the elaboration of a groundwater management plan



Source: Foster and Shah (2012, fig. 4, p. 10).

Importantly, UN Member States are expected to realize the human rights to safe drinking water and sanitation through action plans or strategies, thereby actively promoting awareness and capacity concerning groundwater source protection, the need for treatment before consumption, and aquifer recharge (CESCR, 2002; Grönwall and Danert, 2020).

Plans can be prepared as a cooperative effort between national ministries, provincial and local agencies, and relevant stakeholders, based on dialogue and inclusive technical support (e.g. participatory mapping) to enable co-ownership of the process and the outcome. The process produces a formal document that can be validated, with time-bound actions and indicators that can be monitored, and outputs and impacts/outcomes that can be evaluated. The process includes a budget, linked to outputs that can be subject to review as performance is tracked and conditions change (Groundwater Governance Project, 2016c).

Open and participatory groundwater planning processes can generate greater public support and acceptance of the resulting plan and, by extension, operational management. Such planning involves scientists, resource management specialists, stakeholders and decision-makers, and should be accessible to non-specialists, inviting users to participate (Quevauviller et al., 2016). Planning of groundwater resources is as much a matter for government bodies as for the end users, collectively or individually. At the local scale, data gathering and information analysis will by necessity be limited; yet, all levels can benefit from capacity-building and awareness-raising. Likewise, sex-aggregated data, and ensuring the participation of women in data generation (a usually male-dominated topic), are vital in order to acquire a gendered dimension.

Policies, strategies and plans should be tailored to the local context, based on the priorities and aspirations of the local population, and informed by sound scientific evidence

While a groundwater and aquifer management plan could be part of a national IWRM plan (GWP, 2017), basin-level planning needs to consider the systems as a whole. Indeed, surface water and shallow groundwater are usually closely interconnected. However, it needs to be observed that groundwater basin boundaries do not always coincide with those of surface drainage areas. Moreover, as not all aquifers are linked hydrologically to rivers or lakes, the upstream–downstream relationships and power dynamics that influence the use of surface waters and groundwater may be very different (Smith et al., 2016).

National goals and local development objectives, priorities, approaches and levels of activity that are area-specific give guidance to optimal development, use, management and protection of the groundwater resource and the connected environment and ecosystems (Groundwater Governance Project, 2016c). Policies, strategies and plans should be tailored to the local context, based on the priorities and aspirations of the local population, and informed by sound scientific evidence.

A plan should set goals for groundwater management and serve as a roadmap to guide implementation of policy and diagnostic resource assessments. The management plan should set out the actions needed to address specific problems or pressures on groundwater for specific contexts, for instance as shown in Table 10.1.

Table 10.1 Examples of actions that can be specified in groundwater management plans

Types of measures	Purpose	Examples
Source-directed	Minimization and prevention of impacts at source; mitigation	• Authorization and licensing requirements; enforcement • Quality standards for wastewater discharge; control of injection wells • Requirements for on-site and landscape management approaches to control non-point, diffuse pollution • Economic incentives to reduce pollution • Development of low-waste and no-waste technologies • Application of source-to-sea/catchment-to-coast/ridge-to-reef approaches to address flows of water, biota, sediment, pollution, materials and ecosystem services • Mandatory and voluntary demand management to avoid over-abstraction
Resource-directed	Management of the resource; maintenance and operation	• National classification system for groundwater • Assignment of groundwater management classes • Setting quality objectives according to management classes • Establishment of drinking water protection zones • Application of adequate drinking water treatment methods • Setting of a volume-based reserve to meet basic human needs and an ecological reserve to protect ecosystems • Land subsidence control through pumping limits and managed aquifer recharge
Remediation	Restoration of groundwater quality and quantity, and/or aquifer storage	• Clean-up of abandoned sites • Emergency response to spills • Reduced abstraction to re-establish the reserve • Managed aquifer recharge, rainwater harvesting and enhanced infiltration • Development of a physically based model of land subsidence to plan for remedy strategies

Source: Adapted from Smith et al. (2016, table 3.1, p. 53).

10.4 Examples of groundwater management planning

The European Union's *Water Framework Directive* (European Parliament/Council, 2000) stipulates River Basin Management Plans as the main tool for presenting water status and analyses of impacts and responses, and for reporting to the European Commission. The Parties implementing the *Paris Agreement* under the UN Framework Convention on Climate Change highlight their climate actions in nationally determined contributions plans (NDCs). To date, groundwater features in 20 countries' submitted plans and is mentioned in 8, out of a total of 75 Parties to the Agreement (UNFCCC, 2021). These plans include references to the need for investments in aquifer buffering to increase adaptation capacities, enhancement of groundwater recharge, protection and management of groundwater and wetlands, and risk mapping. The NDCs mention nature-based and technology-driven mitigation as well as adaptation-directed measures.

In Tonga, there is a risk of groundwater depletion given the urgent need for economic development, for instance through agricultural intensification (Kingdom of Tonga/World Bank Group/IFAD/UNDP, 2016). The island's second NDC (Kingdom of Tonga, 2020) identifies salinization of groundwater as a potential impact of sea level rise, which threatens to reduce availability of freshwater resources. Means to address the situation include provisions of the Tonga Agriculture Sector Plan, which suggests assessing groundwater resources and their current exploitation, and identifying the potential areas for protection. The plan also suggests that, following previous drought years, there is an increased interest in using groundwater for irrigation.

In California (USA), the Sustainable Groundwater Management Act of 2014 tasks local agencies with regulating pumping in relation to aquifer recharge. These agencies have mandates to track and monitor abstraction and are required to map aquifer recharge areas. The Act requires planning of land use to achieve sustainability with transparency and stakeholder engagement, and learning within and between basins (Kiparsky et al., 2017).

China's take on groundwater policy and planning shows how the two are sometimes indistinguishable. The 1988 Water Law (People's Republic of China, 1988) lists planning in an independent chapter to emphasize its importance and legal status. It states that integrated water planning should be centred on watersheds rather than on administrative boundaries, with the regional planning complying with watershed planning, and based on a comprehensive scientific survey, investigation and assessment at relevant administrative levels. However, the stipulated segmentation in managing water quantity and quality inevitably hinders effective integration (Liu and Zheng, 2016). A Plan of Groundwater Pollution Control and Remediation, and a National Plan for Land Subsidence Prevention and Control provided official directives for groundwater management up to 2020 (Liao and Ming, 2019). These and other plans apply in parallel with the 'Three Red Lines' policy of 2012, which sets targets on total water use, efficiency improvement and water quality improvement. Further scientific planning should protect soils and groundwater to meet the 14th Five-Year Plan. Moreover, the Water Pollution Prevention and Control Action Plan (also known as the "Water Ten Plan") aims to control groundwater quality (Xinhua, 2020; China Water Risk, 2015).

Australia's National Groundwater Strategic Framework followed on a National Groundwater Action Plan. In New South Wales, planning and resource allocation builds on Water Sharing Plans, and the Water Reform Action Plan outlines how the government will deliver on its goals (NSW Government, n.d.a, n.d.b). The state employs a Bulk Access Regime to determine how much water will be available for extraction by all licensed water users within a Water Sharing Plan (see also Box 2.3). For instance, the Great Artesian Basin Shallow Groundwater Sources Order 2020 establishes rules according to which water allocations are to be adjusted, recognizing *inter alia* the effect of climatic variability on the availability of water (NSW Government, 2020).

Lessons on participatory planning can also be drawn from Gujarat and Rajasthan (India). Here, researchers engaged villagers to create ownership and behavioural change around groundwater overdraft. End users learned to monitor rainwater, operate automatic weather stations and put data into a repository app. This enabled calculations of the water balance recharge and assessing how much irrigation could be allowed (Maheshwari et al., 2014).

Chapter 11

Groundwater management

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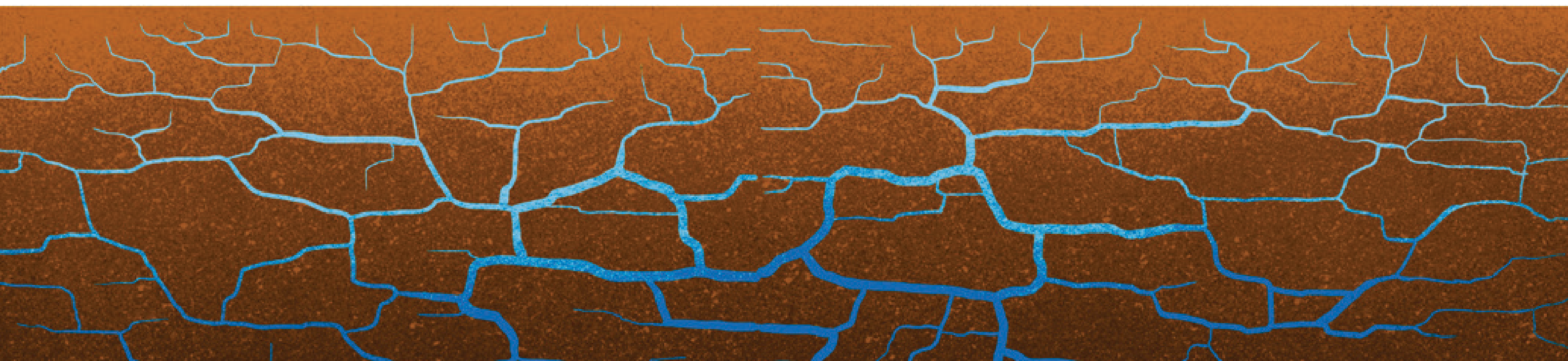


11.1 Introduction

Groundwater management encompasses the day-to-day operational decisions and practices that guide abstraction of groundwater, as well as other activities that have an influence on groundwater and the aquifers through which it flows. Management of groundwater may be undertaken to achieve the goals and objectives of policies set forth by laws and administrative procedures (see Chapter 10) or it may be undertaken by entities and individuals acting on their own accord. Knowledge of local groundwater systems and their conditions provides an important foundation for management, as it identifies what needs to be managed, what actions can be taken, and what the impacts of those actions can be.

As groundwater provides a range of provisioning, regulating, and supporting services (Bergkamp and Cross, 2007; Griebler and Avramov, 2015; see Figure 1.5), groundwater management is multidimensional. Groundwater management aims to control groundwater abstraction and quality as well as to address the effects of groundwater abstraction on ecosystems, surface waters, land subsidence and more. Groundwater management may also seek to allocate water in a manner that aligns with priorities and objectives stipulated in groundwater policies. Crucial to the success of any management effort is the need to examine the potential externalities and multiple effects of any management action, to avoid unintended or unexpected consequences.

This chapter provides an overview of groundwater management. Topics discussed include: gathering data and knowledge for groundwater management, controlling groundwater abstraction, protecting groundwater quality, and managing groundwater for broader sustainability and needs. Integrated groundwater management practices, including managed aquifer recharge (MAR), are also described.

11.2 Data and knowledge requirements

Chapter 9 describes tools and approaches for building the knowledge base for groundwater and keeping it up to date. For groundwater management, a hydrogeological conceptual model – describing structural features, boundary conditions and hydraulic properties of the groundwater system – is needed to estimate groundwater availability and to understand and characterize the main physical processes that are taking place within the system. Since aquifers are dynamic systems subject to change, groundwater abstraction, water levels and water quality need to be regularly monitored to provide information on the state of the groundwater system and trends over time. Hydrogeological conceptual models, the water budget (i.e. recharge, discharge, and their difference) and monitoring data provide the basic ingredients for groundwater models. Groundwater modelling can contribute to a better understanding of flows throughout the groundwater system and can be used for predicting the future state of the system (both with and without management interventions).

11.3 Controlling withdrawals

Perhaps one of the most critical components of groundwater management is control of the location and quantity of water withdrawals from the aquifer. Proper siting and construction of wells and boreholes (also known as drilled wells or tubewells) are fundamental for managing the hydrogeological impacts of withdrawals, both on the aquifer itself and on other environmentally significant assets such as rivers, lakes, wetlands, springs and groundwater-dependent ecosystems. Careful siting of wells is also important to prevent or minimize potential interactions between wells. Control over the quantity of water withdrawn is important because intensive groundwater pumping continuing for extended periods of time may lead to groundwater depletion.

A variety of tools can be used to manage groundwater withdrawals (Table 11.1). Which tools are used depends on the approach to management defined by the governance and policy regimes in place. Not all management occurs through government. Communities and/or groundwater users themselves may independently choose to manage well siting and groundwater abstractions and in doing so, employ similar tools to those used by the government.

Table 11.1

Methods for controlling groundwater withdrawals

Approach to management	Management tools
Regulatory: control well development and withdrawal by specifying the conditions under which groundwater may be abstracted	• Requirements for construction, drilling, and/or spacing of wells and boreholes • Assignment and enforcement of water use entitlements (rights, concessions, licenses, or permits for withdrawal) that specify a volumetric allocation and timing of withdrawals • Curtailment of pumping during drought or based on climatic or streamflow conditions • Quotas or restrictions on energy use for groundwater withdrawal
Market-based: encourage or discourage groundwater withdrawal and related activities by changing the cost of those actions	• Tariffs/fees applied directly to groundwater abstractions or to proxies, such as electricity or land use • Subsidies (grants, loans, access to goods or services at discounted cost, and technical assistance) that reward water savings or facilitate adoption of new technologies and practices
Informational: influence groundwater withdrawal and related activities through education, dissemination of information, and guidance	• Dissemination of information, guidance, or data designed to change behaviour • Awareness-raising campaigns and social marketing • Development of standards or certifications • Provision of technical support
Informal: influence groundwater withdrawal and related activities through cultural norms and situated knowledge	• Social pressures, monitoring and sanctioning • Actions by groundwater users to adapt the timing and quantity of their pumping to changing aquifer conditions

Deployment of different types of management tools can simultaneously influence the location, timing, and quantity of groundwater abstractions.

