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Clean Water and Sanitation

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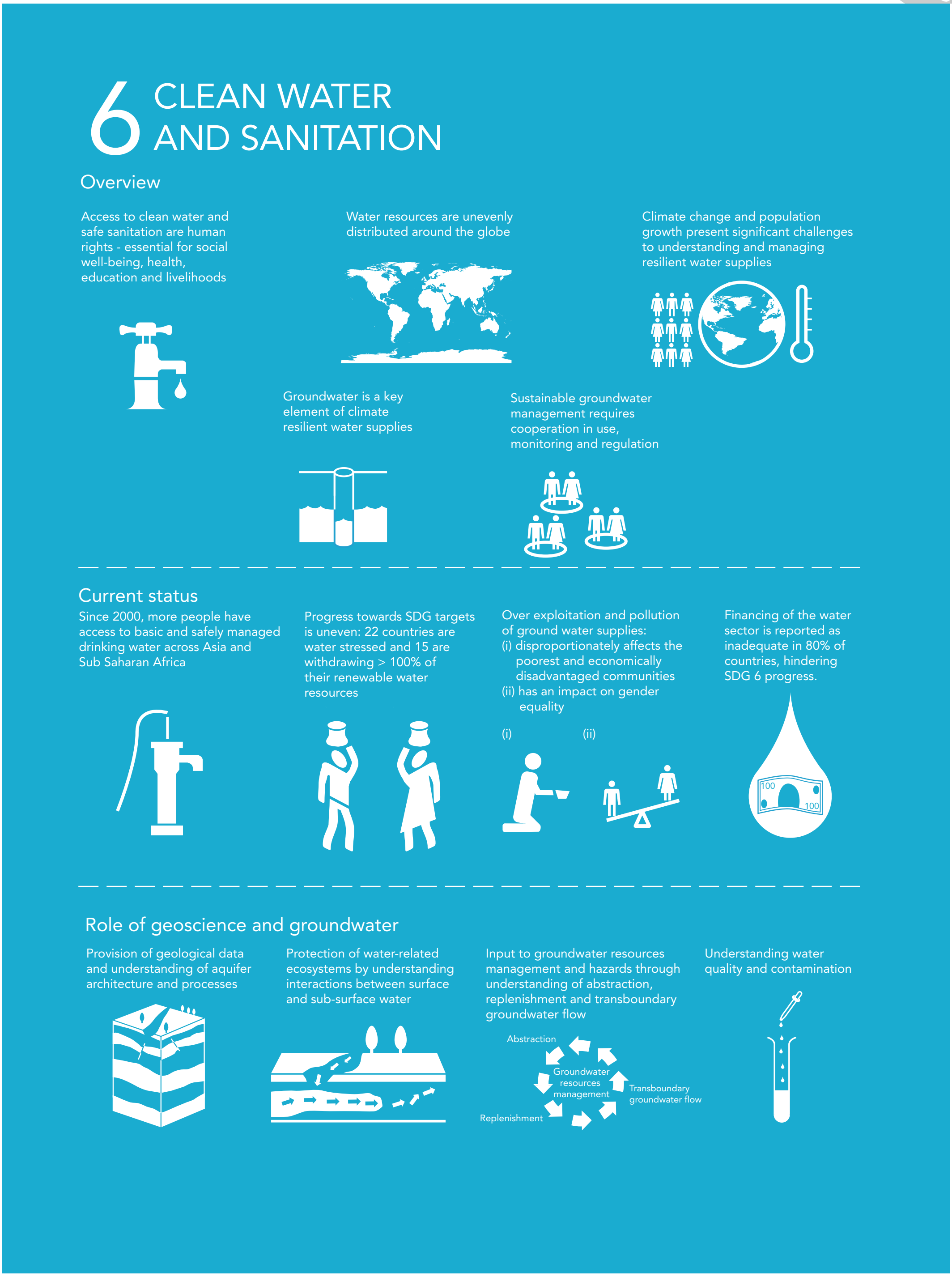
Abstract



6 CLEAN WATER AND SANITATION

Overview

Access to clean water and safe sanitation are human rights - essential for social well-being, health, education and livelihoods

Water resources are unevenly distributed around the globe

Climate change and population growth present significant challenges to understanding and managing resilient water supplies

Groundwater is a key element of climate resilient water supplies

Sustainable groundwater management requires cooperation in use, monitoring and regulation

Current status

Since 2000, more people have access to basic and safely managed drinking water across Asia and Sub Saharan Africa

Progress towards SDG targets is uneven: 22 countries are water stressed and 15 are withdrawing > 100% of their renewable water resources

Over exploitation and pollution of ground water supplies:
(i) disproportionately affects the poorest and economically disadvantaged communities
(ii) has an impact on gender equality

Financing of the water sector is reported as inadequate in 80% of countries, hindering SDG 6 progress.

Role of geoscience and groundwater

Provision of geological data and understanding of aquifer architecture and processes

Protection of water-related ecosystems by understanding interactions between surface and sub-surface water

Input to groundwater resources management and hazards through understanding of abstraction, replenishment and transboundary groundwater flow

Understanding water quality and contamination

6.1 Introduction

Water and sanitation are inalienable rights of humanity as enshrined in the Human Right to Water and Sanitation (HRWS) by the United Nations General Assembly and adopted by all Member States in 2010. Access to safe water and sanitation is essential for social well-being, supporting outcomes in health (**SDG 3**), education (**SDG 4**), livelihoods (**SDG 8**), and gender equality (**SDG 5**) for urban and rural populations globally (Bartram and Cairncross 2010). Water and sanitation-related diseases, particularly diarrhoeal diseases, remain one of the major causes of death in children under five (Wang et al. 2016). The health burden associated with poor water and sanitation services, along with the burden placed on women and children to collect water when services are located away from the home, impacts on levels and equality of education, as well as economic productivity (Hutton et al. 2007). The role of water in the agricultural sector, particularly where irrigation supports agricultural production and development, contributes to economic growth through revenue and employment and increases food security at a household, national, and even global scale. Through hydropower and renewables, water can also contribute to improved access to affordable and clean energy (**SDG 7**).

Realisation of the social and economic benefits of safe water and sanitation requires an increase in service levels, particularly across sub-Saharan Africa, and the sustainable management and protection of water resources across the globe. This is the focus of ***SDG 6: Ensure availability and sustainable management of water and sanitation for all***, which strives to achieve universal access to safe and affordable drinking water and sanitation and aims for efficient use, integrated management, and protection of freshwater resources and water-related ecosystems, as summarised by the targets and associated indicators in Tables 6.1 and 6.2.

The SDGs build on decades of work aimed at improving lives, reducing poverty, and protecting the environment at a national and global level. Preceding the SDGs, the Millennium Development Goals (MDGs), which were adopted by the United Nations General Assembly in 2000, aimed (under Goal 7: Ensure Environmental Sustainability) to halve the proportion of

Table 6.1 SDG 6 targets and means of implementation

Target	Description of Target (*6.1* to *6.6*) or Means of Implementation (*6.A* to *6.B*)
6.1	By 2030, achieve universal and equitable access to safe and affordable drinking water for all
6.2	By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
6.3	By 2030, improve water quality by reducing pollution, eliminating dumping, and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
6.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
6.5	By 2030, implement integrated water resources management (IWRM) at all levels, including through transboundary cooperation as appropriate
6.6	By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes
6.A	By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling, and reuse technologies
6.B	Support and strengthen the participation of local communities in improving water and sanitation management

Table 6.2 SDG 6 indicators

Indicator	Description of indicator
6.1.1	Proportion of population using safely managed drinking water services (see Table 6.3 for definition)
6.2.1	Proportion of population using safely managed sanitation services (see Table 6.3 for definitions), including a hand-washing facility with soap and water
6.3.1	Proportion of wastewater safely treated
6.3.2	Proportion of bodies of water with good ambient water quality
6.4.1	Change in water-use efficiency over time
6.4.2	Level of water stress
6.5.1	Degree of IWRM implementation (0–100)
6.5.2	Proportion of transboundary basin area with an operational arrangement for water cooperation
6.6.1	Change in the extent of water-related ecosystems over time
6.A.1	Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan
6.B.1	Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management

the global population without sustainable access to an improved drinking water source and sanitation facility by 2015.

- An *improved drinking water source* has the potential to provide safe water as it is protected from contamination through its design and construction; these include piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water.
- An *improved sanitation facility* is designed to separate excreta from human contact, including flush or pour flush to piped sewer system, septic tanks or pit latrines, ventilated improved pit latrines, composting toilets, or pit latrines with slabs.

As outlined in the final MDG Report (United Nations 2015), the drinking water target was achieved in 2010, and by the end of the MDG period in 2015, almost 90% of the global population had access to an improved drinking water source. However, significant inequalities persisted across the globe: sub-Saharan Africa, for example, missed the drinking water target completely with only around 68% of the population accessing an improved source in 2015. While globally, urban dwellers achieved a higher level of access to improved sources than those in rural areas (96% compared to 84%). The MDG target for sanitation was not achieved with around one-third of the global population still using unimproved sanitation facilities in 2015, with a starker contrast between urban and rural access to improved facilities (82% compared to 50%).

Targets 6.1 and **6.2** of the SDGs go beyond the aims of the MDGs for access to improved services, introducing a service ladder (Table 6.3), which ultimately aims for the much more ambitious goal of safely managed services (note that the MDG for improved services equates to a limited level of service under the SDGs). Moving to Safely Managed services is a considerable challenge (Table 6.3), with less than 30% of the population in sub-Saharan Africa estimated as having a safely managed source in 2017, and 71% globally (Joint Monitoring Programme (JMP) 2019c). The SDGs also go beyond the focus of the MDGs and incorporate the sustainable management and protection of all water resources. This is necessary not only to achieve the drinking water target, but to balance multiple competing demands for water while maintaining the resilience and biodiversity of water-related ecosystems (see **SDG 15**), which provide many

Table 6.3 Service ladder for drinking water and sanitation. Outlined by the Joint Monitoring Programme (JMP) of the World Health Organisation (WHO) and UNICEF

Service Level	Drinking water definition	Sanitation definition
Safely Managed	Drinking water from an improved source that is located on premises, available when needed, and free from faecal and priority chemical contamination	Use of improved facilities which are not shared with other households and where excreta are safely disposed in situ or transported and treated off-site
Basic	Drinking water from an improved source, provided collection time is not more than 30 min for a round trip, including queuing	Use of improved facilities which are not shared with other households
Limited	Drinking water from an improved source for which collection time exceeds 30 min for a round trip, including queuing	Use of improved facilities shared between two or more households
Unimproved	Drinking water from an unprotected dug well or unprotected spring	Use of pit latrines without a slab or platform, hanging latrines, or bucket latrines
Surface Water (6.1) / Open Defecation (6.2)	Unsafe or unimproved drinking water directly from a river, dam, lake, pond, stream, canal or irrigation canal (example in Fig. 6.1)	Disposal of human faeces in fields, forests, bushes, open bodies of water, beaches, and other open spaces or with solid waste

Notes (1) an improved drinking water source has the potential to provide safe water as it is protected from contamination through its design and construction; these include piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water. (2) An improved sanitation facility is designed to separate excreta from human contact, including flush or pour flush to piped sewer system, septic tanks or pit latrines, ventilated improved pit latrines, composting toilets, or pit latrines with slabs

other services upon which humans depend, such as carbon sequestration and storage, air and water pollution control, nutrient cycling, erosion prevention, food, medicine, livelihoods, recreation opportunities, and spiritual health (Wood et al. 2018).

Target 6.3 aims to improve ambient water quality to protect both ecosystems and humans from harmful pollutants, including hazardous substances. Progress towards this target is measured by the percentage of wastewater treatment, including wastewater derived from households, commercial and industrial activities, urban run-off, and agriculture, and the percentage of water bodies in a country with good ambient water quality. Water quality is measured by a core set of parameters: dissolved oxygen, electrical conductivity, pH, nitrogen, and phosphorous for surface water, and electrical conductivity, pH, and nitrate for groundwater.

Target 6.4 addresses water scarcity by aiming for sustainable withdrawals (defined as freshwater taken from surface or groundwater sources, either permanently or temporarily, for agricultural, industrial or domestic use) and increased water use efficiency. Water use efficiency is measured as a productivity metric, defined as a country's total gross domestic product (GDP) per unit of freshwater withdrawal, where a high GDP per unit of freshwater withdrawal indicates a water-efficient economy. Water scarcity is indicated by the level of water stress at a national scale, defined as the ratio between total freshwater withdrawal and total renewable freshwater resources, after taking into account environmental water requirements. A country would be considered water-stressed if 25–60% of renewable water resources are withdrawn; if this proportion is higher at 60–75% or > 75%, a country would be considered water scarce or severely water scarce, respectively. It should be noted that water scarcity can also be considered in terms of economic or institutional water scarcity—where water shortages are caused, not by a lack of water availability, but by poor accessibility due to inadequate investment or capacity to develop and supply secure water sources.

Integrated water resources management (IWRM), **Target 6.5**, seeks to bring together stakeholders representing different sectors or

Fig. 6.1 **Surface water in Tanzania**. Example of ‘surface water’ (see Table 6.3 for definition) used for drinking and watering animals. © Joel Gill (used with permission)

geographical regions to ensure collaborative, cooperative, and coordinated management of water resources at the scale of individual basins, which may cross national borders. The degree of implementation is assessed through the four components of IWRM: enabling environment, institutions and participation, management instruments, and financing. **Target 6.6** aims to protect water-related ecosystems (Fig. 6.2), by halting degradation and destruction of ecosystems, or regenerating those already degraded. Water-related ecosystems include vegetated wetlands, rivers, lakes, reservoirs, and groundwater, with special mention of those occurring in mountains and forests (linking to **SDG 15**). The indicator for this target tracks changes over time in the spatial extent of water-related ecosystems and inland open waters, and the quantity and quality of water in these ecosystems (overlapping with indicator 6.3.2).

Means of Implementation 6.A and **6.B** recognise that international and local cooperation is needed to achieve SDG 6, aiming for increased funding for water and sanitation, particularly as official development assistance to developing countries, and increased involvement of local communities in water and sanitation management to ensure the needs of all people are being met. Equality is a core principle of the SDGs, particularly achieving gender equality and the empowerment of women and girls to enjoy equal access to education, economic resources, employment, and political participation (helping to deliver **SDG 5**). This has particular relevance for **SDG 6** due to the unequal burden put on women and children to collect water when sources are located off-site.

Achieving **SDG 6** requires an understanding of the interlinkages between targets within the Goal, not simply consideration of the targets in isolation (Fig. 6.3). For example, increased sanitation must be accompanied by wastewater treatment to ensure water quality is maintained for both drinking water and ecosystem services. Likewise, water resources must be managed

Fig. 6.2 **Freshwater resources in Iceland**. The targets of **SDG 6** emphasise both provision of safe and affordable drinking water, and the protection of freshwater ecosystems. Integrated Water Resources Management promotes a coordinated approach to the management of water, land, and related resources. Image by Free-Photos from Pixabay

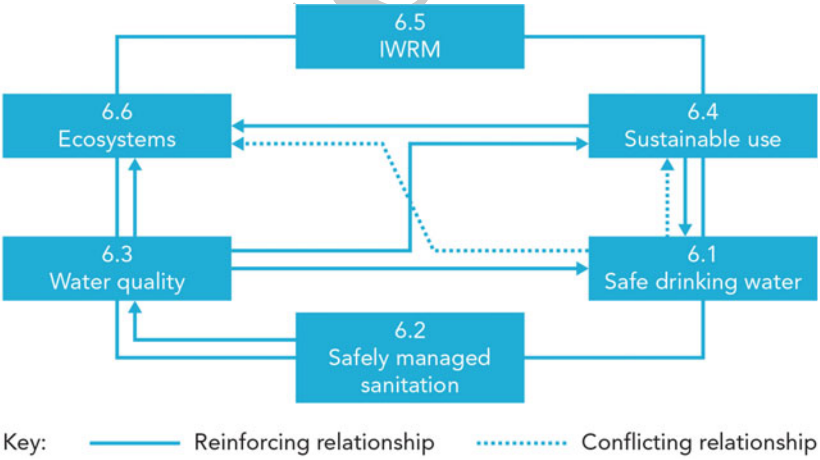


Fig. 6.3 **Interlinkages between targets of SDG 6**. IWRM refers to Integrated Water Resources Management. Solid lines refer to reinforcing relationships, and dashed lines are potentially conflicting relationships

sustainably to ensure sufficient quantity for all services, including drinking water and ecosystems, but also other economic uses such as agriculture, industry, and energy. IWRM links all targets of **SDG 6**, providing a management framework for addressing these linkages (both synergetic and conflicting) to balance competing demands on water resources.

Understanding the linkages between **SDG 6** and the other goals within the development framework is also crucial for supporting decision-making to achieve long-lasting development outcomes. The SDGs are, by design, an integrated set of goals and there are multiple intersection points where individual goals, or targets within them, act to reinforce, or in some cases conflict, with others. There are multiple interlinkages between **SDG 6** and the other 16 SDGs. Water and sanitation underpin many areas of development and poverty reduction—from health and well-being (**SDG 3**) to economic growth (**SDG 8**) and food security (**SDG 2**). Schools have an important role to play in improving WASH outcomes through education and access to services, while the health benefits of improved WASH lead to improved school attendance, particularly for girls (see **SDG 4**). Agricultural productivity can be increased by expanding access to irrigation and increasing the use of fertilisers and pesticides (see **SDG 2**), but this increases the demand for water and potentially pollutes freshwater resources. The strength and nature of the interlinkages often depend on the context, and therefore, vary geographically. A detailed exploration of the interlinkages for **SDG 6** can be found in *'A Guide to SDG Interactions: from Science to Implementation'* (International Council for Science (ICSU) 2017) and *'Water and Sanitation Interlinkages across the 2030 Agenda for Sustainable Development'* (UN-Water 2016).

In this chapter, we will look at global progress towards the targets of **SDG 6** in more detail and introduce some of the key challenges for achieving this goal. We will then focus on groundwater and the crucial role that it can, and is playing in achieving **SDG 6**. We will explore the role that geoscientists can play in improving groundwater management and development so that the potential socio-economic benefits of groundwater are realised without significant environmental degradation and risk to future water resources.

6.2 Challenges and Progress Towards SDG 6

6.2.1 Challenges to Achieving SDG 6: Climate Change, Population Growth, and Conflict

The SDGs represent an ambitious set of targets for sustainable economic, social, and environmental development. For water and sanitation, these targets are set within the context of a changing climate (see **SDG 13**) and rapidly growing population, which puts pressure on global water resources both in terms of supply and demand. On top of these pressures are challenges such as rising inequality, environmental degradation, urbanisation, industrial production, agricultural intensification, conflict and migration, and a lack of investment and adequate governance, which affect the availability, accessibility, and quality of water resources globally.

Water resources are not spread evenly across the globe. Not all areas have access to frequent rainfall throughout the year to replenish reservoirs, rivers, and aquifers and sustain aquatic ecosystems (Fig. 6.4). The availability of year-round water, or the ability to store and transfer water had a direct impact on a nation's economic development (Grey and Sadoff 2007). Much of Africa and South Asia, are challenged by long dry seasons or low annual rainfall. This uneven global distribution is being further affected by climate change.

The most recent climate change synthesis report from the Intergovernmental Panel on Climate Change (IPCC 2014) states that global warming is unequivocal and summarises the impacts that are already being seen in the global climate system. Multi-decadal globally averaged land and sea surface temperatures increased between 1880 and 2012. Precipitation over mid-latitude land areas in the northern hemisphere has increased since 1901 (there is low confidence in precipitation trends at other latitudes). Glaciers have continued to shrink worldwide. Global mean sea level rose by 0.19 m between 1901 and

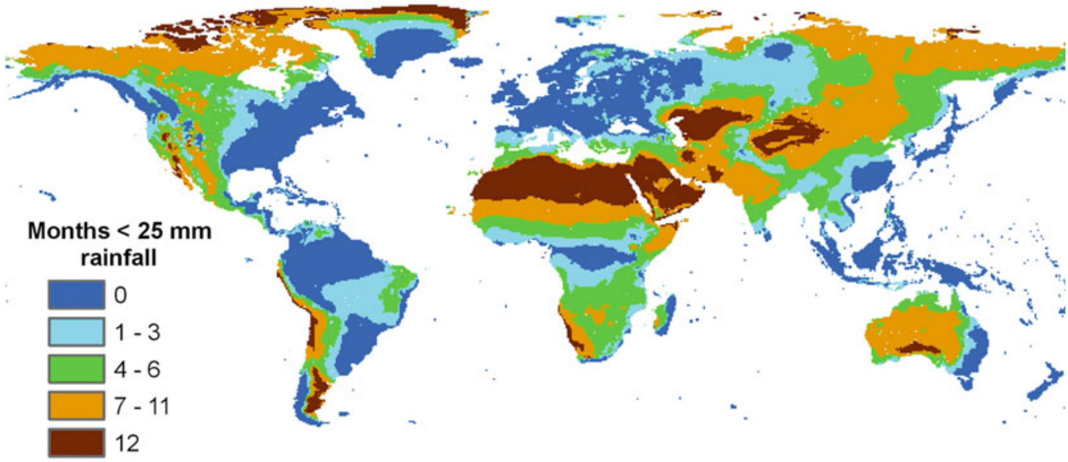


Fig. 6.4 Global distribution of rainfall showing the number of months with limited (<25 mm) rainfall. From: Hunter et al. (2010) Water Supply and Health. PLoS Med 7(11): e1000361. https://doi.org/10.1371/journal.pmed.1000361. Reproduced under a CC BY license

2010. An increase in extreme events has been observed since 1950, with an increase in the frequency of heatwaves across Europe, Asia, and Australia, and more areas experiencing an increase in heavy rainfall events compared to those seeing a decrease in extreme precipitation. Looking to the future, projected changes in temperature and precipitation remain uncertain and vary geographically, but it is very likely that heatwaves will occur more often and last longer, and that extreme precipitation will become more intense and occur more often in many areas. Changes in average precipitation are more variable, with some areas likely to experience an increase in mean annual precipitation and others likely to see a decrease. This has consequences for global water resources, with an increased risk of flood and drought, and in some areas (particularly dry subtropical regions), a reduction in renewable water resources. Risks related to climate change disproportionately affect the poor in part, because most developing countries are in tropical or arid regions where the effects of climate change are likely to be most severe, but also because poorer populations have less capacity to adapt to, withstand, and recover from climate-related risks such as flood and drought.