Perhaps one of the most critical components of groundwater management is control of the location and quantity of water withdrawals from the aquifer

The adoption of good practices in well siting and construction is often the first management action undertaken. Siting of wells must also take account of socio-economic and cultural factors. For example, in the case of rural water wells in Africa and Asia, where women are normally responsible for water collection, well siting needs to account, apart from the impacts on the aquifer, for walking distance and personal security at the well site (Misstear et al., 2017). Proper construction, maintenance and testing of wells are necessary to ensure sustained access to groundwater as well as cost-effectiveness and safety. Declines in handpump functionality and borehole failure due to poor-quality pumps are common problems affecting many wells, especially in parts of Africa (Andres et al., 2018; Tincani et al., 2015).

Deployment of several groundwater management tools is contingent upon first having the legal and institutional structures in place that grant authority for their use and enforcement. Implementation of any new regime to control groundwater pumping and use is not without challenges. In many regions of the world, laws and institutions governing groundwater are in their infancy and not fully operational. With respect to regulatory approaches, there is no single method for determining volumetric allocations, and any method applied will have its strengths and drawbacks. In different locations, governments have defined water rights based on historical pumping rates, current uses, land area, or other methods. Often, governments seek to limit withdrawals to an estimated 'safe' or 'sustainable' yield, though those concepts are ambiguously defined. The interaction between ground and surface waters makes it difficult to define and assign environmentally acceptable flows to rivers when establishing groundwater abstraction permits.

Further, groundwater users may resist the imposition of new efforts to control groundwater pumping. Where groundwater has historically been subject to minimal or no regulation, groundwater users may view management actions as expropriation of private property. Allowing for exempt uses, such as for domestic use or livestock, or a fixed amount of inframarginal pumping (i.e. an allowable and usually small volume of water that can be pumped without being subject to regulations or tariffs, usually for the purposes of meeting basic human needs or household-scale farming), can help overcome resistance to control through regulation and pricing. However, care needs to be taken to ensure that exempt uses do not undermine management objectives (Jakeman et al., 2016; Molle and Closas, 2020). Equity is an important consideration, as management actions that differentially affect groundwater pumpers and users can lead to conflict. Implementation is usually more effective when a combination of 'carrots and sticks' are used to change users' behaviour (Molle and Closas, 2020).

Where groundwater has historically been subject to minimal or no regulation, groundwater users may view management actions as expropriation of private property

For any approach to controlling groundwater withdrawal to be successful, it is important to monitor groundwater extraction rates and aquifer conditions, and to ensure compliance with permits and regulatory requirements. Monitoring also serves to support policy-makers in justifying constraints on abstractions (Moench, 2004). Unfortunately, due to the hidden nature of groundwater, the quantity of groundwater abstracted often remains undetermined. Groundwater users themselves may be unaware of the quantity they are withdrawing, or when they do know, they may even have reasons to keep that information confidential. Metering provides valuable information, yet installation and reading of meters is not without cost and may be perceived by well owners as an infringement of their privacy. Consequently, most wells around the world are unmetered (Kemper, 2007). New and lower-cost technologies for groundwater metering are being developed. Further, pumping quantities can be estimated indirectly through remote sensing, irrigated land acreage and electricity use, among other means (Giordano, 2009; Ursitti et al., 2018). Nonetheless, in many places, social and political resistance to monitoring and data disclosure may impede tracking and enforcement of compliance with groundwater abstraction regulations.

Box 11.1 presents a case study of well permitting and augmentation to reduce groundwater withdrawal impacts.

Box 11.1 Groundwater withdrawal and quantity management: Well permitting and augmentation to reduce impacts (South Platte River basin, Colorado, USA)

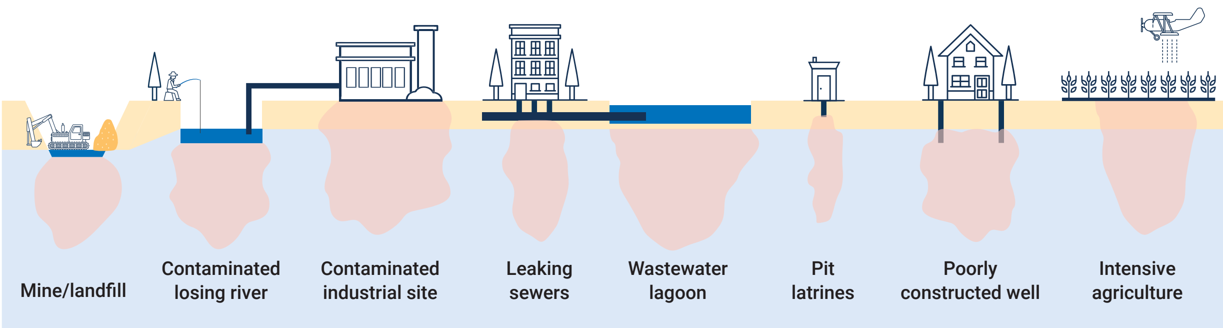
Groundwater levels and surface water flows in the South Platte River basin, Colorado (USA) declined dramatically during the mid and late 20th century due to the expansion of groundwater pumping. These effects created tensions between surface water and groundwater users and threatened the habitat of several endangered species located downstream in the river. To address this issue, the State of Colorado requires all entities who began pumping water after 1997, including any new users, to obtain approval from the State's Water Court. To do so, prospective pumpers must demonstrate that groundwater withdrawals will not negatively affect other uses and users or, if it will, pumpers must conduct what the State terms 'well augmentation'. Well augmentation involves offsetting or eliminating any potential impacts of groundwater withdrawals on streamflow, typically through recharge or substitution. Well augmentation plans must include an assessment of potential stream depletion and a plan to avoid it, taking into consideration the lag time between pumping, well augmentation and river flows. In this manner, the State manages groundwater withdrawals to ensure they do not infringe upon existing surface water and groundwater rights, while also protecting in-stream flows.

See Milman et al. (2021) and Blomquist et al. (2010) for further information.

11.4 Protecting groundwater quality

As described in prior chapters, groundwater quality faces many threats from agricultural intensification, urbanization, industry, mining, population growth and climate change, as well as from naturally occurring contaminants such as arsenic and fluoride (Figure 11.1). Groundwater should be managed to prevent these threats and concerns from reaching problematic levels, to avoid the increase of the pollution and to reverse pollution trends, and to reduce the impacts of water quality degradation on human health and the environment.

Figure 11.1 Pollution sources that threaten groundwater quality



Source: Based on Villholth et al. (2011, fig. 2.6, p. 15).

Sources of pollution can be controlled through standards, monitoring protocols, on-site management practices, and permits that specify requirements for waste discharge and potentially contaminating activities

The most sustainable and cost-effective approach to managing groundwater quality is to ensure adequate protection of groundwater, thus avoiding contamination by human activities. While groundwater remediation can be effective in reducing concentrations of contaminants, it is costly. Groundwater protection can be achieved through: (i) a pollution source-directed approach that prevents and minimizes the impact of development on groundwater quality, and (ii) a groundwater resource-directed approach that implements measures to protect the aquifer and ensure sustainability and suitability for beneficial use. With respect to naturally occurring contaminants, measures such as restricted withdrawal, limited drawdown to avoid ingress of water with a different quality, and operational requirements (e.g. constraints on the timing and rate of pumping to minimize the risk of water quality deterioration) can be defined and implemented.

Sources of pollution can be controlled through standards, monitoring protocols, on-site management practices, and permits that specify requirements for waste discharge and potentially contaminating activities. These management tools generally dictate what chemicals or constituents can be used, and when, where and how. They also specify what technologies and procedures should be followed to avoid or reduce contamination and the risk of accidents or spills. Monitoring, enforcement and sanctioning through fines for non-compliance will improve the effectiveness of those activities.

Protection of the aquifer can be achieved through vulnerability mapping, development of groundwater protection zones to safeguard drinking water (Box 11.2) and land use planning that considers groundwater quality protection. Best management practices, incentive and disincentive programmes for aquifer protection, and educational and awareness campaigns can also contribute to aquifer protection.

Poor well construction often means that the wells themselves provide the main pathway for pollutants to enter the aquifer (or move between aquifers). To help preserve groundwater quality, wells should be constructed with proper sanitary seals and protective headworks.

Management of groundwater quality requires monitoring through regular collection and analysis of water samples over prolonged time periods. Institutional, technical and resource capacity is needed for collecting high-quality data with sufficient frequency and for evaluating trends in water quality to identify risks and determine the effect of management activities.

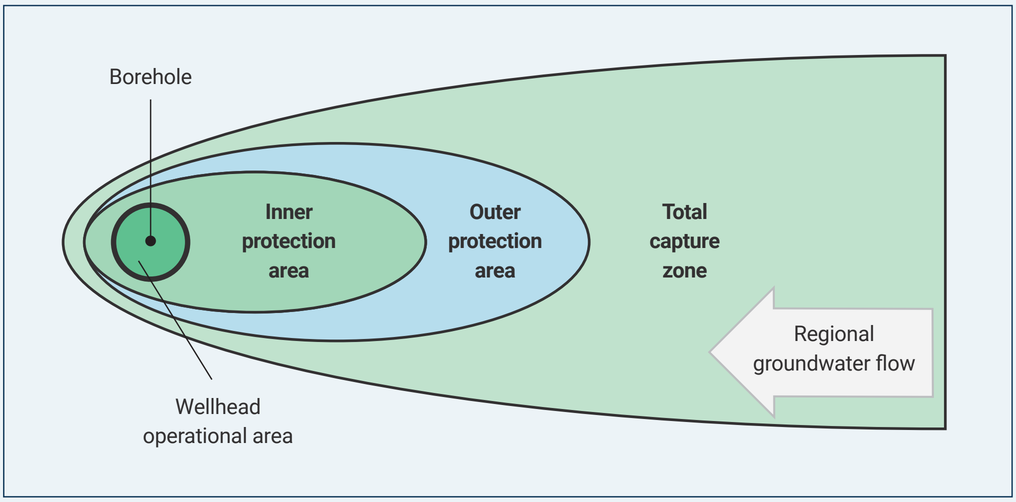
Diffuse pollution and the distributed nature of potential sources of contaminants present very real challenges to controlling groundwater quality. This is because there are many pathways through which contaminants can reach the aquifer and monitoring and enforcement of all pathways is impossible. Contamination of an aquifer system is often detected only a considerable time after it occurred. Indeed, in many places around the world, the sources of pollution no longer exist, yet the contamination plumes are still present or just emerging (e.g. nitrates, dense non-aqueous phase liquids (DNAPLS), etc.).

Preventing pollution and protecting an aquifer frequently require coordination across many agencies and actors. In many countries, separate agencies govern land use, water resources, discharge of waste and the use of hazardous substances. Coordination, communication and regulatory harmonization among the relevant agencies, actors and policy frameworks are among the many challenges that must be overcome to protect groundwater quality effectively and efficiently.

Box 11.2 Groundwater source protection areas

Groundwater source protection areas are employed to prevent pollution of drinking water sources and groundwater used for agricultural purposes. This approach typically establishes a minimum distance between waste disposal areas or other identified pollutant sites, and protected groundwater supply areas. Risk, vulnerability, and important hydrogeological and hydrogeochemical characteristics inform the design of protection zones. There are many examples of this management approach globally, including in Australia, Canada, Europe, India and the USA.

Schematic representation of protection areas around a water source



Source: Based on Nel et al. (2009) and Rajkumar and Xu (2011).

11.5 Integrated management approaches

Groundwater systems do not exist in isolation: they are tightly interconnected with surface water, land, climate and ecosystems. These linkages, as well as their connections with society, culture and the economy must be understood to manage groundwater effectively. In many countries, groundwater and surface water are managed independently. Further, policies and activities from outside the water sector (particularly those related to land, food and agriculture, mining, and the energy sector) affect demands for surface water and groundwater, impact infiltration and recharge, and may create sources of contamination.

Particular attention to the conjunctive management of surface water and groundwater resources and to the potential for 'nature-based' solutions is needed (Van der Gun, 2020). Understanding interactions between surface water and groundwater, by quantifying exchange fluxes, directions and water quality interactions, is vital for ensuring that management achieves its intended outcomes. Land and ecosystem management, coordinated with groundwater management, can enhance storage and retention, protect water quality or conversely, adversely affect groundwater systems. Consequently, policy coherence and consideration of the full range of users, uses and impacts is essential.

Integration with environmental management, with land use management, and with management of space and resources of the subsurface are all important issues within the purview of integrated management

Due to the evolving nature of groundwater management, multiple institutions, policies, and management tools exist concurrently. This may lead to inefficiencies and contradictions. Groundwater management planning (see Chapter 10) provides a mechanism for coordinating across the many actors involved in groundwater management, and for integrating and synergizing across the multiple policies and tools used (Foster et al., 2015; Gage and Milman, 2020).

Integration with environmental management, with land use management, and with management of space and resources of the subsurface are all important issues within the purview of integrated management. MAR is one example of an integrated approach (see Box 7.1).

MAR, also called artificial recharge, entails the use of engineered or natural infrastructure to increase infiltration into an aquifer system (Dillon et al., 2019). Technologies such as MAR are important for securing water resources against drought and saltwater intrusion, as well as for increasing water supply, improving water quality, maintaining the structure and quality of the aquifer, and sustaining groundwater-dependent ecosystems. MAR allows for replenishment of aquifers to complement storage dams and provides a cost-effective alternative that minimizes evaporation and environmental impacts. MAR can also be used to retain unharvested urban stormwater (Box 11.3) and recycled water for productive use when needed. At the watershed scale, MAR can be used to maintain environmental water flows and availability, creating lags in water discharges to a stream (Page et al., 2018).