In 2015, the global population reached 7.3 billion. This is expected to increase to 8.5 billion by 2030, 9.7 billion by 2050, and 11.2 billion by 2100, with more than half the growth occurring in Africa (United Nations Department of Economic and Social Affairs Population Division 2019). This puts obvious pressure on water resources in terms of demand for drinking water, but will also increase the amount of water required for food production and other resources to ensure continued economic and social development. Superimposed on the global trend of population growth, is an increase in the proportion of the population living in urban areas, which is expected to increase from around 55% in 2018 to 68% in 2050 (United Nations Department of Economic and Social Affairs Population Division 2018). This puts particular pressure on water and sanitation services in urban areas, which are already struggling to cope with rapid population growth in many developing countries.

Whether caused by a lack of availability or accessibility, the implications of water scarcity are potentially significant and wide-ranging. In addition to hindering socio-economic development, water scarcity, in extreme cases, can be a contributing factor to migration, conflict, and humanitarian crises, like that witnessed in 2015/16, in East Africa, during the El Nino-related drought (Box 6.1). Even if not the primary cause, water scarcity is often one of many complex environmental, social, economic, and political factors leading to unrest and conflict. One of the most well-known examples of this is in the Middle East, with access to water a critical component of the ongoing conflict in the West Bank and Gaza. Much of the recharge to aquifers exploited in Israel, occurs upstream in the mountains of the West Bank, where abstraction is strictly controlled to protect downstream flows. Similar tension between upstream and downstream users occurs in many river basins with the Nile Basin, Indus, and Mekong river basins all sources of potential conflict. Considering the increasing pressures on global water resources, particularly related to climate and land use change and population growth, water scarcity is likely to become a more widespread and significant issue, making the need for sustainable management and protection of water resources ever more critical.

Box 6.1. Impacts of El Niño in Eastern and Southern Africa

What is El Niño? The El Niño Southern Oscillation (ENSO) is a global climate phenomenon that influences interannual temperature and precipitation patterns across the globe, most significantly in the tropics. The ENSO has a neutral phase and two opposite phases—El Niño and La Niña—driven by changes in the sea surface temperature gradient and atmospheric pressure gradient over the tropical Pacific Ocean (Met Office 2019). The impacts of ENSO are felt beyond the Pacific region. In Africa, El Niño episodes are generally associated with drought conditions in Southern Africa and the horn of Africa, with extreme rainfall often occurring in Tanzania, Uganda, and Kenya.

The 2015–16 El Niño event was one of the strongest on record (Siderius et al. 2018). Rainfall perturbations, occurring on top of multiple preceding dry years, resulted in drought conditions across southern Africa, as well as parts of Ethiopia, Somalia, and Kenya. The hydrological effects of this drought included reduced river flows, unusually low lake levels, exceptional soil moisture deficits, reduced groundwater storage and reduced spring flows across the region (Philip et al. 2018; Siderius et al. 2018; Kolusu et al. 2019; MacDonald et al. 2019).

Impacts of the 2015–16 El Niño event were felt across southern and eastern Africa. There was significant disruption to the urban water supply in Gaborone, Botswana, and hydroelectric load shedding in Zambia (Siderius et al. 2018); severe water shortages and water collection times of more than 12 h were experienced in the Ethiopian Highlands (MacDonald et al. 2019); and crop failures caused food shortages for millions of people across the region. In Ethiopia, the government, along with the United Nations, released a Humanitarian Response Document in 2015, asking for emergency assistance for over 10 million people. Continued below-average rainfall means the region is still experiencing a humanitarian crisis several years later (ReliefWeb 2019). However, people that had access to groundwater through boreholes were much less severely impacted, and many of the boreholes continued to function through the drought (MacDonald et al. 2019) (Fig. 6.5).

6.2.2 Monitoring Global Progress

The monitoring framework for tracking progress towards the SDGs is global, however, the review process is voluntary and country-led, often supported by regional or sub-regional commissions or organisations. In some cases, national baseline data, against which progress is monitored, does

Fig. 6.5 **Queuing for water at a hand dug well in Northern Nigeria**. Photo by Alan MacDonald. © UKRI/British Geological Survey

not exist and the SDGs call for increased support for data collection at a national level to inform the measurement of progress. In 2018, less than half of Member States had comparable data on progress towards meeting the targets of **SDG 6**; just over 40% had data available for more than four indicators, and only 6% had data available on more than eight indicators (United Nations 2018). Targets for water, sanitation, and hygiene (**6.1** and **6.2**), have a long history of data collection under the MDGs, i.e., since 2000, but the others generally have data available over much shorter time periods, if at all.

6.2.3 Global Progress: Drinking Water and Sanitation

Despite the pressures described above, global progress has been made towards achieving the targets of **SDG 6**. The Joint Monitoring Programme (JMP) of the World Health Organisation (WHO) and UNICEF use the service ladders shown in Table 6.3, to monitor progress towards **Targets 6.1** and **6.2**. Continued use of the MDG definitions of improved and unimproved services allows comparison across the MDG and SDG periods, showing a significant increase in the percentage of the total population with access to basic and safely managed drinking water services since 2000, particularly in rural areas, across Asia and sub-Saharan Africa (Table 6.4). A similar trend is seen for sanitation services across Asia, Latin America, and the Caribbean, while progress has been less significant in sub-Saharan Africa (Table 6.5).

There is still some way to go if we are to meet these targets by 2030 (see Figs. 6.6 and 6.7). In 2015, 30% of the global population still lacked access to safely managed drinking water services and 12% lacked access to even basic services—most of these in sub-Saharan Africa and Oceania. More than 60% of the global population lacked access to safely managed sanitation services, while 32% lacked access to basic services—again, mostly in sub-Saharan Africa and Oceania, although central and southern Asia also has some way to go. Oceania is the only region to have experienced a decrease in service levels, which has occurred for sanitation across rural and

Table 6.4 Global progress towards Target 6.1 for drinking water services (Joint Monitoring Programme (JMP) 2019a)

Region	% population with at least basic drinking water services (safely managed services)					
	Total		Urban		Rural	
	2000	2017	2000	2017	2000	2017
Australia and New Zealand	100 (-)	100 (-)	100 (92)	100 (97)	99 (-)	100 (-)
Central and Southern Asia	81 (41)	93 (60)	93 (66)	96 (62)	76 (31)	91 (60)
Eastern and South-Eastern Asia	81 (-)	93 (-)	97 (91)	98 (91)	71 (-)	86 (-)
Europe and North America	98 (90)	99 (95)	100 (97)	99 (97)	96 (-)	98 (-)
Latin America and the Caribbean	90 (56)	96 (74)	96 (82)	99 (82)	71 (-)	88 (42)
Northern Africa and Western Asia	91 (-)	92 (-)	94 (-)	97 (-)	71 (-)	84 (-)
Oceania (not Aus/NZ)	54 (-)	55 (-)	91 (-)	92 (-)	40 (-)	44 (-)
Sub-Saharan Africa	46 (18)	61 (27)	78 (42)	84 (50)	30 (6)	46 (12)

Table 6.5 Global progress towards Target 6.2 for sanitation services (Joint Monitoring Programme (JMP) 2019a)

Region	% population with at least basic sanitation services (safely managed services)					
	Total		Urban		Rural	
	2000	2017	2000	2017	2000	2017
Australia and New Zealand	100 (61)	100 (72)				
Central and Southern Asia	25	61	57 (-)	74 (-)	12 (7)	55 (40)
Eastern and South-Eastern Asia	61 (32)	85 (64)	81 (28)	91 (72)	47 (27)	75 (52)
Europe and North America	95 (69)	97 (76)	98 (79)	99 (85)	89 (-)	94 (48)
Latin America and the Caribbean	74 (12)	87 (31)	82 (15)	91 (37)	47 (-)	70 (-)
Northern Africa and Western Asia	77 (26)	88 (38)	88 (40)	95 (49)	64 (-)	76 (-)
Oceania (not Aus/NZ)	38 (-)	30 (-)	75 (-)	70 (-)	26 (-)	18 (-)
Sub-Saharan Africa	23 (15)	30 (18)	37 (17)	45 (20)	17 (14)	22 (18)

urban areas. Within these regions, levels of access are significantly lower in fragile states. For example, in sub-Saharan Africa, some of the lowest service levels for drinking water and/or sanitation are found in Chad, South Sudan, Democratic Republic of the Congo, and Somalia, which in 2019, were ranked in the top ten most fragile states in the world (The Fund for Peace[1]). Equally, Yemen and Afghanistan, are amongst the most fragile states and have the lowest service levels for drinking water and sanitation in Western and Central Asia.

6.2.4 Global Progress: Sustainable Management

The United Nations Synthesis Report (2018), summarises progress towards all targets of **SDG 6**. In 2014, levels of water stress were highest in Northern Africa and Western, Central and Southern Asia, and lowest in Oceania, sub-Saharan Africa, Latin America, and the Caribbean. In Northern Africa and Western Asia, 79% of available freshwater is withdrawn, while in Central and Southern Asia, the proportion is slightly lower at 66%. Twenty-two countries are defined as water-stressed, indicating a high probability of future

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[1] https://fundforpeace.org/.

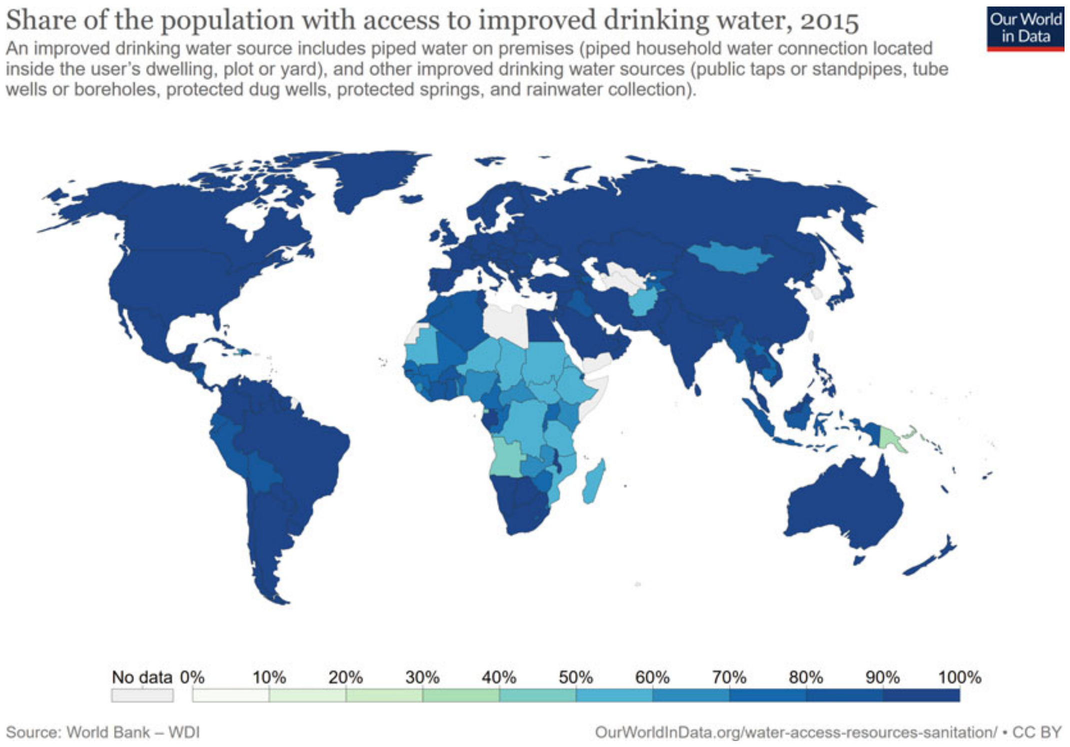
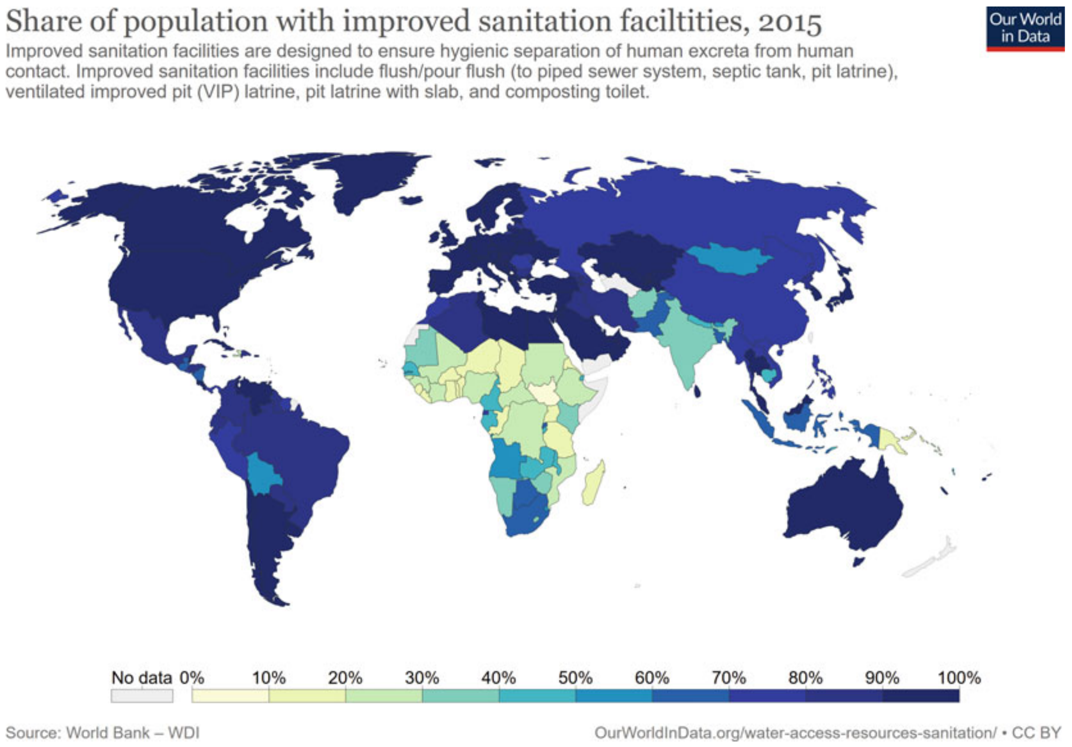


Fig. 6.6 Share of the population with access to improved drinking water (as of 2015). An improved water source includes safely managed, basic and limited services under the SDG service ladder (Table 6.3). *Credit* Ritchie and Roser (2019b), using data from World Bank, World Development Indicators. Reproduced under a CC BY License

water scarcity, with 15 countries already withdrawing more than 100% of their renewable water resources. Most countries need to accelerate their implementation of IWRM to achieve the 2030 target. Levels of implementation are highest in Australia, New Zealand, Europe, and North America, and the lowest in Latin America and the Caribbean. However, even in regions with low overall implementation, there are examples of countries with high levels of IWRM implementation, highlighting that levels of development are not always prohibitive. Levels of cooperation for managing transboundary water resources are generally higher for surface water than groundwater, with around 59% of transboundary basins covered by an operational agreement in 2017. The highest levels of cooperation are seen in Europe, North America, and sub-Saharan Africa, again indicating that levels of development do not have to prohibit effective water governance. Achieving all targets within **SDG 6** will require sufficient financing of the water sector and between 2012 and 2016, funding to the water sector dropped globally by more than 25%. In 2017, 80% of countries reported inadequate financing to meet the targets of **SDG 6**.

6.2.5 Global Progress: The Role of Groundwater

Groundwater makes a significant contribution to water supplies for domestic, agricultural, and industrial use globally. Reliable estimates of groundwater abstraction are not readily available at a global scale due to lack of monitoring, however, in 2010, global withdrawals were estimated to provide around 36% of domestic water supply, 42% of irrigation water for agriculture, and 27% of industrial water supply (Döll



Share of population with improved sanitation faciltities, 2015

Improved sanitation facilities are designed to ensure hygienic separation of human excreta from human contact. Improved sanitation facilities include flush/pour flush (to piped sewer system, septic tank, pit latrine), ventilated improved pit (VIP) latrine, pit latrine with slab, and composting toilet.

Source: World Bank – WDI

OurWorldInData.org/water-access-resources-sanitation/ • CC BY

Fig. 6.7 Share of the population with access to improved sanitation facilities (as of 2015). An improved sanitation facility includes safely managed, basic and limited services under the SDG service ladder (Table 6.3). *Credit* Ritchie and Roser (2019b), using data from World Bank, World Development Indicators. Reproduced under a CC BY License

et al. 2012). In parts of the southern and eastern UK, groundwater accounted for 100% of the total public water supply in 2015 (British Geological Survey 2019). In the USA, California is the state most reliant on groundwater, which in 2015, accounted for 21% of total freshwater withdrawals (United States Geological Survey 2019). India is the largest user of groundwater in the world, estimated to use more than 25% of the global total, with 60% of irrigated agriculture and 85% of drinking water reliant on groundwater (World Bank 2010). Although incomplete for Africa, data from the JMP in 2015, indicated that over 50% of the rural population in Africa, is reliant on groundwater as a primary source of drinking water (UPGro 2017).

Groundwater has an important role to play in achieving **SDG 6**, as will be discussed further in Sect. 6.3, but it is also relevant to other targets through several reinforcing and conflicting linkages (Guppy et al. 2018). Groundwater has the potential to increase resilience to water-related disasters (namely floods and droughts) and climate change as targeted by **SDGs 1.5**, **2.4,** and **13.1**. Through environmentally sound waste management, as targeted by **SDG 12.4**, improvements to groundwater quality will also be achieved. Similarly, achieving sustainable management and efficient use of natural resources, as targeted by **SDG 12.2**, will have positive outcomes for groundwater, and water resources more generally. As mentioned above, increased agricultural productivity may have negative implications for groundwater through increased demand for groundwater-fed irrigation and pollution by the use of fertilisers and pesticides.

6.2.6 Equity and Leaving no One Behind

The SDGs are based on the principle of leaving no one behind, paying particular attention to the least developed countries, in particular African countries, and to the most vulnerable members of society, including children and youth, those with disabilities, those living in extreme poverty, those living with HIV/AIDS, older people, indigenous peoples, refugees, and internally displaced persons. While geoscience undoubtedly plays a critical role in achieving the SDGs, and particularly **SDG 6**, it is important to recognise and understand the complex issues of equality and the challenges associated with addressing inequality in the effort to achieve the SDGs (see **SDG 10**). In the case of **SDG 6**, this predominantly concerns access to water services, which is highly unequal across the globe. Addressing these inequalities has long been an issue for academics and practitioners alike, with many past failures in progressing towards universal access to safe and affordable water attributed to errors or misjudgements by those in power (Chambers 1997). Understanding the realities and prioritising the needs of the most vulnerable members of society is essential to achieving **SDG 6**. For this reason, geoscientists are increasingly working alongside social scientists with the skills and methods to ensure that engineering or environmental solutions to water supply are centred on the needs of the most vulnerable.

6.3 Geology and SDG 6

6.3.1 Groundwater and the Water Cycle

Science, and earth science, in particular, has an important role to play in achieving **SDG 6**, with each of the four main branches of study—lithosphere, hydrosphere, atmosphere, and biosphere—contributing vital knowledge and understanding for addressing one or more of the targets within this goal. Of particular importance is an understanding of the water cycle (Fig. 6.8): how different components of the water cycle interact with one another, and with people, to determine the quantity and quality of water available and how this varies over time and space. Geoscientists can help answer critical questions such as: (1) how much rainfall is lost to evapotranspiration, how much becomes run-off to enter surface water stores such as rivers, lakes, and reservoirs, and how much infiltrates into the ground to enter groundwater stores or aquifers? (2) What is the nature of the subsurface and what does this mean for groundwater flow and storage? (3) How much water can be removed from an aquifer without causing long-term depletion or environmental degradation? (4) What is the natural quality of water stored on the surface or underground, and how is this affected by human activity? (5) How often do extreme climatic events, such as heavy rainfall or prolonged dry periods occur, and what impact does this have on surface and groundwater in terms of flood and drought? Answering these questions to achieve the targets of **SDG 6** requires expertise from many disciplines within the geosciences—climate science, hydrology, hydrogeology, hydrochemistry—as well as other disciplines, such as engineering and the social sciences, to address the technological, environmental, social, and economic aspects of water service delivery.