Artificial recharge consists of two main components: (i) intercepting water (usually surface water), and (ii) mechanisms to enable infiltration of this intercepted water so that it enters the aquifer. Any particular form of artificial recharge combines both components; technical provisions sometimes are focused on the first component (e.g. recharge dams, water intakes from a river), and in other cases on the second one (e.g. spreading techniques with ponds or basins, injection wells); and occasionally a mix of the two (e.g. channel spreading, induced bank infiltration). Proper design of the MAR system and adequate operation and maintenance can improve the qualitative and quantitative performance of the system.

Best practice examples of MAR applications are widely available. The MAR Portal,[42] accessible via the International Groundwater Resources Assessment Centre's Global Groundwater Information System, contains detailed information on some 1,200 MAR sites from about 50 countries around the world, as well as regional MAR suitability maps. Dillon et al. (2019) present an overview of the spread of MAR techniques around the world during the past 60 years.

[42] For more information, see ggis.un-igrac.org/view/marportal.

Box 11.3 Stormwater harvesting for aquifer storage and recovery: Example of a MAR project, Adelaide area (Australia)

In Adelaide (Australia), stormwater runoff is collected in small, constructed wetlands that have a retaining and treatment functionality, providing for biodiversity and forming a recreational destination. During several days of retention in the wetlands, pollutants and pathogens are removed. Then, the water is injected in the deep Tertiary aquifer by means of Aquifer Storage and Recovery (ASR) wells. Stormwater harvested via aquifer storage and recovery represents about 10% of Adelaide's water supply. By 2017, 58 MAR schemes were in operation, with a combined recharge capacity of more than 20 million m^3/year.

MAR schemes have low costs and high public acceptance.

11.6 Conclusions

Groundwater management presents many challenges and opportunities. For groundwater to be effectively managed, the links between groundwater, society (including population growth), environment and ecosystems, and climate change must be taken into consideration. Policies and activities from outside of the water sector influence demands for groundwater as well as infiltration and recharge, and may also create sources of contamination. Groundwater management also has implications for society, the environment and the economy.

Historically, groundwater has usually not received management attention until after a problem has magnified to the extent that it becomes visible. Management has thus been reactive. Proactive approaches to managing groundwater are required to prevent degradation and depletion of the resource.

Management of groundwater must concurrently take into consideration the multiple dimensions of groundwater systems: groundwater storage, flows, quality and behaviour, and the structure and properties of the aquifer itself.

Management of groundwater must occur at all levels. While governments and their mandated agencies may take the lead in the overall coordination regarding groundwater management, there may also be important roles to be played by communities, water companies, industries, farmers and other individuals.

Limited data and knowledge remain key impediments to evidence-based groundwater management. Monitoring, assessments and investigations are critical (see Chapter 9).

Capacity and capability (both people and knowledge) are required for effective and successful groundwater management. Educating the young and ensuring that their voices are heard are vital for the future success of groundwater management globally. Well-resourced groundwater science and education programmes are needed to train managers, and governance and policy must create the enabling environment for management. Developing and sustaining groundwater management requires substantial financial and political support from governments, and adequate mandates for the agencies that will play the lead role.

Chapter 12

Transboundary aquifers

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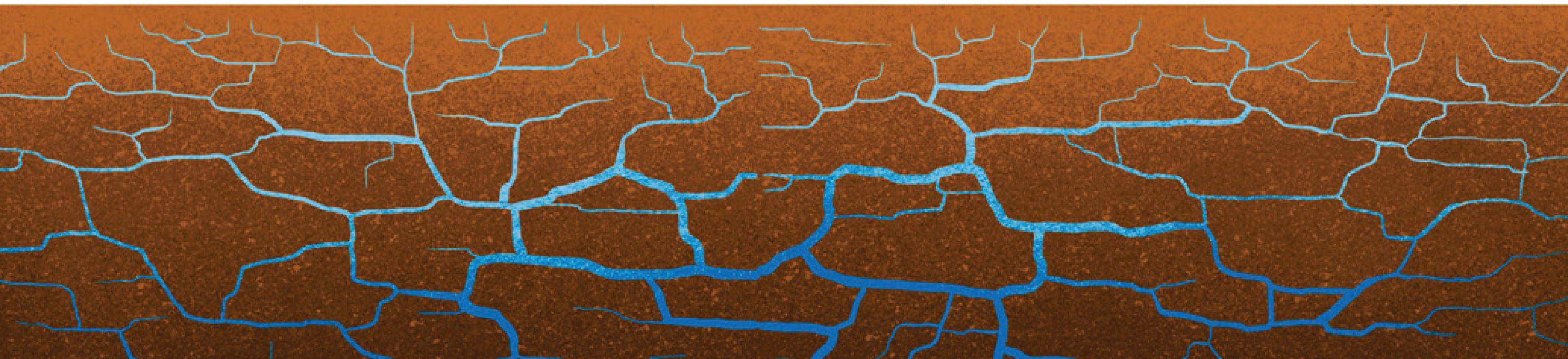


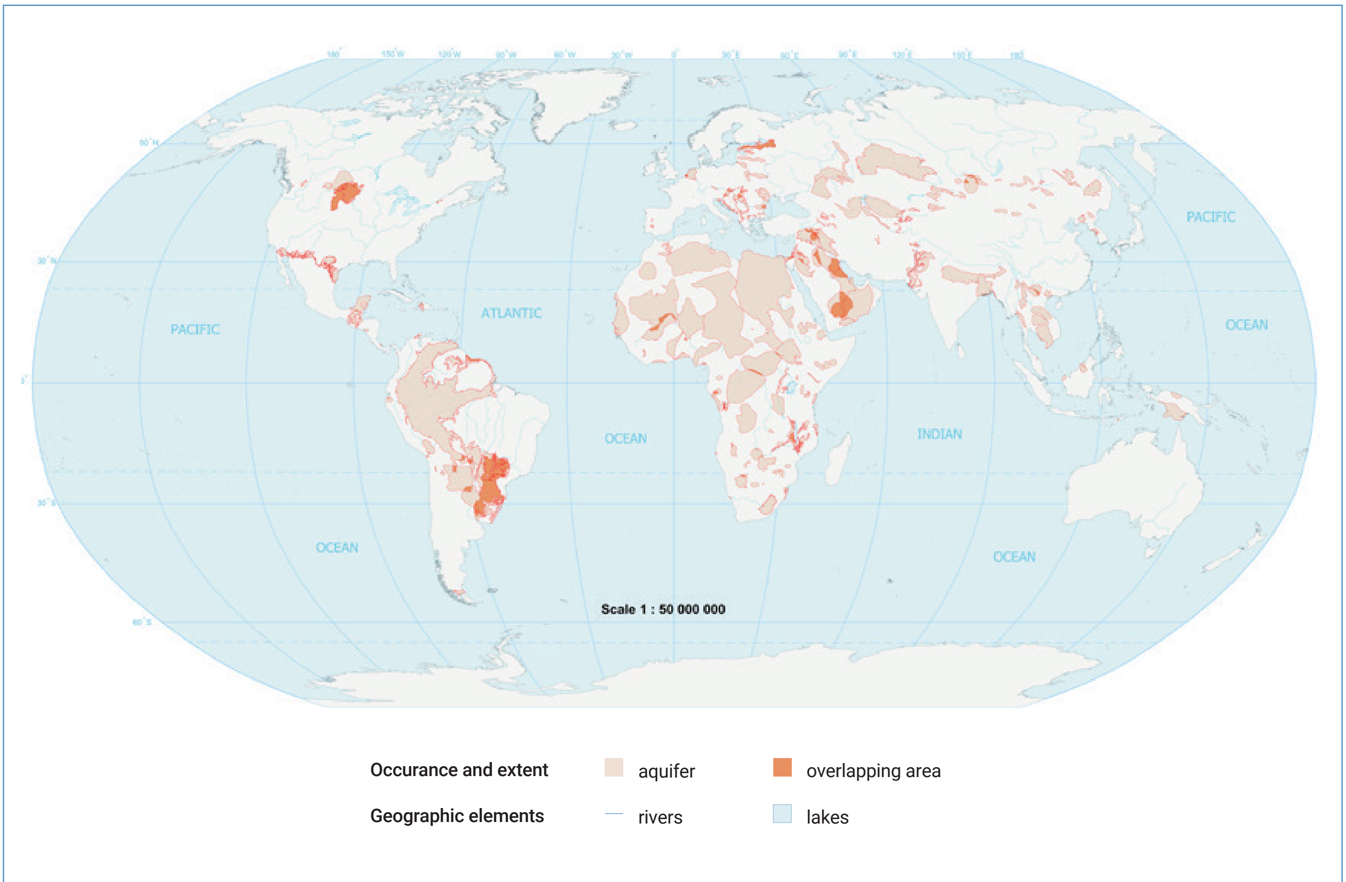
12.1 Introduction

This chapter gives an overview of the status of transboundary aquifers and the cooperation related to shared groundwater resources, highlighting the complexity of the assessment, analysis and management of these systems. It summarizes the main challenges regarding transboundary aquifers and the need for more comprehensive and integrated management, which would include technical, legal and organizational aspects as well as training and cooperation.

12.2 Current understanding of transboundary aquifers

When an aquifer or aquifer system is referred to as 'transboundary', that means that parts of it are situated in different states (UNGA, 2009). Transboundary aquifers include a natural subsurface path of groundwater flow, crossing an international boundary, such that water can flow from one side of the boundary to the other (UNESCO, 2001). The first global inventory of transboundary aquifer was undertaken by UNESCO-IHP, which launched the Internationally Shared Aquifers Resources Management initiative (ISARM) in 2000 (Box 12.1). The currently known global distribution of transboundary aquifers is shown in Figure 12.1, based on an inventory of global and regional projects and initiatives.[43] The first global baseline assessment of 300 of the world's largest transboundary aquifers was undertaken by the Transboundary Waters Assessment Programme (UNESCO-IHP/UNEP, 2016). This programme described transboundary aquifers in terms of human dependence on the resource. It elaborated scenarios based on population pressures and identified future hotspots in Sub-Saharan Africa, part of Eastern Asia and Central America. The exact delineation of a large number of transboundary aquifers is still incomplete, particularly at the local level where transboundary aquifers may be small but vital for communities' livelihoods (Eckstein, 2013; Fraser et al., 2020).

Figure 12.1 Transboundary aquifers of the world



[43] Including the First and Second UNECE assessment of transboundary aquifers located in South-Eastern Europe, Caucasus and Central Asia (UNECE, 2007, 2011); Inventory of Shared Water Resources in Western Asia (UNESCWA/ BGR, 2013).

Box 12.1 International Shared Aquifer Resource Management Initiative

In 2000, UNESCO's Intergovernmental Hydrological Programme launched the Internationally Shared Aquifer Resource Management initiative (ISARM) (Resolution XIV-12 – UNESCO-IHP, 2000), aimed at preparing a global inventory of transboundary aquifers and developing and supporting cooperation between countries through the improvement of knowledge of transboundary aquifers (TBAs). The initiative carried out regional studies designed to delineate the aquifers, as well as to assess and analyse hydrogeological, legal, socio-economical, institutional and environmental aspects. The regional inventories revealed that some of the most important aquifers in Africa and in Latin America are transboundary (UNESCO-IHP, 2009).

The initiative contributed towards building the knowledge base and provided guidance for countries' cooperation on TBAs. Substantial advancement has also been achieved with regards to the legal component. UNESCO-IHP assisted the International Law Commission (ILC) in the preparation of a set of 19 draft articles on the Law of Transboundary Aquifers that are annexed and mentioned in several resolutions of the General Assembly of the United Nations (UNGA).

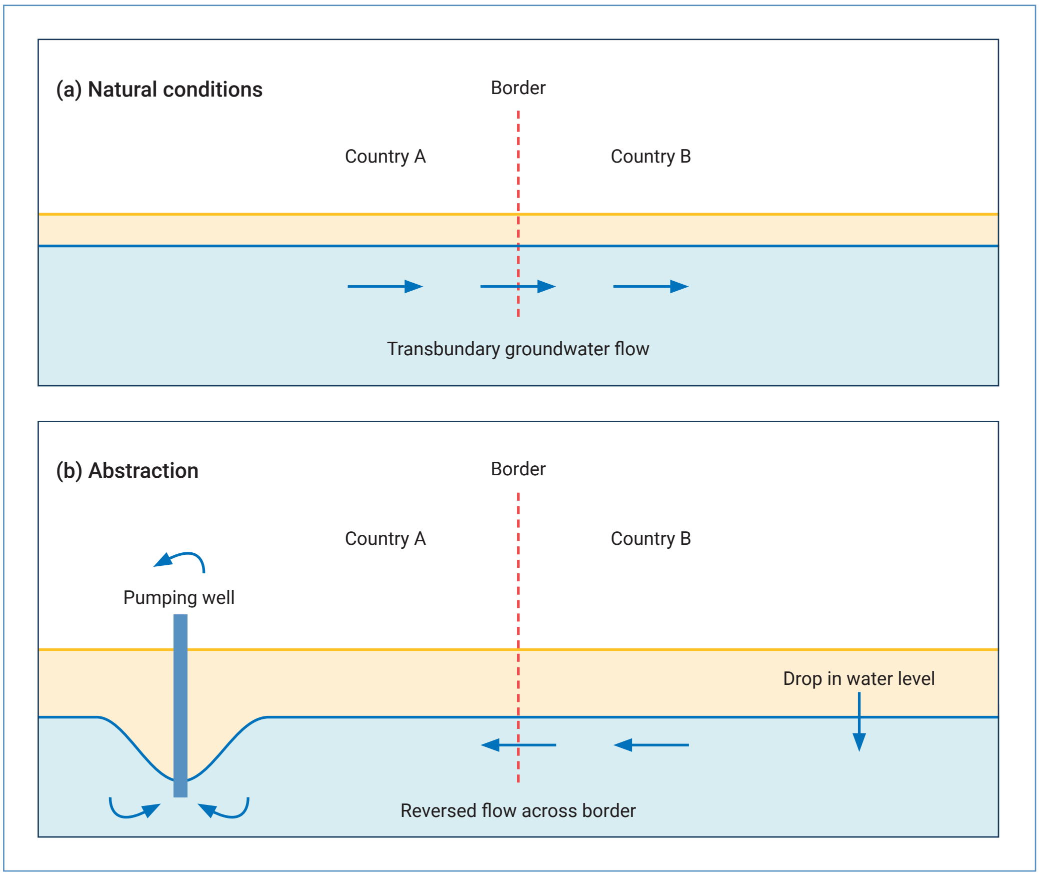
As a result of ISARM's activities, projects have been initiated in different regions to help countries in establishing cooperative mechanisms for the management of TBAs.

12.3 Challenges specific to transboundary aquifers

Generally, drivers of stress are the same for domestic and transboundary aquifers. Political boundaries add specific challenges. Actions on the aquifer in one country can have a significant impact on the other side of the border. Figure 12.2 illustrates a simple example of the effects that abstracting groundwater from a transboundary aquifer can have across borders. Heavy abstraction on one side of the border can cause the lowering of the water table in a neighbouring country. It can even at times cause groundwater flows to reverse across the border. Groundwater abstraction can also impact systems that are hydraulically connected to the transboundary aquifer, for instance by reducing river flows or affecting groundwater-dependent ecosystems. In addition, contamination of the aquifer on one side of the border can flow across political boundaries, causing potentially severe impacts for neighbouring states and complicating any remediation efforts.

Figure 12.2

Pumping groundwater from a well in country A can have an impact on the part of the aquifer in country B



Source: Adapted from Fraser et al. (2018, fig. 6, p. 45).

The extent of transboundary aquifers can vary greatly, from a few to over a million square kilometres, and from tens to several thousands of metres in depth. This raises the question whether joint management and monitoring should necessarily encompass the total extent of a transboundary aquifer, or rather concentrate on specific hotspot areas where transboundary impacts may be most likely to occur. One possible approach to this dilemma is found in the agreement on the Saq-Disi aquifer (shared between Jordan and Saudi Arabia), which considers the establishment of protection areas around the border.

The integration of gender considerations into transboundary cooperation represents an element for creating opportunities of more socially equitable management of transboundary groundwater resources

Cooperative management of transboundary aquifers can be complex due to obstacles in aquifer-sharing countries, which may include (AFD, 2011):

- lack of perception of the transboundary character among the authorities, managers and concerned populations;
- absence of a specific legal and institutional framework;
- different management and governance approaches and priorities;
- lack of political will for cooperation and implementation of long-term management;
- tensions between countries, unequal resource partitioning, groundwater quantity and quality decline, and different management capacities within the social, economic and environmental contexts of aquifer-sharing countries;
- fragmented knowledge of the aquifers;
- precise data not being shared (see Table 12.1 below);
- insufficient financing;
- lack of knowledge and capacity for developing and executing scientific/technical studies, and for setting up formal institutions; and
- different languages spoken, or different cultural or political orientations, on both sides of the border.

Furthermore, the integration of gender considerations into transboundary cooperation represents an element for creating opportunities of more socially equitable management of transboundary groundwater resources.

Training and capacity-building programmes are key for empowering technical and administrative staff to understand the different challenges involved in the assessment and management of transboundary aquifers (Nijsten et al., 2016).

Sharing data represents the first step in cooperation between neighbouring countries, as it is essential to reaching an agreement about a reliable conceptual model of the aquifer, which is in turn a prerequisite for the formulation of management plans.

When data are lacking, or states are unwilling to share them, this can hamper the sustainable management of transboundary groundwater systems. Transboundary aquifer management often suffers from a lack of institutional will and insufficient resources to collect the necessary information (AFD, 2011). Although global data can enlighten general trends, a more detailed understanding at the regional and local level is required for joint decision-making and transboundary aquifer management (IGRAC/UNESCO-IHP, 2015; Fraser et al., 2018; Rivera, 2015, 2020).

Data management and data sharing within transboundary aquifers can be supported by both information management systems and and web-based platforms that assist in data collection, storage, processing, visualization and sharing (IGRAC/UNESCO-IHP, 2015), such as the Global Groundwater Information System (GGIS) (IGRAC, n.d.). Advances in technologies, from space-based observations to telemetry, combined with citizen science, may facilitate the heavy burden and cost of data collection (see Chapter 9).

The data and information requirements suggested in Table 12.1 apply both to domestic and transboundary aquifers, except for the legal and institutional components. Data that have been collected and analysed at the national level, using different methods and approaches, may need to be harmonized before they can be used across borders.

A vital component of transboundary aquifer management is monitoring, which should include time series observation of groundwater levels and quality (IGRAC/UNESCO-IHP, 2015). For monitoring to be effective, data should be coordinated, harmonized and shared among aquifer states (SADC-GMI/IGRAC/IGS, 2019b). In view of the complexities in transboundary aquifer assessment and monitoring, guidelines have been developed to assist aquifer states and stakeholders in the process (e.g. the UNECE Task Force on Monitoring and Assessment, 2000; AFD, 2011; IGRAC/UNESCO-IHP, 2015).

12.4 International legal and institutional aspects

International water law was initially developed for surface waters. Considerations on groundwater started progressively with the growing awareness of the importance of transboundary aquifers. The Convention on the protection and use of transboundary watercourses and international lakes[44] (Water Convention – UNECE, 1992) covers any surface or groundwater bodies that mark, cross or are located on boundaries between two or more states. It has provided the basis for various bilateral and multilateral agreements (UNECE, 2013). The Convention on the law of non-navigational uses of international watercourses (United Nations, 1997)[45] considers transboundary groundwater only when it is connected to an international surface water system and flows to the same terminus. It does not consider the specific characteristics of the diverse types of aquifers.

To fill this gap, the International Law Commission (ILC) prepared an international law instrument composed of 19 draft articles that contemplate all types of aquifer characteristics (Stephan, 2011). The articles are the topic of five non-binding UN General Assembly (UNGA) resolutions.[46]

The UNGA commends the draft articles to the attention of governments, "*as guidance for bilateral or regional agreements and arrangements for the proper management of transboundary aquifers*" (UNGA, 2013, 2016, 2019). All types of transboundary aquifers, including non-recharging aquifers, are covered in the scope of these draft articles. They also consider land use, as they apply to "*other activities that have or are likely to have an impact*" (art. 1§b). The draft articles have adapted the core principles of international water law to the aquifers' characteristics. They include considerations related to non-rechargeable aquifers, groundwater management and monitoring, and the protection of ecosystems and the aquifer recharge and discharge zones. In 2012, the Meeting of the Parties to the Water Convention adopted the Model Provisions on Transboundary Groundwaters (UNECE, 2014), which build upon the draft articles, aiming to provide guidance for the implementation of the principles of the Convention to transboundary groundwater, and to improve cooperation on integrated management of transboundary surface water and groundwater bodies.

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[44] In force since 1996, 44 Parties.

[45] In force since 2014, 37 Parties.

[46] These resolutions are 63/124, 66/104, 68/118, 71/150 and 74/193 (UNGA, 2009, 2012, 2013, 2016, 2019). The draft articles are annexed to resolutions 63/124 and 68/118.

Table 12.1

Data and information required to assess and manage a transboundary aquifer

Hydrogeology, physiography and climate	
Aquifer geometry (boundary, type, depth of water table, aquifer thickness)	Climate (temperature, precipitation, evapotranspiration)
Aquifer recharge and discharge identification	Land use
Lithology and soil type	Topography
Porosity, permeability	Surface water network (rivers, lakes)
Transmissivity and vertical conductivity	Groundwater volume
Groundwater levels and flow direction	Groundwater flow systems
Environmental	
Groundwater quality	Groundwater-dependent ecosystems
Pollution sources	Solid waste and wastewater control
Socio-Economic	
Population	Abstraction rates/well density
Refugee/Internally displaced people (IDP) camps	Human groundwater dependency
Groundwater use	Surface water use
Legal and institutional	
Transboundary legal framework	Domestic legal framework
Transboundary institutional framework	Domestic institutional framework
Ownership of groundwater	Water resource planning and protection
Groundwater abstraction control	Groundwater pollution control
Enforcement of legislation	Water institutions

Sources: Based on Rivera (2015, 2020) and IGRAC/UNESCO-IHP (2015).

12.5 Cooperation over transboundary aquifers

Transboundary relations can involve different degrees of cooperation.

There are very few cases worldwide of interstate agreements regarding transboundary aquifers in force (Burchi, 2018b): the Genevese aquifer (France, Switzerland), the North Western Sahara Aquifer System (Algeria, Libya, Tunisia), the Nubian Sandstone Aquifer System (Chad, Egypt, Libya, Sudan), the Guarani Aquifer (Argentina, Brazil, Paraguay, Uruguay), the Saq-Disi Aquifer (Jordan, Saudi Arabia), and the Calcaires Carbonifères (Belgium, France).

Frequently, transboundary aquifers are part of a broader water cooperation agreement developed for transboundary river basins. Such broader agreements may apply to transboundary groundwater to different degrees. They do not necessarily consider the aquifer in its complete extension, as the areal extents of surface water basins often do not align with the underlying groundwater systems.

Scientific cooperation initiatives exist around the world in the framework of technical projects on transboundary aquifers. Such initiatives can have various scopes, some of them aiming at joint scientific assessment, while some others tackle the management of specific issues. In these cases, the role of regional and international organizations and donors can be critical, particularly when the countries concerned are not on a par as regards to capacity, knowledge, information and confidence. The study of the Dinaric Karst Aquifer, one of the world's largest karst aquifer systems, is an example of collaborative efforts between countries. The project facilitated the establishment of technical cooperation that resulted in political commitments to adopt management measures (Box.12.2).

Until now, experiences in setting up and operationalizing a fully empowered and functional institution charged with the governance of a transboundary aquifer system have remained limited. Recent progress has been made in establishing consultation mechanisms within existing institutions, such as for the Stampriet Aquifer (Box 12.3) shared by Botswana, Namibia and South Africa. Experience suggests that formal institutional arrangements favourable for transboundary cooperation can be achieved when neighbouring countries first build trust through the joint identification of needs and interests, and by carrying out multidisciplinary assessments of the aquifer they share.

Box 12.2 Protection and use of the Dinaric Karst Transboundary Aquifer System (DIKTAS)

Some of the countries sharing the Dinaric Karst Transboundary Aquifer System (Albania, Bosnia and Herzegovina, Croatia, and Montenegro) initiated in 2010 a collaborative effort to facilitate its equitable and sustainable management of the aquifer system, and to protect the unique ecosystems that depend on it. The project improved the knowledge of karst aquifers in the area and the coordination among countries, agencies and other stakeholders. Being the first major project globally to address transboundary karst aquifers, it has been used as an opportunity for introducing new, integrated management principles in shared karst aquifers of such magnitude. The project identified regional management actions, such as measures regarding policy and legislation, monitoring and data management, training and awareness-raising, as well as necessary investments.

Further information on the DITKAS project can be found here: http://diktas.iwlearn.org/

Box 12.3 The Stampriet Multi-Country Cooperation Mechanism: The first transboundary aquifer cooperative mechanism nested in a River Basin Organization

The Stampriet Transboundary Aquifer System (STAS) lies entirely within the Orange-Senqu River basin, in an area shared by Botswana, Namibia and South Africa. In 2017, the countries sharing the STAS agreed to establish a Multi-Country Cooperation Mechanism, nested in the structure of the Orange-Senqu River Commission (ORASECOM), that considers surface water and groundwater conjunctive management. The mechanism set the baseline for institutionalizing the cooperation for the joint governance and management of the aquifer. The Stampriet aquifer is the first example of the establishment of a transboundary aquifer coordination mechanism in the southern Africa region.

Through its inclusion of Sustainable Development Goal (SDG) Target 6.5, the 2030 Agenda for Sustainable Development has raised awareness of the need to "*implement integrated water resources management [IWRM] at all levels, including through transboundary cooperation as appropriate*". The SDG Indicator 6.5.2 monitors progress towards SDG Target 6.5 by assessing the proportion of transboundary basin area (rivers, lakes and aquifers) covered by an operational arrangement for water cooperation. The indicator allows for an assessment of whether transboundary aquifers are covered by their own specific arrangements or are covered within river and/or lake basin arrangements or broader bilateral arrangements.

A lack of groundwater knowledge has proven to be a key limitation in the calculation of the overall value of SDG Indicator 6.5.2. Thirty-five of the countries that reported in 2020 could not produce an indicator value for their aquifers, and a lack of groundwater data may have deterred others from submitting national reports. In turn, the efforts of countries to gather basic aquifer information and data (e.g. transboundary aquifer delineation) can be an important first step towards awareness and progressing cooperation on transboundary aquifers. The number of countries that provided information about aquifers-related cooperative arrangements in their report has increased in 2020 as compared to 2017 (Table 12.2). By preparing the national reports through a consultative process, at the national level or with neighbours, countries were able to establish new cooperation programmes such as the one regarding the Senegalo-Mauritanian aquifer (Box 12.4).

Table 12.2 Summarized outcomes of global monitoring Indicator 6.5.2, 2017 and 2020

	2017	2020
Countries sharing transboundary basins (rivers, lakes and aquifers)	153	153
Countries having reported on the status of their transboundary cooperative arrangements	107	129
Countries having reported that 100% of their transboundary basin area was covered by operational cooperative arrangements	17	24
Countries reporting on having at least one operational aquifer-specific cooperative arrangement in place	5	12
Countries reporting about at least one aquifer covered by an operational river basin arrangement or bilateral arrangement	36	47

Source: Based on UNECE/UNESCO (2021).