Groundwater plays a key role in achieving **SDG 6**, particularly **Target 6.1**, because it is widely distributed, resilient to drought, and generally of good natural quality. The widespread distribution of groundwater across the globe (Fig. 6.9), means it can often be accessed close to the point of use where other sources, e.g., rainwater or surface water, are absent or insufficient. This is particularly relevant for dispersed rural communities that are distant from large-scale water supply infrastructure. Groundwater sources are generally more resilient to drought than surface water sources due to the significant amount of water that can be stored in aquifers compared to rivers, lakes, and reservoirs. This storage provides a buffer against short-term rainfall variability, often allowing a reliable supply of water when other sources fail during prolonged dry

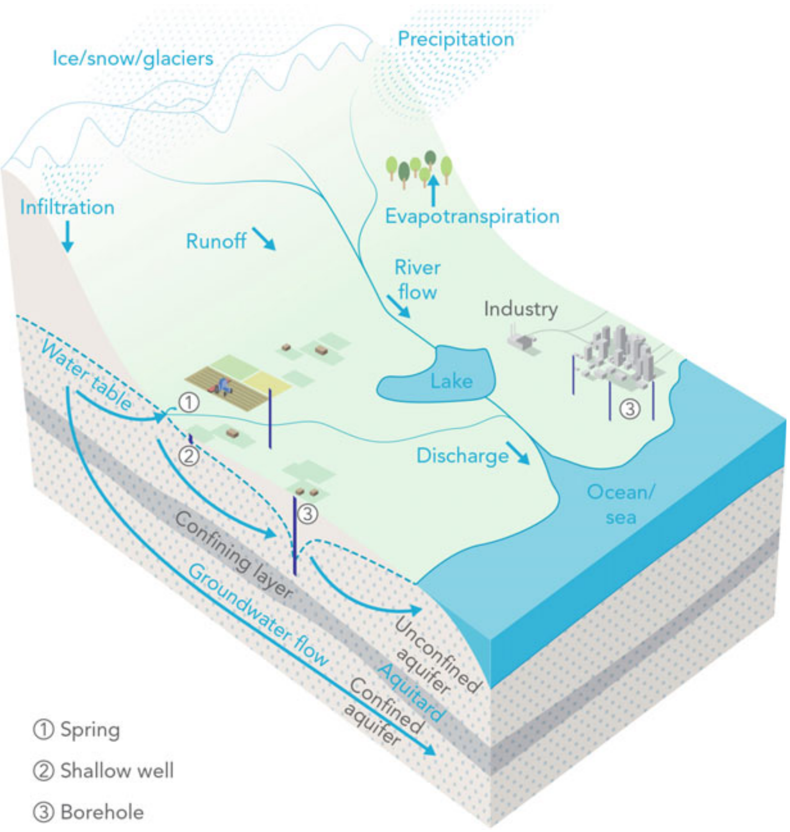


Fig. 6.8 The Water Cycle

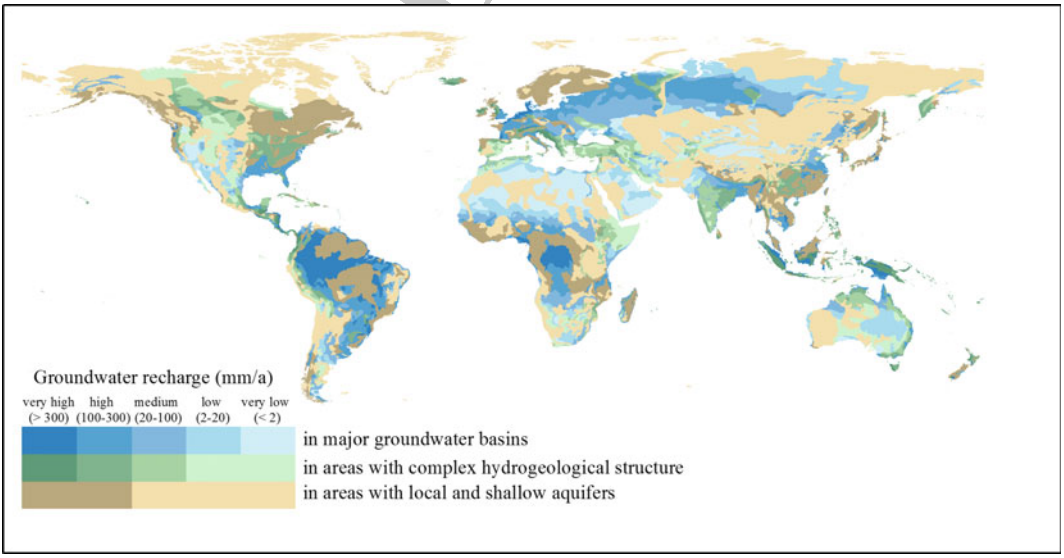


Fig. 6.9 Groundwater resources of the world. © BGR & UNESCO (2010)

periods. The quality of groundwater is generally very good due to the natural filtration process that occurs when water infiltrates into the ground and flows through the pore spaces in a rock. Being underground also provides a level of protection from potentially polluting activities at the surface, meaning that groundwater often requires less treatment to achieve safety standards for drinking than surface water.

Exploiting groundwater for water supply, whether for domestic, agricultural, or industrial use, is not, however, always straightforward. The groundwater environment is complex and needs to be properly understood to ensure that aquifers are exploited appropriately and sustainably, without risk to the long-term quality or availability of the resource. A sound understanding of the groundwater environment is also necessary for protection, integrated management, and efficient use of groundwater resources, as targeted by **SDGs 6.3** to **6.6**.

6.3.2 Key Groundwater Concepts

Groundwater—the freshwater stored in rocks and sediments beneath the ground surface—accounts for 30% of the total freshwater on Earth. Considering almost 70% of this freshwater is locked up in ice caps, glaciers, permanent snow, and permafrost, the majority (>98%) of accessible freshwater exists as groundwater (Gleick 1996). Hydrogeology, meaning water in rocks, is the discipline within the geosciences concerned with the study of groundwater. Groundwater can be found, to some extent, in almost all rock types but its potential usefulness as a resource is dependent on the quantity, quality, and sustainability of available water.

The amount of groundwater present at any given location will largely depend on the porosity and permeability of the rock and the amount of water entering the ground as recharge (see Box 6.2 for definitions). If the porosity, permeability, and recharge are high enough, water will accumulate in the pore spaces and fractures in a rock, usually above an impermeable base layer. If the rock becomes fully saturated, this forms an aquifer (Fig. 6.8). Groundwater flows naturally through an aquifer from the point of recharge to a point of discharge—usually a spring, river or the sea. Where groundwater is exploited for human use, wells or boreholes also act as points of discharge. The quantity of groundwater that can be stored and transmitted through an aquifer to a discharge point is dependent on the characteristics of the aquifer: mainly the transmissivity, storage, and 3D architecture (Box 6.2). These characteristics are largely controlled by geology. The depth and lithology of an aquifer also determine how easily accessible the groundwater is and what technology is required to exploit it. Rocks that do not transmit water easily are called aquitards.

Box 6.2. Basic Hydrogeological Concepts

Porosity (%) is the total void space within a rock and therefore defines the total amount of groundwater stored within an aquifer. Primary porosity refers to the pore space between grains, while secondary porosity refers to the space within fractures.

Permeability (measured in m^2) describes the ability of a porous media to allow fluids to pass through it.

Hydraulic conductivity (m/day) describes the ease with which a fluid would flow through a rock; it is dependent on the permeability of the rock and the properties of the fluid.

Transmissivity (m^2/day) describes the ability of an aquifer to transmit volumes of water; it is calculated by multiplying the hydraulic conductivity of an aquifer by its saturated thickness.

Yield (m^3/day or litres per second) describes the average volume of water that can be abstracted from an aquifer from a borehole, well or spring.

Storativity (dimensionless) describes the volume of water released from an aquifer per unit drop in groundwater head per unit area.

Depth to groundwater is the depth to the water table (or to the top of a confining layer where the water table has risen above the top of an aquifer and is therefore under pressure).

3D architecture describes the way in which the properties of the aquifer (i.e., permeability and storativity) vary with depth.

Piezometric level is a way of expressing the pressure in a confined aquifer. It is the level at which water would rise in a borehole drilled into the confined aquifer.

Water table is the upper surface of a groundwater body in an unconfined aquifer. It can be measured by the static water level in a well or borehole in an unconfined aquifer.

Recharge describes the amount of water that replenishes an aquifer, usually from precipitation, but also from seepage from rivers, lakes, or canals.

Discharge describes the amount of water removed from an aquifer, either by natural discharge to the environment (e.g., rivers, springs, lakes, wetlands), or through abstraction for human consumption.

Aquifers are generally classified or mapped according to the dominant groundwater flow mechanism—whether flow occurs mainly through the pore space or fractures in a rock—often combined with a measure of the productivity of an aquifer, lithology, or average recharge to an aquifer (Fig. 6.9). As for geology, the hydrogeology of any region is complex and spatially variable, both laterally and vertically. However, the main types of aquifer found across the globe can be summarised into just a few key hydrogeological environments, which are described in Table 6.6, and illustrated in Fig. 6.10. In some hydrogeological environments, for example, an alluvial plain that is homogeneous, laterally extensive, permeable, and receives significant recharge, groundwater is readily available and easily accessed by a shallow hand dug well or manually drilled borehole. In more complex hydrogeological environments, such as deep, fractured basement rocks with low primary porosity, developing a successful groundwater source is more challenging. However, even relatively low permeability rocks can be capable of providing sufficient flow to a well to support an individual household or community water supply, or small-scale irrigation scheme.

6.3.3 Water Supply

In those parts of the world with most work to do to achieve **SDG 6.1**, the challenges of groundwater development for water supply are different in urban and rural contexts. In many urban areas, the public water supply infrastructure cannot expand fast enough to provide a piped water supply to the rapidly growing population. As a result, urban populations often obtain water from multiple sources according to availability and cost. Sources may include private water vendors, utility standposts, and kiosks (Fig. 6.11), and unimproved shallow wells and surface water, with many individuals drilling their own private wells or boreholes to ensure they have a reliable source of water for drinking and other domestic uses (Box 6.3). Private borehole development is, however, often completely unregulated resulting in issues of over abstraction and contamination, as documented in parts of Asia and Africa (Foster and Vairavamoorthy 2013). Although in many rapidly expanding urban areas, private wells or boreholes are helping to bridge the gap between supply and demand, there are equity issues in terms of access as low-income households often lack the resources, both in terms of land ownership and capital, to instal a private well. Private borehole development may also ultimately lead to a reduction in revenue for water utilities, further reducing their ability to expand piped water infrastructure and provide lower tariffs to poorer households.