12.6 Benefits of transboundary cooperation

Transboundary aquifer cooperation has the potential to generate significant benefits. For example, in the case of the North-Western Sahara Aquifer System, countries sharing the aquifer pursue benefits that include social, economic and environmental aspects (UNECE, 2015). An example could be the resilience of local communities, which is increased through enhanced capacity and mutual learning to resolve common challenges related to natural resources scarcity and security, food safety and climate change; as well as preservation of sensitive wetland ecosystems (NWSAS Consultation Mechanism, 2020).

The sharing of benefits provided by the use of groundwater represents an important facet of hydro-diplomacy (Grech-Madin et al., 2018), a process that can be applied at different stages of actors' interactions (from preventing tensions to contributing to the effective resolution of conflicts) and levels of intervention (from local to international power dynamics) (Vij et al., 2020; Bréthaut et al., 2019).

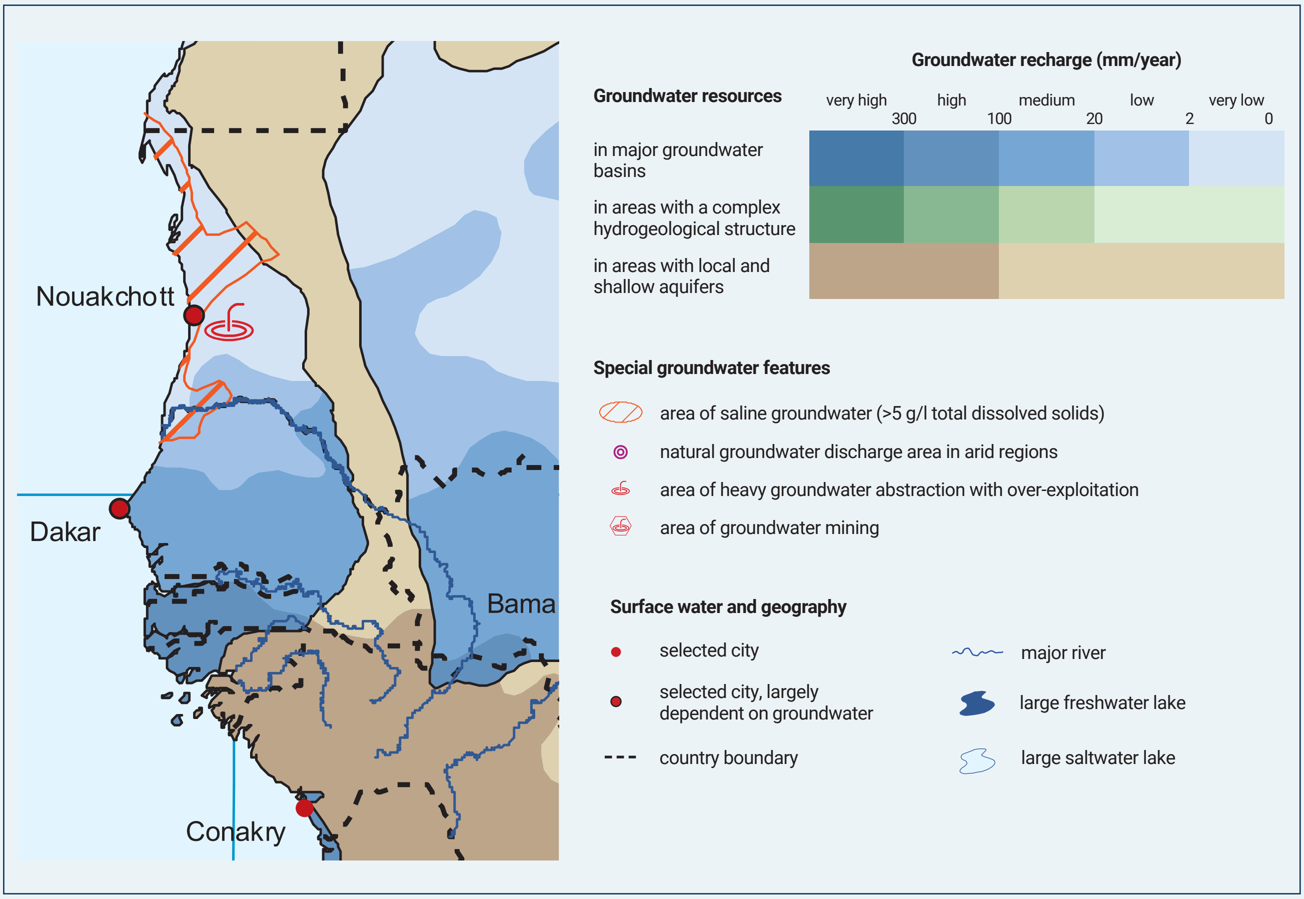
Box 12.4 Towards cooperation in the Senegalo-Mauritanian Aquifer Basin to promote peace and resilience among States

The Senegalo-Mauritanian Aquifer Basin (SMAB), shared between Gambia, Guinea Bissau, Mauritania and Senegal, extends over approximately 1,300 km and underlies a surface area of 331,450 km² with an estimated population of over 15 million inhabitants. The resource is under pressure due to an increasing demand for water caused by population growth, rapid urbanization and the development of agriculture for food self-sufficiency.

The first monitoring on SDG Indicator 6.5.2 highlighted that this transboundary aquifer is not yet subject to a bilateral or multilateral agreement or arrangement for cooperation. Riparian states have begun discussions with a view to developing transboundary collaboration. A Regional Working Group (RWG) for Transboundary Cooperation on the SMAB, comprising the states as well as the transboundary basin organizations in place in the Senegalo-Mauritanian aquifer basin, namely, the Organization for the Development of the Gambia River and the Senegal River Basin Development Authority, was established in May 2020. The RWG has the mandate to provide support and advice to establish transboundary cooperation for the concerted sustainable management of the SMAB. The RWG is engaged in the project conception and action plan in order to fulfil this mandate, with the support of the Geneva Water Hub, the Secretariat of the Convention on the Protection and Use of Transboundary Watercourses and International Lakes provided by the United Nations Economic Commission for Europe (UNECE), and the International Groundwater Resources Assessment Centre (IGRAC).

Ministers from The Gambia, Guinea-Bissau, Mauritania and Senegal signed, in September 2021, a declaration on the establishment of institutional transboundary cooperation around the Senegal–Mauritanian Aquifer Basin. The ministers also agreed to begin talks on the creation of a mechanism to ensure the concerted and sustainable management of their shared groundwater resources.

The experience of Senegalo-Mauritanian Aquifer basin cooperation provides an example of how the SDG reporting process can help to identify gaps in cooperation and lead to concrete improvements.



Source: Adapted from BGR/UNESCO (2008).

Chapter 13

Financing for sustainability

World Bank
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With contributions from:

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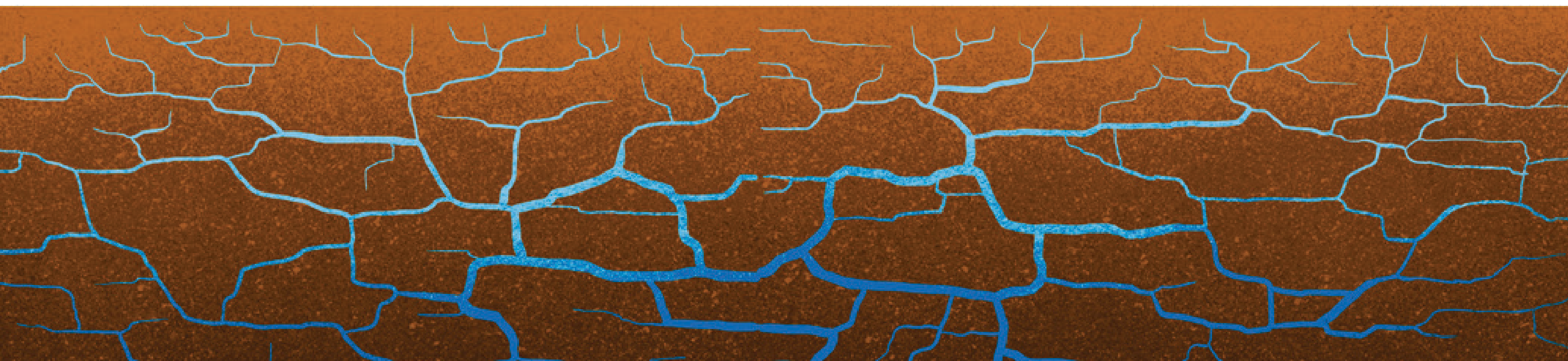


13.1 Currently available and required financing

13.1.1 The current level of investment is insufficient to achieve SDG6 targets

Estimates of required investments to achieve Sustainable Development Goal (SDG) 6 vary due to the lack of accurate and reliable data, but there is a clear agreement (Hutton and Varughese, 2016; WWC, 2018; OECD, 2019b) that the current level of investment is insufficient to meet the agreed targets. Projections of global financing needs for water infrastructure to achieve SDG 6 range from US$6.7 trillion by 2030 to US$22.6 trillion by 2050 (OECD, 2018). Estimates also show that governments and development agencies have insufficient funds to meet these requirements (Kolker et al., 2016). Official Development Assistance (ODA) for water is around US$13 billion per year – far short of what is required (United Nations, 2018) – and about 80% of countries reporting to the United Nations on SDG 6 say they have insufficient financing to meet the national water targets (United Nations, 2018). There is a need to improve the use of existing public and aid resources to catalyse blended finance solutions and to mobilize additional and innovative forms of domestic and international finance. The private sector and global private financial institutions also need to be leveraged to close the funding gap.

13.1.2 Data on current and required investments in groundwater development, governance and management are insufficient

Groundwater resources are essential for long-term socio-economic security and prosperity, and to build resilience in water supply systems

In contrast with surface water, where capital costs tend to be covered by the public sector, groundwater development infrastructure is usually financed by the end user, be it an industry, a household, a farmer, or a community. Users access the resource directly and in a decentralized way. This makes it challenging to track financing flows and to gather data on groundwater investments. The end users invest their private capital for the cost of accessing groundwater, which usually consists of a fixed cost for a well and a variable cost for pumping (World Bank, 2010; Groundwater Governance Project, 2016a). In some countries, there might be an abstraction fee or a groundwater tariff, but these fees and tariffs rarely reflect the true costs and value of the resource.

Furthermore, while some data exist on general water resource management government budgets (OECD, 2012b), data specifically on groundwater are very limited. The UN *Summary Progress Update 2021 on SDG 6* raises the issue of the lack of groundwater data[47] and the lack of groundwater monitoring initiatives, emphasizing that groundwater monitoring is a 'neglected area' (United Nations, 2018; UN-Water, 2021). Groundwater is also considered to be under-represented in the monitoring of the achievement of SDG 6 (UN Water, 2018). Several reports (Groundwater Governance Project, 2016a, 2016b; OECD, 2017b) agree that shortage of funding is a constraint to groundwater governance and management in most countries, including those where groundwater represents a significant share of the supply for domestic, irrigation, or industry/mining.

13.2 Establishing permanent, structural and adequate sources of financing

13.2.1 There is a need to establish adequate government budgets for groundwater-based water supplies, governance and management

Groundwater resources are essential for long-term socio-economic security and prosperity, and to build resilience in water supply systems. Nevertheless, in most countries, there are very limited resources allocated to the monitoring, management and preservation of these valuable resources. Given the characteristics of groundwater use and the challenges of measurement and monitoring, many state-centred initiatives fail or are ineffective in developing, governing and managing groundwater (Garduño and Foster, 2010; Foster et al., 2010c; World Bank, 2010, 2018a; Molle and Closas, 2019). Therefore, governments

[47] Only 14 countries reported data on groundwater bodies quantity, and 25 countries reported data on groundwater quality (out of the 193 member states requested to provide data) (United Nations, 2018). In the updated version, only 52 countries have some information about groundwater, which is problematic because groundwater often represents the largest share of freshwater in a country (UN-Water, 2021).

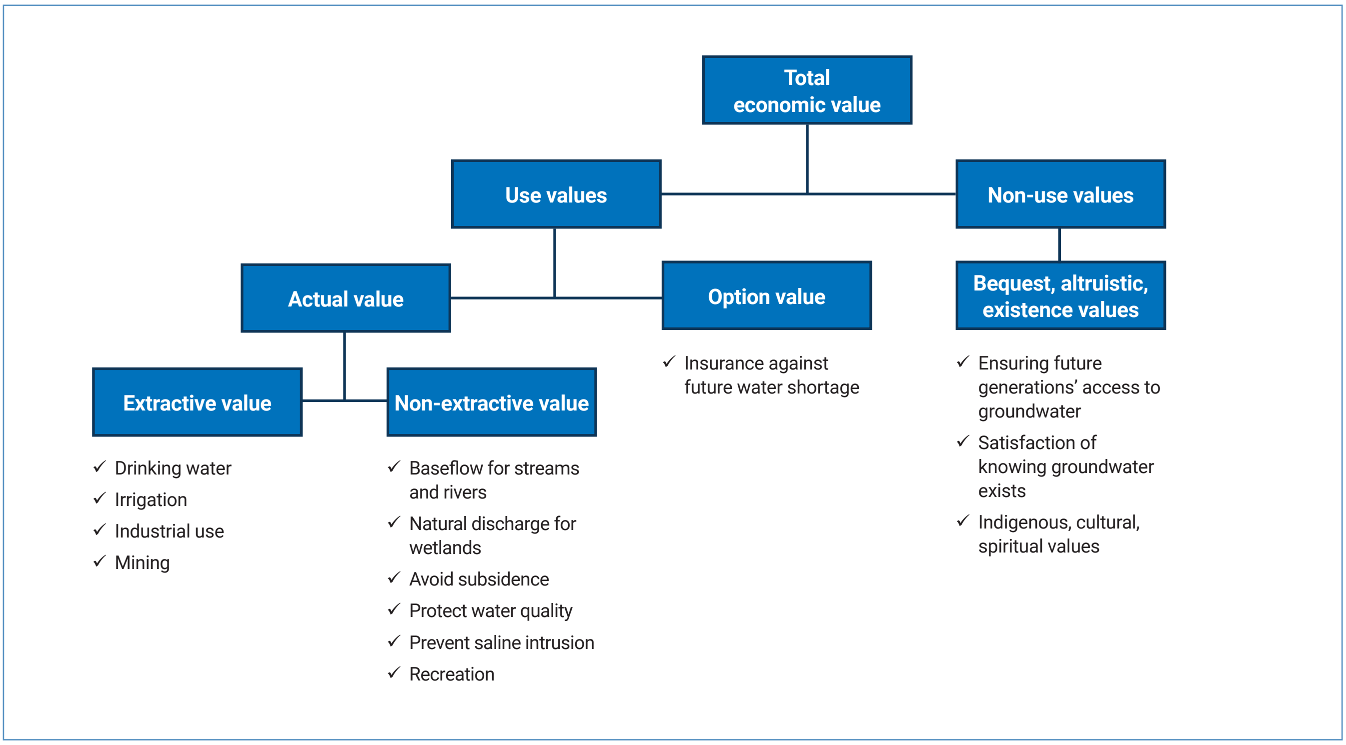
Groundwater storage and abstraction can be included as part of urban water supply in order to add security and flexibility in case of seasonal resource variation

need to assess and accept their potential role in promoting the sustainability of groundwater resources in the context of local conditions (Garduño and Foster, 2010; Foster et al., 2010c; World Bank, 2010; Groundwater Governance Project, 2016a, 2016b; OECD, 2017b), and use the limited financial resources more efficiently through tailored initiatives. Government budgets should, at minimum, fund groundwater monitoring – quality and quantity, and related operating and maintenance (O&M) costs – and leverage private investment by funding initial exploratory and management initiatives.

13.2.2 Proper financing requires recognizing the value and potential of groundwater

Groundwater resources tend to be undervalued, especially where their exploitation is uncontrolled (Garduño and Foster, 2010) and their quality not protected. Groundwater resources are used for multiple purposes and provide an array of benefits (see Figure 13.1). There is an opportunity to better integrate sustainable groundwater development and management as part of other water sector projects and initiatives. For example, groundwater storage and abstraction can be included as part of urban water supply in order to add security and flexibility in case of seasonal resource variation (World Bank, 2018a). This would allow to further leverage existing funding from ODA, from water supply and sanitation tariffs, and even from public–private partnerships. It is also necessary to better analyse and understand the costs and benefits of groundwater management action (and inaction[48]) in economic terms, considering opportunity costs, externalities, and social and environmental benefits. This could help put groundwater issues higher up the political agenda to secure commitment and leverage different types of financing (Groundwater Governance Project, 2016c).

Figure 13.1 Total economic value of groundwater



Source: OECD (2017b, fig. 1.2, p. 20).

[48] The counterfactual risk of not financing water infrastructure should also form part of the 'bankability' evaluation and decision process (WWC, 2018).

13.3 Making better use of currently available financing

13.3.1 Towards more efficient and innovative ways of using finance

If groundwater accounts for a sizeable proportion of the total volume distributed through water supply infrastructure, the water tariff, if properly set, can provide financing for groundwater management (for the case of Denmark, see OECD, 2017b). However, even cost recovery is challenging in most countries (United Nations, 2021) and costs for water resources management are rarely reflected in the water bill. Therefore, water resources management is financed by a mix of abstraction levies, fees or tariffs, effluent or pollution charges, taxes, government budgets, and ODA (OECD, 2012b, 2017b; EEA, 2013).

Groundwater abstraction fees and/or tariffs can be levied on a volumetric basis and these instruments need to internalize the economic and social value of groundwater, using the polluter-pays, the beneficiary-pays, the equity and the policy coherence principles (OECD, 2012b). Charges can also be based on other parameters that serve as a proxy for water withdrawn (land area, pump capacity, etc. – Molle and Berkoff, 2007; EEA, 2013). Collected revenues should be earmarked to finance groundwater-related initiatives, such as monitoring infrastructure and related operating and maintenance costs (Box 13.1). There are examples of countries with groundwater tariffs and/or groundwater abstraction fees, such as certain member states of the European Union (ARCADIS, 2012; EEA, 2013), as well as Australia (Goulburn-Murray Water, 2013), China, Israel, Jordan, Peru (Box 13.1) and the USA (OECD, 2010a), among others. However, in many countries there is no water price or water tariff for groundwater, especially for irrigation purposes, in part due to the difficulties in monitoring and enforcement and the political importance of the agricultural sector (which also results in the lack of political will). Molle and Berkoff (2007), ARCADIS (2012) and Berbel et.al. (2019) further discuss water pricing for irrigation (including groundwater).

Box 13.1 Combining fees and tariffs to improve the management, monitoring and development of groundwater resources in Peru

The National Water Authority (ANA – in Spanish) collects water abstraction (for surface and groundwater) and water pollution fees to finance the management of water resources. This fee is an innovative instrument as it incorporates scarcity risk in its design, is based on the polluter-pays principle, and is charged according to the volume used. For groundwater, Peru's aquifers are classified into three categories: underexploited, in equilibrium, and overexploited, depending on the demand/availability ratio of each aquifer. Although there are challenges with groundwater monitoring and enforcement, ANA is making improvements and currently 23% of total revenues collected by ANA come from groundwater fees. In addition, in 2018 Peru started implementing a groundwater management and monitoring services tariff for non-agricultural users with their own wells. This tariff is to be charged by the water utility (EPS – Empresas Prestadoras de Servicios in Spanish) and is linked to an investment plan to monitor, restore, preserve and manage aquifers.

Source: OECD (2021) and SUNASS (2017).

Given the abovementioned challenges, traditional financing (tariffs, taxes and transfers) needs to be used more efficiently and innovatively, in combination with other instruments, arrangements and mechanisms in order to attract other financing sources and successfully finance sustainable groundwater development, governance and management. New technologies, such as remote sensing, mobile payments, swipe cards, solar pumping and pre-paid meters (Box 13.2), can help improve the efficiency of service delivery, regulate the use of groundwater, collect revenues from such tariffs/fees, and reach local communities (Groundwater Governance Project, 2016a). Fees and taxes in other sectors, such as in agriculture, can also help finance groundwater initiatives and reduce potential negative externalities. For example, the State of Montana (USA) charges pesticide and fertilizer registration fees and uses the revenues to fund groundwater quality monitoring initiatives (OECD, 2010b). Blended finance (OECD, 2019b; see also Box 13.2), public–private partnership (PPP) arrangements and other incentive mechanisms (Box 13.3) can be used to leverage the private sector, together with government budgets and ODA to finance groundwater initiatives. For example, under a PPP arrangement, the city of San Luis Potosí in Mexico was able to protect its aquifer by treating and using wastewater instead of groundwater for non-potable uses, such as for agriculture and industry (World Bank, 2018b). Funds from other sectors, such as energy and climate, can also be leveraged to finance groundwater initiatives, such as solar pumps (Box 13.2) or dedicated electricity lines to replace diesel-powered groundwater wells, to improve reliability, decrease costs and better regulate consumption in areas that are under threat of depletion (Groundwater Governance Project, 2016c).

Box 13.2 Combining blended finance with emerging technologies to provide safe water to rural villages in Tanzania

The Government of Tanzania, with support from the World Bank, is helping Community Water and Supply Organizations (COWSOs) to replace old and inefficient diesel-powered pumps with clean solar photovoltaic-powered pumps in about 150 villages in rural Tanzania. Diesel pumps are expensive to operate and maintain, which directly impacts the price of water, with further related concerns on equity and sustainability. However, COWSOs do not have the financial capital needed to invest in solar pumps, nor do they have the creditworthiness to raise capital on the financial market. The World Bank's Global Partnership for Results-Based Approaches (GPRBA) provides 60% of the capital as grant resources and the rest is financed through a four-year loan from the TIB Development Bank. In addition, the COWSOs use an innovative mobile-banking payment platform and pre-paid meters to better manage revenue collection from water sales and to manage loan payments. The benefits of this initiative are several, including:

- harnessing the power of private sector financing through blended subsidy-loan combinations;
- realizing environmental and economic benefits from transitioning from diesel pumps to solar pumps, in the form of lower CO_2 emissions and high life cycle cost savings; and
- each COWSO generating, through participating in the project and repaying the investment loan, a 3–5 year credit history: an important step towards creditworthiness.

Source: Welsien (2016).

13.3.2 Identifying, assessing, and redirecting subsidies for the sustainable development and management of groundwater resources

Reforming harmful subsidies and aligning them with groundwater policies should be part of the water financing agenda

In many countries, publicly funded activities in other sectors contribute to the depletion or pollution of groundwater resources (Garduño and Foster, 2010; Groundwater Governance Project, 2016a; OECD, 2017b; World Bank, 2018a). Many times, subsidies are designed and implemented without considering the impact on the sustainability of groundwater and on those who depend on the resources. For example, subsidies in the energy sector that incentivize the over-extraction of groundwater by reducing electricity charges, or farm subsidies that encourage crops with high water demands, can become perverse incentives (Garduño and Foster, 2010; Groundwater Governance Project, 2016a). Moreover, this type of subsidy can be regressive in nature, benefiting wealthy users (Venkanta, 2021; World Bank, 2018a). Similarly, fertilizer subsidies lead to overuse and contamination of groundwater with nitrates. Hence, coherence in policies of different sectors needs to be ensured. Reforming harmful subsidies and aligning them with groundwater policies should be part of the water financing agenda (Garduño and Foster, 2010; OECD, 2018). The financial resources freed from perverse subsidies can be used to protect and restore groundwater resources and to subsidize those who need it the most (vulnerable and disadvantaged groups). Instead of subsidizing farmers with low energy costs to overpump groundwater, governments could subsidize water efficiency programmes[49] or community-led/owned initiatives[50] to monitor and develop groundwater resources (World Bank, 2020), or support payment for environmental services to recharge groundwater (Box 13.3), carefully making sure that the most vulnerable groups reap the benefits of all these interventions (Groundwater Governance Project, 2016a). For example, poor farmers can become the beneficiaries of the payments for ecosystems, and community-led or women-led initiatives can ensure that vulnerable groups are included and represented.

13.3.3. The role of global financial institutions

Financial institutions' largest impact on water stems from the activities they enable through their loans, investments and insurance underwriting (CDP, 2020). Banks, shareholders, insurers and the financial institutions that own them currently enable companies to undertake economic activities, which in many cases are profoundly detrimental to the environment. The financial services sector has an especially critical role to play in the transition to a water-secure future (Hogeboom et al., 2018; WWF, 2019). Global financial institutions can offer unique, systemic incentives for change by ensuring that their investment, insurance, lending, rating and underwriting practices drive these water users to use water wisely, to not pollute water and to promote its reuse (WWF, 2019; CDP, 2020).

Box 13.3 Payment for Ecosystem Services with private sector financing: The case of Kumamoto (Japan)

Groundwater in the Kumamoto region provides for 100% of the drinking water of Kunamoto City, and it is also an essential source of water for agriculture and industry in the region. Irrigated rice paddy fields in the area are the main source for groundwater recharge. However, a government supply restriction policy limits the amount of rice acreage, which together with urbanization, has forced some farmers to abandon their paddy fields, decreasing groundwater levels. A subsidiary of Sony Semiconductors, which depends on the availability of groundwater for its operations, reached an agreement with farmers to prevent groundwater depletion and secure their business activities in the future while also becoming 'water-neutral'. Through a Payment for Ecosystem Services (PES) scheme, the company paid farmers to recharge groundwater by voluntarily flooding old rice fields that had been converted to crop fields. The PES scheme was so successful that eventually the city's government, the Council for Sustainable Water Use in Agriculture and other industries joined the effort, expanding the programme. This case shows how PES can help reverse groundwater depletion and demonstrates the importance of policy coherence across agricultural, urban and water policies.

Source: OECD (2017b).

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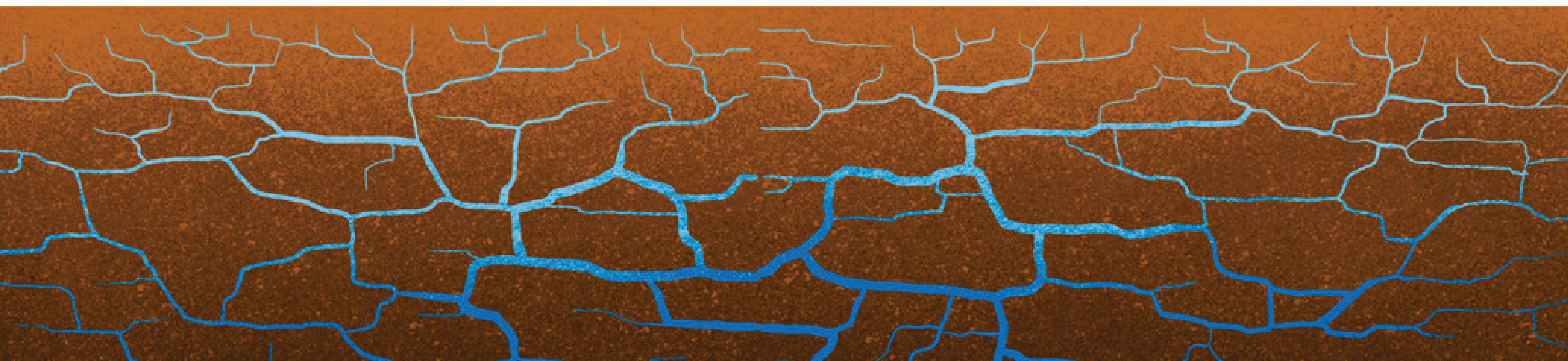
[49] "*Existing studies reveal that technical measures aimed at the modernisation of the irrigation system, followed by the implementation of volumetric pricing, have much higher water saving potential compared to simple price increases*" (EEA, 2013, p. 12).