Table 6.6 Hydrogeological Environments. Adapted from MacDonald et al. (2005)

Hydrogeological Environment	Lithology	Flow Mechanism	Productivity	Description
Crystalline basement aquifers	Highly weathered/fractured metamorphic or magmatic rocks	Fracture flow	Moderate	Groundwater can be found in well-developed fracture networks and/or a thick weathered zone
	Poorly weathered/fractured metamorphic or magmatic rocks	Fracture flow	Low	Groundwater can exist in small fractures and may be locally important, but is difficult to find
Consolidated sedimentary aquifers	Sandstones	Intergranular or fracture flow	Moderate to high	Groundwater can be found in pore spaces and fractures; productivity will increase with coarseness and degree of fracturing
	Limestones	Fracture flow	Moderate to high	Groundwater can be found in fractures, which may be enhanced by dissolution; limestones have low primary permeability
	Mudstones	Fracture flow	Low	Groundwater can be found in fractures in hard, consolidated mudstones; often interbedded with sandstone or limestone layers
Unconsolidated sedimentary aquifers	Major alluvial or coastal sands and gravels	Intergranular flow	High	Groundwater can be found in thick unconsolidated sands and gravels deposited in major rivers basins or shallow seas
	Valley and coastal dune sands and gravels	Intergranular flow	Moderate	Groundwater can be found in smaller, dispersed sand and gravel deposits found in many modern-day river valleys and coastal dune environments
Volcanic	Lava, ash, and pyroclastic deposits	Fracture flow	Low to high	Groundwater often found along fractured contacts between lava flows in complex layered aquifer systems

Box 6.3. Informal urban water supply and sanitation in Lusaka, Zambia

In Lusaka, Zambia, repeated cholera outbreaks during the rainy season, are linked to contaminated drinking water. During an outbreak in 2017–18, one of worst in recent years, more than 5000 cases were reported in Lusaka, eliciting an emergency response (International Federation of Red Cross and Red Crescent Societies 2018) and requiring a multifaceted public health response including increased chlorination of municipal water supplies, provision of emergency water supplies, a vaccination campaign, and rapid training for health care workers.

Lusaka sits on carbonate rocks that are overlain by permeable superficial deposits of varying thickness (Nkhuwa et al. 2018). Groundwater in the karstic aquifer flows through a system of well-developed conduits and channels, making it a highly productive aquifer, which satisfies more than half the city’s water requirements. However, its high permeability and limited protection also means that contaminants

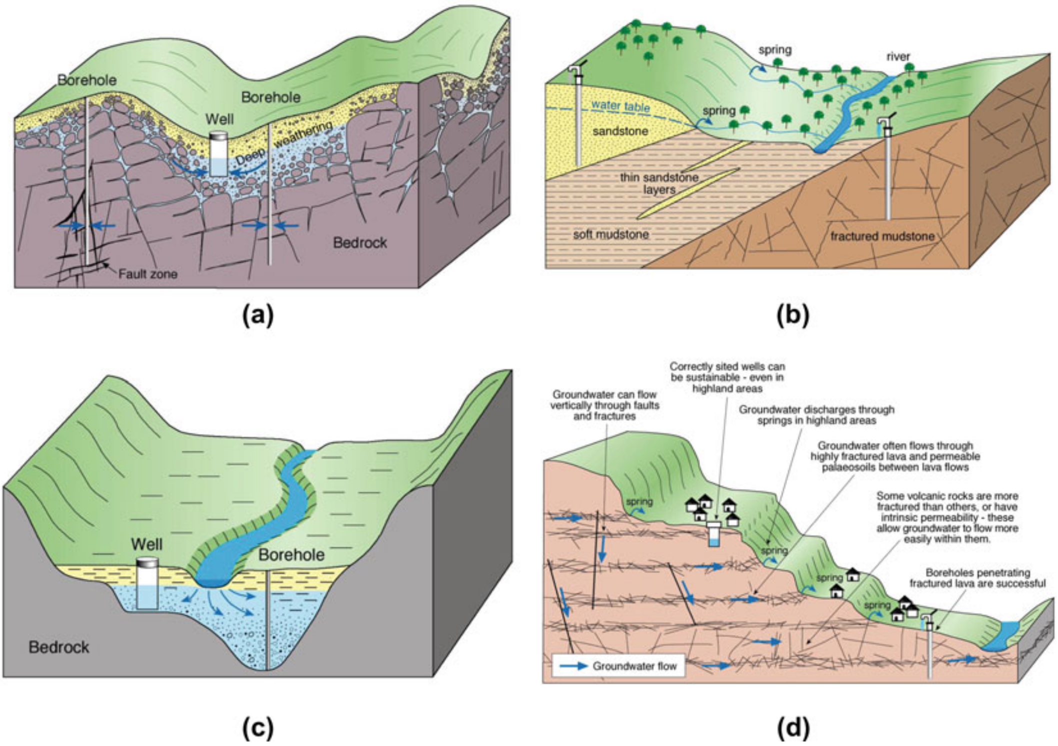


Fig. 6.10 **Hydrogeological Environments**. **a** weathered basement aquifer; **b** sandstone and mudstone sedimentary aquifers; **c** major alluvial aquifer; **d** volcanic aquifer. From MacDonald et al. (2005), and used with permission from ITDG publishing. © NERC

can easily infiltrate and be transmitted through the aquifer. This, combined with poor sanitation and waste management, results in the aquifer being extremely vulnerable to contamination.

As occurs in many rapidly expanding African cities, inadequate water supply and sewerage service provision has led many residents across Lusaka to instal their own private water supplies and on-site sanitation facilities. These are largely unregulated, often resulting in inadequately protected pit latrines being located very close to wells or boreholes (Fig. 6.12). This can result in untreated sewage leaking or discharging to the underlying aquifer, which residents then use for water supply (FRACTAL and LuWSI 2018).

Low-income, high-density peri-urban areas are most vulnerable to issues of groundwater contamination as service provision is lower and inhabitants can often only afford to access shallow groundwater through unprotected wells, which are highly susceptible to contamination (Nkhuwa 2006). However, groundwater contamination due to inadequately maintained septic tanks has also been observed in high-income, low-density parts of the city (Nkhuwa et al. 2015).

If the water quality and water supply targets of **SDG 6** are to be met, these issues need to be addressed through increased service provision, regulation, source protection, and water treatment.

Fig. 6.11 **Water Kiosk in Chipata, Zambia**. *Credit* GIZ Rahul Ingle (reproduced under a CC BY SA 2.0 License)

In rural settings, where water supply infrastructure is sparse or non-existent, groundwater often represents the only viable option for safe and reliable water supply through either household or community wells or boreholes. In sub-Saharan Africa, the majority of the rural population source their drinking water from groundwater through wells, boreholes, and springs. Properly sited and constructed boreholes, equipped with handpumps, have proved an excellent method for increasing access to safe drinking water, and have revolutionised rural water supply over the past 50 years. However, questions still remain about the best methods to maintain and manage these supplies over the long-term and how to increase their current low levels of functionality (Box 6.4). It should be noted that community water points are considered a basic level of service under the SDG indicators because water is not available on an individual’s premises, but it is likely that many rural populations will be reliant on these for decades to come, particularly in sub-Saharan Africa. As in urban settings, achieving equitable access is a challenge in rural areas, with the possibility of the location of a community water point privileging some members of the community over others.

Geoscientists have a key role to play in improving access to safe drinking water. Expertise is required in: planning and designing programmes; siting and commissioning individual water points; mapping the location, quantity, quality, and renewability of available groundwater resources; and carrying out research into the reliability and sustainability of supply. In many areas, groundwater resources are relatively easy to find and standard techniques and methods can be used to develop sustainable supplies (MacDonald et al. 2005), however, in other areas, groundwater resources can be much more difficult to develop. Geoscientists, therefore, have

Fig. 6.12 **Close proximity of groundwater well and pit latrine in peri-urban area of Lusaka**, Zambia. *Credit* Kenedy Mayumbelo (reproduced under a CC BY 2.0 license)

a vital role in helping to design appropriate drilling programmes, ensuring the correct techniques and methods are employed. Geophysics is often used to site individual boreholes, and pumping tests and water quality sampling undertaken on individual sources. These methods require qualified geoscientists to correctly apply the methods and interpret the results. In many parts of the world, groundwater resources are yet to be mapped at a sufficient scale to be useful for helping to design drilling programmes, with a particular gap in variability in water quality. There are still many unanswered questions for research to address—particularly around the sustainability of groundwater as demand for water increases—and in the successful management of water services, which requires geoscientists to work with other disciplines to make progress.

6.3.4 Groundwater Quality

The natural, or baseline, quality of groundwater is generally very good, but varies considerably in different hydrogeological environments due to reactions between the water and rock. Groundwater naturally contains many dissolved constituents, which at certain concentrations are not harmful, and in fact, in many cases are essential for human health. However, groundwater quality can be affected by both naturally occurring and

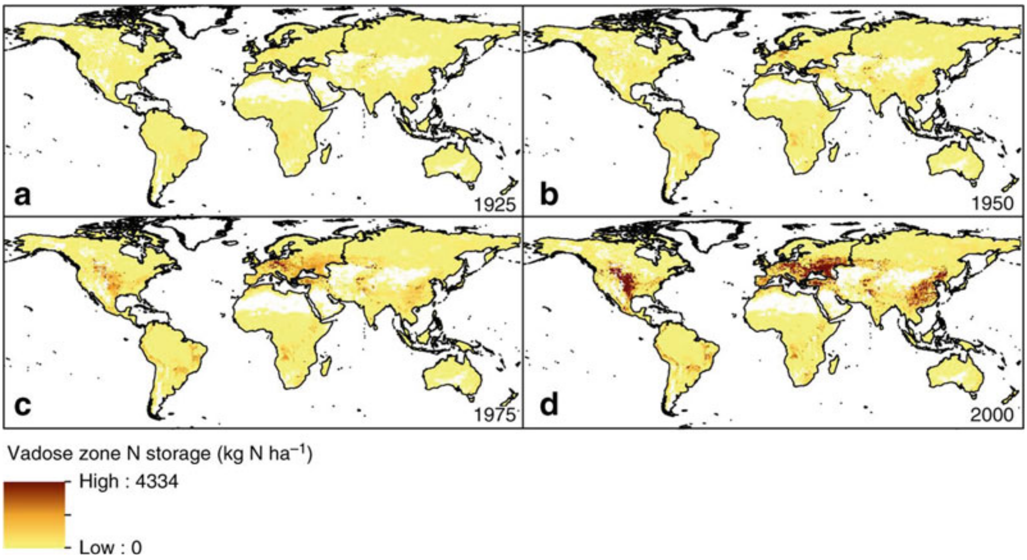


Fig. 6.13 **Build-up of nitrate in the unsaturated (vadose) zone over time.** From Ascott et al. (2017). Reproduced under a CC BY 4.0 License

human-induced contaminants, which at elevated concentrations can have serious implications for human and ecosystem health. The World Health Organisation provides guidelines and standards for drinking water, which set recommended limits for microbial, chemical, and radiological aspects of water quality (World Health Organisation (WHO) 2017). Some of the major contaminants of concern for groundwater globally are summarised below and in Table 6.7.