[50] Given their decentralized nature, strong community participation is key to ensure the sustainable development, monitoring and management of groundwater resources. Involving the communities helps ensure that the most vulnerable groups have access to the benefits (Garduño and Foster, 2010; World Bank, 2010, 2018a).

Chapter 14

Conclusions

WWAP
Richard Connor, Jac van der Gun and Michela Miletto



14.1 Prospects and challenges

14.1.1 The multiple roles and facets of groundwater

Human society currently relies heavily on groundwater to meet domestic needs as well as to produce food and support economies. Groundwater supplies approximately 25% of all freshwater abstracted on Earth, but its share in consumptive water use is much higher, as are the overall benefits that it provides. Groundwater plays an essential role in climate change adaptation and mitigation, and its contribution to meeting the targets of Sustainable Development Goal (SDG) 6 as well as the other water-related SDGs is fundamental. Yet, groundwater itself, as well as its direct and indirect benefits, has all too often remained unseen or ignored, leaving numerous aquifers inadequately protected.

Many of the world's largest cities, and numerous smaller cities and towns, rely on groundwater as their major source. This dependence will intensify, particularly in the rapidly urbanizing areas of developing countries and emerging economies. Groundwater is also the primary source of domestic water in most rural areas.

Agriculture is increasingly reliant on groundwater for irrigation and watering livestock, especially in arid and semi-arid areas. Groundwater is a particularly important source of water for smallholder farmers, and will play an essential role in meeting the growing demand for food.

Groundwater itself, as well as its direct and indirect benefits, has all too often remained unseen or ignored, leaving numerous aquifers inadequately protected

Groundwater supports all sorts of manufacturing industries, especially where surface water is limited or when high-quality water is required. It serves multiple purposes, from process water to cleaning and cooling. Industries with significant subsurface activities, such as the oil, gas and mining sectors, interact intensively with groundwater, aquifers and the subsurface environment, and thus bear special responsibility for protecting these resources.

Relationships between ecosystems and groundwater are a two-way street. The ecology of many rivers, lakes and wetlands is directly supported by aquifers. These groundwater-dependent ecosystems (GDEs), which also include a great deal of terrestrial biomes, are critical to maintaining biodiversity. Many GDEs serve to enhance aquifer recharge – hence the two-way relationship – such that ecosystem (and especially wetland) protection is good for groundwater, and vice versa. Worldwide, GDEs are degrading as a consequence of intensive groundwater abstraction and a lack of protective measures.

Due to the huge volumes of groundwater (representing 99% of all liquid water stored on Earth), aquifers can serve as a buffer in times of water scarcity, enabling people to survive in even the driest of climates. Depending on their depth and geological setting (such as overlying unsaturated zones and confining layers), aquifers are comparatively well protected against pollution incidents on the surface. However, once groundwater becomes contaminated, it can be extremely difficult and costly to remedy.

14.1.2 Supply by utilities versus self-supply

Urban water supply is commonly entrusted to utilities. While local water supply operators struggle to keep up with increasing demand, groundwater self-supply – often self-financed – provides a rapid solution in urban zones where it is technically feasible to those who can afford it. Groundwater is also very well suited for rural self-supply and it is often the most cost-effective way of providing a secure water supply to villages.

In the agricultural sector, groundwater is most commonly abstracted by farmers themselves. Self-supply is also the predominant mode among the larger industrial groundwater users. Self-supply implies extremely fragmented decision-making, which is difficult to control.

14.1.3 Groundwater and energy

On average, extracting groundwater undoubtedly requires much more energy than diverting surface water, because it has to be lifted to the surface. On the other hand, it usually requires much less energy for conveyance (due to a smaller average distance between the site of abstraction and the user) and for treatment (as the water quality is usually much better). Affordable solar-powered irrigation systems, adopted at scale to service farming operations, may provide a renewable, low-carbon energy source to pump up groundwater.

Groundwater is also used in power generation as well as in primary energy production, such as the coal, oil and gas sectors. Specific data on this type of groundwater use is only readily available for a few industrialized nations. The extraction of underground resources, and the various methods used, can pose severe threats to groundwater quality.

14.1.4 Climate change and other challenges

Although located underground, groundwater is not excluded from being affected by climate change. Changes in the Earth's water cycle through processes of precipitation and evaporation have their impacts on groundwater recharge. Shallow or near-surface aquifers, which are most commonly relied upon as a source of freshwater, are also the most vulnerable. Yet, for climate change mitigation and adaptation, groundwater also offers solutions.

Although located underground, groundwater is not excluded from being affected by climate change

In terms of mitigation, geothermal power plants are, contrary to wind and solar energy plants, well suited to produce a stable electrical base load and offer a great deal of opportunities for expansion. Groundwater can also be used for direct heating and cooling purposes. Certain geological sites, including deep aquifers, are suitable for the storage of CO_2 as part of carbon capture and storage processes. In terms of climate change adaptation, aquifers offer a relatively low-cost alternative for surface water storage and – above all – they offer a unique buffer capacity, which reduces the impacts of increasing climatic variations and facilitates the smooth transition to water use practices that are compatible with changing climatic conditions. Making water supplies resilient to climate change will, in many parts of the world, involve using groundwater conjunctively with rivers, lakes and surface water reservoirs.

In spite of the relatively high abundance of groundwater, many of the world's aquifers are overexploited, including even some that are receiving significant recharge. This has resulted in steady declines of water levels, in some cases beyond the limits of economically feasible withdrawal. In addition to reducing overall freshwater availability, intensive groundwater extraction has led to land subsidence in many areas.

The abstraction and use of groundwater is not necessarily limited to renewable groundwater. Even non-renewable resources can be considered. Certain regions in Africa, for example, hold considerable quantities of non-renewable groundwater supplies that can be made available during periods of severe water stress in order to maintain water security. Caution in doing this is essential, though. Consideration for future generations and for the economic, financial and environmental aspects of storage depletion should not be overlooked.

Groundwater pollution is a major challenge worldwide. Many sources of pollution are ubiquitous in urban and other settlements. The existence of ill-constructed or poorly maintained on-site sanitation facilities has led to persistent pathogen contamination of water abstracted from nearby shallow wells, particularly in rural settlements. Yet agriculture is the primary cause of groundwater pollution in rural areas. Increased pollution control efforts, in both urban and rural settings, are sorely needed. Industry, including its subsurface components such as hydrocarbon development and various forms of mining, produce a large diversity of pollutants, forming severe threats to groundwater quality. Protection of groundwater quality by effective regulation and strict enforcement is urgently required in all sectors, but adequate practices are still rare.

14.1.5 Data, information and knowledge on groundwater and aquifers

The lack of detailed information and knowledge about local groundwater resources is a major challenge in many countries. The UN *Summary Progress Update 2021 on SDG 6* raises the issue of the lack of groundwater data and the lack of groundwater monitoring initiatives, emphasizing that groundwater monitoring is a 'neglected area'. Outside of Europe, North America and large Asian countries like India and China, regular monitoring of groundwater levels or quality, the first step towards groundwater management, is restricted to only a few countries.

14.2 Moving forward

14.2.1 Groundwater deserves to be put high on the agendas

The General Assembly of the United Nations, as well as the Human Rights Council, recognize that equitable access to safe and clean drinking water and sanitation are distinct human rights. UN Member States are expected to realize the human rights to safe drinking water and sanitation through action plans or strategies, thereby actively promoting awareness and capacity-building. Due attention should be paid, among other things, to sustainable water supplies, treatment before consumption if raw water quality is inadequate, and – since groundwater is an essential component of water supply and sanitation – to groundwater protection and aquifer recharge.

Groundwater plays also a very important role in other sectors such as agriculture, industry and the environment, with positive impacts on economies, incomes, welfare and ecosystems. Pro-active and capable groundwater custodians are needed to ensure the sustainability of the required groundwater services.

14.2.2 Good groundwater governance and management are crucial

It is essential that countries commit themselves to developing an adequate and effective framework for groundwater governance. This requires that governments take the lead and assume responsibility to set up and maintain a fully operational governance structure, including: the knowledge base; institutional capacity; laws, regulations and their enforcement; policy and planning; stakeholder participation; and appropriate financing. It is also incumbent upon countries to ensure that their policies and plans are fully implemented (groundwater management).

14.2.3 Data, information and knowledge are indispensable guides towards proper groundwater development and management

Scientific knowledge in hydrogeology and the methods and tools available are sufficient to address most groundwater management issues, like siting wells, optimizing abstraction and predicting its effect at the local and regional scales, and preventing contamination. The challenge lies more with the scarcity of reliable area-specific data on groundwater, especially in low-income countries, and with the limited dissemination of data, information and knowledge among researchers, practitioners and decision-makers. Effective government responses include – first and foremost – developing and maintaining a dedicated groundwater knowledge base.

Regarding aquifer exploration and assessment, the data and information acquisition of groundwater agencies may be complemented by the private sector. Particularly the oil and mining industries possess a great deal of data, information and knowledge on the composition of the deeper domains underground, including aquifers. It is highly desirable that they would share these with public sector professionals in charge of groundwater assessment and management. In addition to exploration and assessment, groundwater monitoring activities are also essential. They have to provide spatially differentiated information on changes over time of water levels, groundwater abstractions and groundwater quality – which is essential for underpinning proper decisions on groundwater development and management.

14.2.4 Strong institutions are key to progress in groundwater management

Qualified personnel with the capacity to conduct hydrogeological and geophysical studies are often scarce. Siting and constructing the higher-yielding boreholes that are necessary for large-scale irrigation or town supplies in complex hydrogeological environments requires considerable expertise. The same is true for activities like groundwater policy and planning, and for implementing and enforcing groundwater management measures.

However, in many countries, the general lack of groundwater professionals among the staff of institutions and local and national government, as well as insufficient mandates, financing and support of groundwater departments or agencies, hamper effective groundwater assessment, monitoring, planning, development and management. The formation of human and institutional capacity can be reinforced by, for example, long-term bilateral cooperation projects, academic exchange programmes or postgraduate training opportunities abroad. Crucial, however, is the commitment of governments to build, support and maintain institutional capacity related to groundwater.

It is imperative that governments assume their role as resource custodians in view of the common-good aspects of groundwater and ensure that access to (and profit from) groundwater is distributed equitably and that the resource remains available for future generations

14.2.5 Stakeholders have a diversity of interests and should not be ignored

Groundwater governance and management can be challenging because of the common-pool nature of groundwater resources, along with information gaps and the diversity of stakeholders and their interests. As groundwater can be accessed over vast geographical areas, it is often difficult for governments to quantify, allocate and regulate withdrawals, particularly if their resources are limited. The corollary is that almost everywhere, groundwater governance and management must include public and private stakeholder interests, as well as local communities. It is imperative that governments assume their role as resource custodians in view of the common-good aspects of groundwater and ensure that access to (and profit from) groundwater is distributed equitably and that the resource remains available for future generations. Where feasible, it is advantageous to involve stakeholders in the processes of assessing, monitoring, planning and decision-making.

14.2.6 Legal provisions clarify agreed rights and rules of the game regarding groundwater

Laws and regulations that incorporate societal goals and policy objectives, and that set an enabling and regulatory framework for achieving those goals, are fundamental components of groundwater governance and management. Stable legal frameworks also enable governments and groundwater users to plan for resources management over the long term and to deal with competing interests, including those of the environment and of future generations. International water law identifies the rights and obligations of sovereign states in relation to rivers, lakes, basins and aquifers that are bisected by, form, or underlie (in the case of groundwater) an international boundary line. It has recently begun to specifically address aquifers and groundwater, and a few agreements have been successfully concluded by countries sharing transboundary aquifers and groundwater.

Legal instruments to control groundwater abstraction include the mandatory licensing for constructing wells and for abstracting groundwater, and the obligation to pay charges for volumes of water abstracted and taxes as a component of the price of water supplied.

Groundwater contamination prevention measures include: prohibiting or limiting certain polluting and water-using activities; limiting the use of pesticides, herbicides and fertilizers; restricting certain cropping patterns; reducing animal grazing intensity; reclaiming agricultural land; and managing drainage. Illegal emission and discharge of substances into water bodies or into the ground, or unlawful treatment of wastewater, may be considered an offence or crime. Most of these measures require regulations based on legislation. Enforcement efforts and the prosecution of polluters, however, are often challenging due to groundwater's invisible nature.

14.2.7 Transboundary aquifers call for cooperation

Transboundary aquifers (i.e. aquifers with segments in two or more countries) require special attention because groundwater pollution and changes in groundwater levels and pressures may have their origin in a neighbouring country. This adds a distinct, international, dimension to groundwater governance and management, making it more complex. Their importance has only recently come to the attention of the international community, opening additional opportunities for promoting transboundary cooperation through new dedicated financial resources. The main outputs so far include global and regional inventories, the Draft Articles on the Law of Transboundary Aquifers (commended by several resolutions of the United Nations General Assembly), and formal interstate cooperation agreements in force for six transboundary aquifers. Nevertheless, there are several hundreds of important transboundary aquifers in the world. Together, they represent a sizable share of global groundwater resources and many of them are connected to valuable freshwater ecosystems. Increased efforts for establishing transboundary aquifer cooperation therefore need to be a priority.

14.2.8 Groundwater policy and planning provide road maps for concerted action

Due attention needs to be given to policy and planning, in order to provide guidance for groundwater governance and for consistent and concerted groundwater management activities, to the benefit of the entire society. Groundwater policy should be contingent on the legal status and nature of ownership of groundwater (public or private) of the water users, the interrelated surface water features, and the land use in aquifer recharge areas. It also should provide for integrated decision-making on groundwater resources and aquifer systems, and connect to other sectors and domains of society beyond the water sector – such as socio-economic development, gender equality and poverty alleviation, food and energy, ecosystems, climate change, and human health.