Chemical contaminants, which are naturally occurring in the environment, can be introduced to a groundwater system by natural and anthropogenic processes. The main natural contaminants (also referred to as geogenic contaminants) of concern globally are fluoride and arsenic. Fluoride occurs in groundwater where it dissolves fluorine-bearing minerals such as fluorite, apatite, and micas, which are particularly common in crystalline rocks such as granites. Elevated fluoride is more likely to occur where groundwater has a long residence time in an aquifer as this provides more time for water-rock interactions to occur. In active volcanic regions, elevated fluoride in groundwater can also occur due to mixing with hydrothermal fluids or gases. Fluoride is an issue across many parts of the world, particularly arid parts of northern China, India, Sri Lanka, North Africa, the East African Rift System, and Argentina (Box 6.4).

The occurrence of arsenic in groundwater is complex and can be related to a number of natural and anthropogenic processes. It can occur naturally where groundwater interacts with arsenic-bearing minerals such as sulphide minerals precipitated from hydrothermal fluids in volcanic environments, and pyrite and iron oxides that often accumulate in sedimentary environments. Human activities such as mining (particularly for coal and sulphide minerals), industry, and the use of certain arsenic-bearing pesticides, can also be sources of arsenic in groundwater. High arsenic concentrations tend to occur in strongly reducing (low oxygen) groundwaters or oxidising groundwaters with high pH, which inhibit adsorption of arsenic onto sediments and soils. Arsenic is a well-documented issue in anaerobic alluvial and deltaic aquifers in Bangladesh, West Bengal (eastern India), Nepal, northern China, Vietnam, and Cambodia, and in aerobic but high pH loess (wind-blown sediment) aquifers in Argentina and Chile.

Long-term exposure to elevated concentrations of these elements can cause dental and

Table 6.7 Chemical and biological constituents of groundwater

Inorganic chemical constituents		Pathogens	Organic compounds	Others
Major Elements[a b]: Sodium[c] Sulphate[c] Nitrate[c] Magnesium[c] Potassium[c]	Trace Elements[a]: Fluoride[c] Iron[c] Manganese[c] Arsenic Selenium[c] Cadmium Nickel[c] Chromium[c] Lead Aluminium	Coxsackievirus Echovirus Norovirus Hepatitis Rotavirus *E. Coli* *Salmonella* *Shigella* *Campylobacter jejuni* *Yersinia* *Legionella* *Cryptosporidium parvum* *Giardia lamblia*	Chlorinated solvents Aromatic hydrocarbons Pesticides	Pharmaceuticals Radionuclides Salinity

[a] Naturally occurring in groundwater
[b] The other major chemical constituents in groundwater, also considered essential for human health, are Bicarbonate (HCO_3), Calcium (Ca), Chloride (Cl), and Silicon (Si).
[c] Essential for human health at certain concentrations.

skeletal fluorosis in the case of fluoride, and a vast number of dermatological, cardiovascular, neurological, and respiratory issues, as well as several cancers, in the case of arsenic.

Box 6.4. Health Impacts of Elevated Fluoride in Groundwater, India

More than 200 people worldwide are believed to be drinking water with fluoride in excess of the WHO guideline of 1.5 mg/L (Edmunds and Semdley 2013). India is one of the worst affected countries (Podgorski et al. 2018), with parts of Sri Lanka, China, Mexico, and East African also significantly impacted.

Groundwater normally contains low concentrations of fluoride (<1.5 mg/l), which we require to maintain good dental health. However, high fluoride concentrations in drinking water can lead to health complications when consumed over long periods of time (BGS and WaterAid 2000; Edmunds and Semdley 2013). Long-term exposure to concentrations of 1.5–4 mg/l can lead to dental fluorosis, the most common issue associated with excessive fluoride consumption, which in extreme cases causes the tooth enamel to become pitted and discoloured. Higher concentrations (>4 mg/l) can cause skeletal fluorosis—a bone disease causing painful damage to bones and joints—or, in the worst cases crippling fluorosis which can ultimately lead to paralysis. Children under the age of seven, whose teeth and are still developing, are most vulnerable to dental fluorosis, which can be exacerbated by calcium and vitamin C deficiency.

Endemic fluorosis affects at least 17 States in India, with Andhra Pradesh, Rajasthan, Haryana, and Gujarat being the worst affected (BGS and WaterAid 2004). Much of India is underlain by Precambrian basement rocks, which mainly comprise gneisses and granites, with lesser amounts of metasedimentary rocks. In some areas the basement is overlain by younger sedimentary rocks and about half the land area of non-peninsular India is covered by Quaternary alluvial deposits. The alluvial deposits form the most productive aquifers, but Tertiary sediments and the Precambrian basement are also widely used for water supply. Elevated fluoride is most commonly (but not exclusively) associated with groundwater circulation in granitic basement rocks in arid and semi-arid areas of the country.

Fluoride can be removed from the water, but many individuals or countries lack the resources to treat water adequately. One of the best-known methods—the Nalgonda technique—was developed in India. This involves adding a combination of alum, lime, and bleaching powder to contaminated water, which is stirred and left to settle, allowing fluoride to be removed through the process of flocculation, sedimentation and filtration (BGS and WaterAid 2000). This method can be applied at the household level in a bucket, and at the community level in defluoridation plants.

Nitrate, although naturally occurring, is generally elevated in groundwater by human activities. The most common sources of nitrate in groundwater are nitrogen fertilisers, sewage, and wastewater. The use of nitrogen fertilisers to increase crop yields has grown significantly since the 1970s. Intensive application of fertilisers, particularly where double or triple cropping is practiced alongside poorly controlled irrigation, can lead to leaching of nitrate from the soil to an underlying aquifer. This occurs in agricultural areas across the world (Box 6.5). Intensive livestock farming, through manure and slurry pit leachate and effluent, is another potential source of nitrate contamination in groundwater, along with untreated sewage and wastewater. This is a particular problem in urban areas where sanitation infrastructure, much like water supply infrastructure, cannot expand fast enough to meet the needs of a growing population. In these circumstances, many households instal their own private waste disposal facilities—usually a pit latrine or septic tank—that can leak if not properly constructed and maintained. This poses a potential threat to an aquifer, and ultimately human health, particularly where unimproved sanitation facilities are combined or co-located with unimproved drinking water services (Box 6.3).

Box 6.5. The Nitrate Time-Bomb

When nitrate is leached from the soil it travels through the unsaturated zone before reaching the water table below. The travel time will depend on the geology and thickness of the unsaturated zone, and it can take as long as 100 years for nitrate to travel from the soil to an underlying aquifer. This large delay is sometimes referred to as the Nitrate Time-Bomb since the full impact of nitrate contamination from the use of nitrogen-based fertilisers, may not be observed for many years to come.

In areas with a history of intensive agriculture, such as Europe, North America and China, a significant amount of nitrate has built up in the unsaturated zone. This may cause groundwater contamination issues for decades to come, despite the introduction of legislation to control the use of fertilisers (Ascott et al. 2017). While this is a more significant problem in agriculturally intense countries, it is an issue that could become more severe in less developed countries as agriculture intensifies to meet the growing food demand (Fig. 6.13).

Elevated nitrate in groundwater, which ultimately discharges to rivers, lakes and coastal areas, can cause significant damage to ecosystems and increase the cost of water treatment. There are also health issues associated with high concentrations of nitrate—most notably a rare condition referred to as ‘blue-baby syndrome’, whereby nitrate reduces to nitrite in the stomach of young children, oxidising haemoglobin to methaemoglobin, which is unable to transport oxygen around the body. There are no reliable estimates of the extent of the problem worldwide (WHO).

Poor sanitation practices are also the primary source of microbiological contaminants, particularly in shallow aquifers in urban and peri-urban areas (Lapworth et al. 2017). Pathogens that are easily transported in groundwater and potentially very harmful to human health include *Norovirus*, *Hepatitis*, *E. Coli*, *Salmonella*, and *Legionella*. Other contaminants, such as heavy metals, synthetic organic compounds, and a range of emerging contaminants including food additives, caffeine, pharmaceuticals, and synthetic hormones, can be introduced to groundwater systems from industrial, agricultural, and domestic sources, posing a potential threat to vulnerable aquifers. Emerging contaminants in particular are mostly unregulated and not effectively removed by conventional treatment practices (Stuart et al. 2011), requiring an improved understanding of how they behave in the environment.

Groundwater vulnerability is often considered in the context of source-pathway-receptor. The vulnerability of a receptor (this may be an aquifer, well, borehole, spring, or river), will depend on the pathways that exist to transport a contaminant from its source to the receptor. The vulnerability of an aquifer to contamination from any of the sources discussed above is dependent on the properties of the soil and unsaturated zone, through which contaminants have to travel before reaching an aquifer, and the properties of the aquifer itself. In high permeability rocks, contamination can move quickly from the surface to an aquifer, then through an aquifer to a receptor (e.g., a borehole, spring, river, or wetland). Wells or boreholes in shallow fractured aquifers located close to the source of contamination will be highly vulnerable as there is little opportunity for attenuation, either in the unsaturated or saturated zone. Deep aquifers with low permeability will provide greater opportunity for attenuation between the source and receptor and are therefore less vulnerable to contamination.

Groundwater salinity is a widespread problem, which at shallow depths can be a major constraint on the development of groundwater resources. Elevated mineral concentrations have health impacts when water is routinely used for drinking and can reduce the value of water for industry and agriculture, causing damage to the soil if used for irrigation. The processes that lead to groundwater becoming saline are complex and can be divided into two broad categories: natural and those that are exacerbated by human activity. The source of naturally occurring saline groundwater can be marine, where seawater enters coastal aquifers, or terrestrial, associated with low rainfall, shallow water tables and high rates of evaporation. Some aquifers have also become increasingly saline due to irrigation, either from leaching of salts in the soil, or waterlogging and subsequent salinization. Pakistan and the Indus valley have seen some of the worst increases in groundwater and soil salinization due to a long history of irrigation.

Geoscience has a role to play in addressing **Targets 6.2** and **6.3** through groundwater and source protection as part of IWRM, waste management, and groundwater remediation. As described above, there are many potential sources of contamination than can negatively impact groundwater systems, including human excreta and sewage from poor sanitation practices, wastewater from domestic, agricultural or industrial activities, solid waste, and hazardous waste from industry. Management of any type of waste requires capture, storage, transport, treatment, and disposal or reuse, which may involve simple domestic-scale systems such as pit latrines up to large-scale infrastructures such as centralised sewer systems, wastewater treatment plants, and landfills. Whether considering small-scale storage of human excreta and sewage in a pit latrine or large-scale storage of solid waste in a municipal landfill, an understanding is required of how this waste behaves in the environment and what mitigation measures are required to minimise any negative impacts on both the environment and people. Geoscientists can help answer questions such as.

1. What are the potential sources of contamination and how close are these to environmental or human receptors such as drinking water sources, ecological sites, or areas used for recreation?
2. Is there potential for contaminants to be mobilised by water infiltrating at the surface?

3. If mobilised, how easily could contaminants move through the subsurface?
4. Is the waste well contained given the nature of the subsurface and what additional measures are required for safe storage?

Again, these questions require inputs from various disciplines within the geosciences, along with others involved in the waste management process.

6.3.5 Sustainable Groundwater Management

Groundwater is not an easy resource to manage. It is out of sight, and therefore, often overlooked by both the public and governments. This can lead to the misconception that wells, boreholes, and springs will continue to supply high quality water indefinitely, irrespective of how much water is abstracted or polluting activities occurring in the surrounding area (Smith et al. 2016). At the catchment scale, groundwater can have many users with competing demands: drinking water, industrial production, and agriculture. Trade-offs also develop between urban and rural users, and between groundwater abstraction and the ecological functioning of wetlands or baseflow to rivers. Balancing these abstraction demands, along with the environmental requirements for groundwater, is a challenge, but is essential if all targets within **SDG 6** (and other linked goals, e.g., **SDG 2**, **SDG 8**, **SDG 15**) are to be met. Achieving sustainable groundwater management requires local groundwater users, technical experts (including geoscientists) and policymakers to work together to develop understanding, drive change, and develop and implement appropriate tools (Smith et al. 2016).

Pressures on groundwater are increasing from both abstraction and pollution, and resources need to be protected and managed. High abstraction in parts of the world have led to rapidly falling water tables, sometimes accompanied by land subsidence or degradation of water quality through saline intrusion. Parts of India, Pakistan, the USA, Iran, Saudi Arabia, and China have been identified as experiencing severe overexploitation of groundwater (Gleeson et al. 2012). In other areas, such as parts of sub-Saharan Africa, groundwater resources remain less developed, and opportunities exist to develop groundwater for social economic and health benefits (Cobbing and Hiller 2019). Changing land use—and in particular intensive agriculture and urbanisation—have led to widespread groundwater contamination (Morris et al. 2003). Nitrate concentrations are high in many aquifers in agricultural areas; and beneath many cities, groundwater has been polluted by a cocktail of different organic and inorganic chemicals. Because of the long residence times of groundwater, it can take many years, decades or centuries for contaminants to be flushed out of an aquifer. Management of groundwater is important not just for today but for future generations.

Groundwater systems vary considerably—based on the geology, climate, links to surface water systems, and land use—which means they respond differently to pressures and require different management solutions. The starting point for groundwater management is, therefore, to characterise how groundwater systems work: what is the geological and hydrogeological environment; how much recharge does the system receive; how much groundwater is naturally discharged, and where; and what is the vulnerability of an aquifer to pollution? Using this knowledge, effective monitoring systems can be designed to bring to light the impact on groundwater from abstraction and land use. Given the nature of groundwater as a common pool resource many different stakeholders then need to be involved to develop reasonable visions and plans for groundwater governance that leave no one behind (Villholth et al. 2017). As well as considering groundwater as a source for human consumption, the role of groundwater in maintaining ecosystems, which provide many services to both humans and the environment, is also of concern. Integrated Water Resources Management (IWRM) provides a framework to help manage water resources across catchments, taking into account the uses of water from all parts of the water cycle. This paradigm shift in management approach moved the emphasis away from individual well fields or aquifers to entire water systems. The European Union has been at the forefront of applying the principles of IWRM to groundwater and are set out in the Water Framework Directive of 2000, and supplemented by the Groundwater Protection Directive of 2006 (Quevauviller 2007). In summary, these approaches manage the balance of abstraction from groundwater with the recharge and unwanted impact to others and the environment and protect groundwater quality through groundwater friendly rural land use, regulation to penalise point source pollution, and the development of precautionary engineering structures to contain point source pollution such as landfill sites.

To achieve sustainable groundwater management various methodologies have been developed and proved useful, for example, detailed 3D mapping of aquifers and groundwater systems; monitoring systems with in situ monitoring of water levels and chemistry and the use of satellite data such as InSAR, and GRACE; sophisticated land zoning methods based on the vulnerability of groundwater to contamination, or travel times to abstraction boreholes; the development of numerical groundwater models to test possible future scenarios or track sources of pollution. Some technical engineered interventions are also sometimes used, such as rainwater harvesting and managed aquifer recharge (MAR) to increase the natural recharge to the system (Box 6.6); the use of scavenger wells to control pollution particularly in saline areas; and the construction of engineered structures to control pollution or flooding. Geoscientists are fundamental to developing and adapting these methods and technologies.

Box 6.6. Managed Aquifer Recharge (MAR)

MAR involves artificially recharging aquifers with excess surface water during wet periods, or in some cases treated wastewater, which is stored underground and can be accessed during dry periods when surface water is scarce. MAR is gaining increased attention as an adaptation measure to improve water security and resilience to climate variability. It is increasingly important as a management strategy in conjunction with demand management to maintain stressed groundwater systems (Dillon et al. 2019). However, there are limitations to the applicability of MAR, which always need to be fully considered when assessing the viability of this solution.

The International Groundwater Resources Assessment Centre (IGRAC[2]) document over 1000 examples of MAR schemes worldwide, which use different methods and technologies to artificially recharge an aquifer (Stefan and Ansems 2018). The application of MAR has grown rapidly since the 1960s, with an estimated capacity of 10 km^3 per year in 2018 (Dillon et al. 2019). However, with estimated annual global groundwater abstraction of 800 km^3, there is still room for growth. Natural groundwater recharge through rainfall and river and lake leakage remains the overwhelming method by which groundwater is renewed.

Techniques to enhance groundwater recharge range in scale and sophistication (Dillon et al. 2019). Enhanced recharge from rivers is widely used across India, where hundreds of thousands of constructed dams create ponds within the river channel to increase infiltration. Recharge can be further induced from the river by drilling abstraction boreholes close to the banks of the river. This pulls water from the river into the aquifer and naturally filters the water through the aquifer material. Water spreading is a method used to capture floodwater and spread it over a larger area to increase soil moisture and promote infiltrate to an aquifer. Some schemes

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[2] https://www.un-igrac.org/.

involve dedicated recharge boreholes which pump treated surface water directly into the aquifer. All methods come with risks of increasing contamination of the groundwater and need to be monitored carefully.

Although groundwater is essentially a local resource with a flow rarely more than one metre per day, aquifers do not respect international borders. Large aquifers crossing international or state borders (referred to as transboundary aquifers) require some level of cooperation to be successfully and sustainably managed. The level of cooperation could extend from a shared understanding of the extent and nature of an aquifer to joint monitoring and agreed regulation. Given the slow nature of groundwater movement, transboundary aquifers can be viewed more as a vehicle and opportunity for technical cooperation, rather than a source of conflict.

6.4 Conclusions

Groundwater has an important role to play in achieving the SDGs, particularly through meeting the targets of **SDG 6**. Geoscientists have a critical role to play in achieving safely managed drinking water and sanitation for all (**Targets 6.1** and **6.2**), protecting the quality of the globe's water resources (**Target 6.3**), ensuring sustainable water use and reduction of water scarcity (**Target 6.4**), achieving integrated water resources management (**Target 6.5**), and protecting water-related ecosystems (**Target 6.6**). Understanding, characterising, monitoring, forecasting, and communicating groundwater dynamics and the connections with the wider ecosystem are not straightforward. In addressing these targets, geoscientists are required to work alongside policymakers, and often water users, to ensure the best evidence informs decisions about water resource development and allocation. This may happen from the local scale—where scientists work alongside communities or local authorities to inform water resources management in small basins or catchments—up to the regional or continental scale—where scientific evidence is used by national governments to inform the development and management of large transboundary water resources. With an increasing rate of global environmental change, the demand for groundwater as a reliable source of water will only increase.

AQ1

Key Learning Concepts

- Water and sanitation are key components of economic and social development
- Progress towards the targets of SDG 6 is highly unequal across the globe and often, but not always, related to levels of development
- There are significant challenges to achieving SDG 6, such as climate change and population growth, the effects of which are also unequal across the globe
- Groundwater has a key role to play in achieving SDG 6, particularly through the provision of sustainable and climate resilient water supplies
- Groundwater resources are out of sight and often difficult to understand, requiring expertise across a range of disciplines
- Overexploitation and pollution of groundwater is a global issue, but can be addressed through IWRM and sound management and governance strategies

Educational Ideas

In this section, we provide examples of educational activities that connect geoscience, the material discussed in this chapter, and scenarios that may arise when applying geoscience (e.g., in policy, government, private sector international organisations, NGOs). Consider using these as the basis for presentations, group discussions, essays, or to encourage further reading.

- From 1990 to 2015 (25 years), access to improved drinking water in Tanzania has gone from 53.90% to 55.60% of the population.[3] At

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[3] https://ourworldindata.org/grapher/share-of-the-population-with-access-to-improved-drinking-water?tab=chart&time=1990..2015&country=OWID_WRL+IND+KEN+BRA+TZA.

this rate of progress, it will be 2667, before Tanzania has 100% access to improved drinking water. Explore the reasons for this rate of progress and the actions (from geoscientists and others) that may help catalyse action towards 100% access to improved drinking water in Tanzania.

- Review the information in this chapter on groundwater and fluoride. Prepare an information sheet for NGOs drilling boreholes, summarising key geological environments associated with elevated fluoride.
- Integrated water resources management aims to bring different stakeholders together to ensure collaborative, cooperative, and coordinated management of water resources. Reflecting across the SDGs, and how demand for water may change by 2030, consider the range of stakeholder this may include, and what priorities each may have in terms of the quantity and quality of water required to fulfil their needs. As a class, discuss what recommendations you would make to resolve conflicting demands on water resources in an equitable way, leaving no one behind, while protecting resources for future generations.

Further Reading and Resources

Books and Articles

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IAH Strategic Overview Series. https://iah.org/education/professionals/strategic-overview-series

WaterAid/British Geological Survey Groundwater Quality Fact Sheets: Country. https://www.bgs.ac.uk/downloads/browse.cfm?sec=9andcat=115. Element https://www.bgs.ac.uk/downloads/browse.cfm?sec=9andcat=116

GW-MATE Briefing Note Series, Case Profile Collection, Book Contributions and Strategic Overview Series. available via IGRAC. https://www.un-igrac.org/special-project/gw-mate

Videos

IGRAC Groundwater, the Hidden Resource. https://www.youtube.com/watch?v=tzkBvLXa8jsandt=13s

RWSN A borehole that lasts a lifetime. https://vimeo.com/128478995

Tools and Online Resources

Africa Groundwater Atlas. https://www.bgs.ac.uk/africagroundwateratlas/index.cfm

USGS Water Science School. https://www.usgs.gov/special-topic/water-science-school

UK Groundwater Forum. https://www.groundwateruk.org/

IGRAC Global Groundwater Information System. https://www.un-igrac.org/global-groundwater-information-system-ggis/

World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP). https://www.whymap.org/whymap/EN/About/about_node_en.html

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