Open and participatory groundwater planning processes can generate greater public support and acceptance of the resulting plan and, by extension, of operational management

Open and participatory groundwater planning processes can generate greater public support and acceptance of the resulting plan and, by extension, of operational management. Such planning involves scientists, resource management specialists, stakeholders and decision-makers, and should be accessible to non-specialists, inviting users to participate. Planning of groundwater resources is as much a matter for government bodies as for end users, collectively or individually. At the local scale, data gathering and information analysis will by necessity be limited; yet, all levels can benefit from capacity development and awareness-raising. Likewise, sex-disaggregated data, and ensuring the participation of women in data generation and decision-making (usually male-dominated), are vital in order to acquire a gendered dimension.

Groundwater management plans translate policy into a programme of action, providing a blueprint for its implementation. A variety of tools can be used to manage groundwater withdrawals. Which tools are used will depend on the approach to management defined by the governance and policy regimes in place. Not all management occurs through government: for instance, communities and/or groundwater users themselves may independently choose to manage well siting and groundwater abstractions. Where groundwater has historically been subject to minimal or zero regulation, groundwater users may view management actions as expropriation of private property. Allowing for exempt uses, such as for domestic use or livestock, or a fixed amount of inframarginal pumping (usually a small volume of water that can be pumped without being subject to regulations or tariffs, usually for the purposes of meeting basic human needs or household-scale farming), can help overcome resistance to control through regulation and pricing. However, care needs to be taken to ensure exempt uses do not undermine management objectives. Equity is an important consideration, as management actions that differentially affect groundwater pumpers and users can lead to conflict.

The interrelationships between aquifers and surface water, land use, ecosystems, and the use of subsurface space and resources imply that groundwater policy and planning need to be embedded in a wider policy context (i.e. horizontal integration), as each of these are directly linked to groundwater availability and quality. Approaches such as managed aquifer recharge (MAR) and conjunctive water management embrace these interrelationships. The potential and feasibility of tapping into unconventional groundwater resources (e.g. brackish groundwater, offshore fresh or brackish groundwater) should also be explored.

14.2.9 Financing: the fuel for action

Groundwater governance and management require substantial structural financing. However, mechanisms for allocation of government funds or for raising funds from private sources are in many cases rather poorly developed. In many countries, there is no price or tariff for groundwater, especially for irrigation purposes, in part due to the difficulties in monitoring and enforcement, and the political importance of the agricultural sector (which also results in the lack of political will).

If groundwater is included as part of distributed water supply infrastructure, the water tariff, if properly set, can provide financing for groundwater management. However, even cost recovery is challenging in most countries and costs for water resources management are rarely reflected in the water bill. Therefore, water resources management is financed by a mix of abstraction levies, fees or tariffs, effluent or pollution charges, taxes, government budgets, and Official Development Assistance (ODA). In addition, there are opportunities to better integrate sustainable groundwater development and management as part of water sector projects and initiatives. For example, MAR projects can be included as part of urban water supply in order to add security and flexibility in case of seasonal resource variation. It is also worthwhile to better analyse and understand the costs and benefits of groundwater management action (and inaction) in economic terms, considering opportunity costs, externalities, and social and environmental benefits. This could help put groundwater issues higher up the political agenda to secure commitment and leverage different types of financing.

14.3 Coda

The Earth's total groundwater resources represent an enormous supply of freshwater. In a world of ever-growing water demand, where surface water resources are often scarce and increasingly stressed, the value of groundwater is poised to become progressively recognized by everyone, as a resource that has allowed human societies to flourish since millennia.

However, in spite of its overall abundance, groundwater remains vulnerable to overexploitation and pollution, both of which can have devastating effects on the resource and its availability. Unlocking the full potential of groundwater will require strong and concerted efforts to manage and use it sustainably. And it all starts by making the invisible visible.

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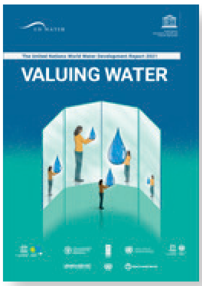
Abbreviations and acronyms

ANA	National Water Authority (in Peru)
ATES	Aquifer Thermal Energy Storage
ASR	Aquifer Storage and Recovery
CDP	formerly the Carbon Disclosure Project
CMIP5	Coupled-Modelled Inter-Comparison Project Phase 5
COWSO	Community Water and Supply Organizations
DBP	Disinfection By-Products
DDT	Dichlorodiphenyltrichloroethane
DIKTAS	Dinaric Karst Transboundary Aquifer System
EGS	Enhanced Geothermal System
EIPs	Eco-Industrial Parks
ENSO	El Niño Southern Oscillation
ET	Evapotranspiration
EU	European Union
EUWI+	European Union's Water Initiative Plus
GAA	Guarani Aquifer Agreement
GAS	Guarani Aquifer System
GDE	Groundwater-Dependent Ecosystem
GEF	Global Environment Facility
GGIS	Global Groundwater Information System
GGRETA	Governance of Groundwater in Transboundary Aquifers
GPCP	Global Precipitation Climatology Project
GRACE	Gravity Recovery and Climate Experiment
GSHP	Ground Source Heat Pumps
GWB	Groundwater Body
GWS	Groundwater Storage
HDPE	High-density polyethylene
IEA	International Energy Agency
IGRAC	International Groundwater Resources Assessment Centre
IHP	Intergovernmental Hydrological Programme
ILC	International Law Commission
ISARM	Internationally Shared Aquifer Resources Management initiative
IWRM	Integrated Water Resources Management
JMP	Joint Monitoring Programme
LULC	Land Use and Land Cover
MAR	Managed Aquifer Recharge
MOEF	Ministry of Environment and Forestry (Indonesia)
NDCs	National Determined Contributions
ODA	Official Development Assistance
P	Precipitation
PES	Payment for Ecosystem Services
PPP	Public–Private Partnership
RECP	Resource Efficient and Cleaner Production
RWG	Regional Working Group
SAAB	Amazon Aquifer System in Brazil
SADC	Southern African Development Community
SDG	Sustainable Development Goal
SIDS	Small Island Developing States
SLR	Sea Level Rise
SMAB	Senegalo-Mauritanian Aquifer Basin
SPIS	Solar-Powered Irrigation Systems
TBA	Transboundary Aquifer
TSF	Tailings Storage Facility
TWS	Total Water Storage
UAE	United Arab Emirates
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNIDO	United Nations Industrial Development Organization
UNICEF	United Nations Children's Fund
USA	United States of America
WASH	Water, Sanitation and Hygiene
WHYMAP	World-Wide Hydrogeological Mapping and Assessment Programme
WHO	World Health Organization
WFD	Water Framework Directive
WWDR	World Water Development Report
ZLD	Zero Liquid Discharge

THE UNITED NATIONS WORLD WATER DEVELOPMENT REPORT



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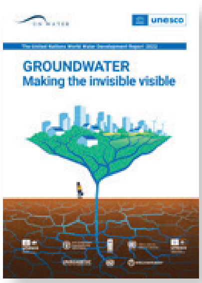

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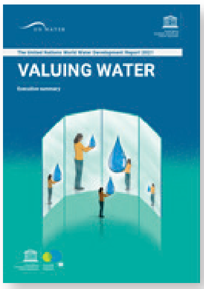

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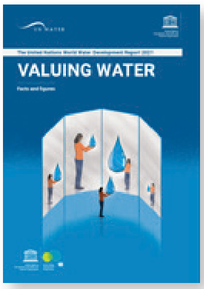

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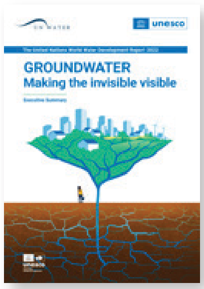

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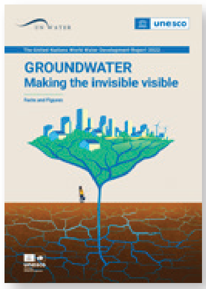

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WORLD WATER DAY AND THE UNITED NATIONS WORLD WATER DEVELOPMENT REPORT

The United Nations designates specific days, weeks, years and decades as occasions to mark particular events or topics in order to promote, through awareness and action, the objectives of the Organization.

International observances are occasions to educate the general public on issues of concern, to mobilize political will and resources to address global problems, and to celebrate and reinforce achievements of humanity.

The majority of observances have been established by resolutions of the United Nations General Assembly. World Water Day (22 March) dates back to the 1992 United Nations Conference on Environment and Development where an international observance for water was recommended.

The United Nations General Assembly responded by designating 22 March 1993 as the first World Water Day. It has been held annually since then and is one of the most popular international days together with International Women's Day (8 March), the International Day of Peace (21 September) and Human Rights Day (10 December).

Every year, UN-Water — the UN's coordination mechanism on water and sanitation — sets a theme for World Water Day corresponding to a current or future water-related challenge. This theme also defines the theme of the United Nations World Water Development Report that is presented on World Water Day. The publication is UN-Water's flagship report and provides decision-makers with tools to formulate and implement sustainable water policies. The report also gives insight on main trends including the state, use and management of freshwater and sanitation, based on work by the Members and Partners in UN-Water.

The report is published by UNESCO, on behalf of UN-Water, and its production is coordinated by the UNESCO World Water Assessment Programme.

Accounting for the vast majority of all liquid freshwater on Earth, groundwater has the potential to provide societies with tremendous social, economic and environmental benefits and opportunities. Groundwater is central to the fight against poverty, to food and water security, to the creation of decent jobs, to socio-economic development, and to the resilience of societies and economies to climate change.

However, this natural resource is often poorly understood, and consequently undervalued, mismanaged and even abused. In spite of its overall abundance, groundwater remains vulnerable to over-exploitation and pollution, both of which can have devastating effects on the resource and its availability. In the context of growing water scarcity across many parts of the world, the enormous potential of groundwater and the need to manage it sustainably can no longer be overlooked.

The 2022 edition of the United Nations World Water Development Report, titled "Groundwater: Making the invisible visible", describes the challenges and opportunities associated with the development, management and governance of groundwater across the world. The report addresses groundwater-related issues from the perspective of the three main water use sectors (agriculture, human settlements and industry), as well as its interactions with ecosystems and its relation with climate change. It highlights different regional perspectives and presents a number of response options concerning data and information, policy and planning, management and governance, as well as financing.

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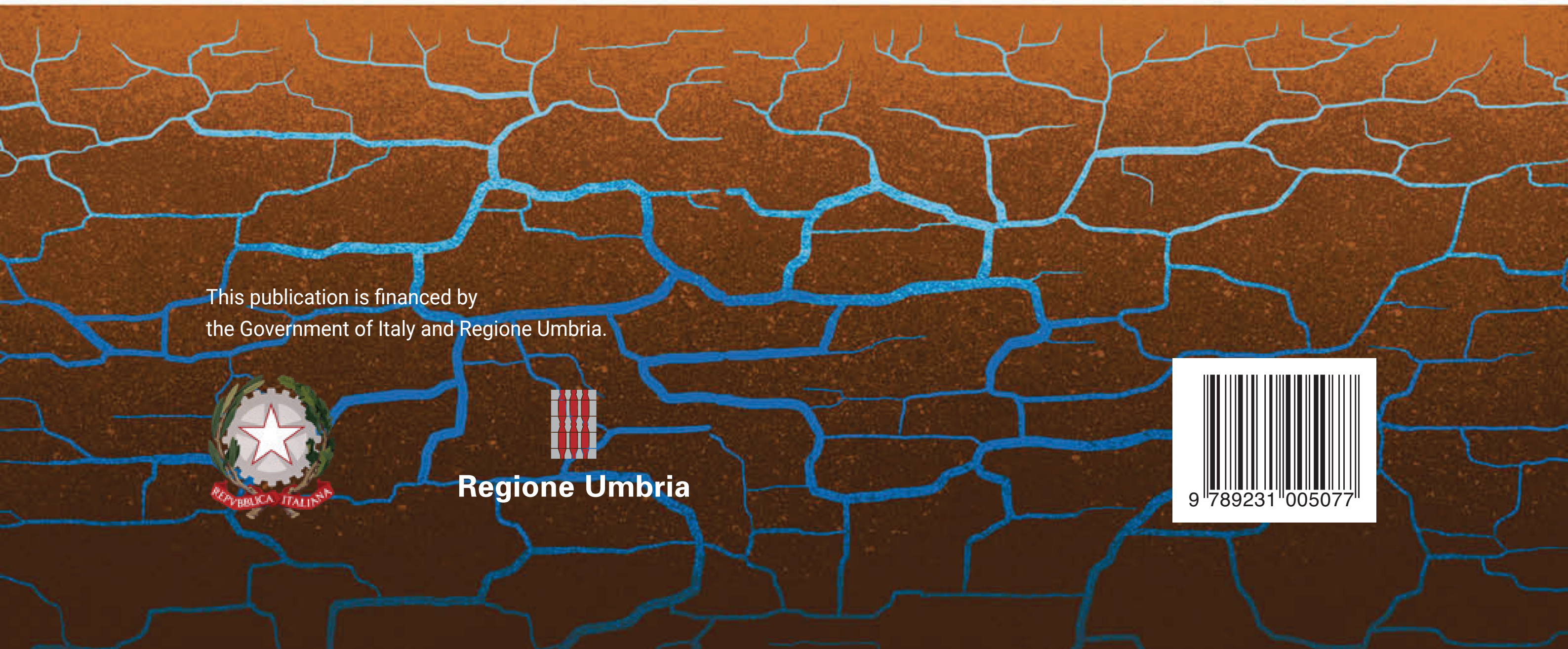

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