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The United Nations World Water Development Report 2022

GROUNDWATER
Making the invisible visible

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The United Nations World Water Development Report 2022

GROUNDWATER
Making the invisible visible

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SHORT SUMMARY

The vast potential of groundwater and the need to manage it sustainably can no longer be overlooked

Accounting for approximately 99% of all liquid freshwater on Earth, groundwater has the potential to provide societies with tremendous social, economic and environmental benefits and opportunities. Groundwater already provides half of the volume of water withdrawn for domestic use by the global population, including the drinking water for the vast majority of the rural population who do not get their water delivered to them via public or private supply systems, and around 25% of all water withdrawn for irrigation. However, this natural resource is often poorly understood, and consequently undervalued, mismanaged and even abused.

Groundwater accounts for approximately **99%** of all liquid freshwater on Earth

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. Reliance on groundwater will only increase, mainly due to growing water demand by all sectors combined with increasing variation in rainfall patterns.

The report describes the challenges and opportunities associated with the development, management and governance of groundwater across the world. It aims to establish a clear understanding of the role that groundwater plays in daily life, of its interactions with people, and of the opportunities for optimizing its use in order to ensure the long-term sustainability of this largely available yet fragile resource.

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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"Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed"

UN WATER

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Foreword

by **Audrey Azoulay**, *Director-General of UNESCO*

The hydrological cycle teaches us that water is in constant movement. Water melts, evaporates, condensates and circulates – but it is never static. As part of this process, water seeps into soil, collecting in underground reservoirs. This groundwater is a critical natural resource, invisible but indispensable for life on our planet.

Indeed, nearly 50% of the world's urban population depends on underground water sources. Yet more and more aquifers are being polluted, overexploited, and dried up by humans, sometimes with irreversible consequences. Moreover, many decision-makers in the water field lack a clear notion of groundwater, despite its essential role in the water cycle.

That is why UNESCO, in cooperation with UN-Water, is organizing a global summit on groundwater in December 2022. That is also why this issue will be the theme of World Water Day on 22 March. And, finally, that is why groundwater is the focus of this year's edition of the United Nations World Water Development Report.

This report, entitled "Groundwater, making the invisible visible", raises awareness of this abundant yet fragile resource. It provides in-depth information on groundwater availability and underlines its importance in the provision of water to humans and the environment.

Importantly, the report expands on current opportunities and imminent challenges and explores how we can use, manage and govern this resource sustainably. This means, among others, making smarter use of the potential of still sparsely developed groundwater resources, protecting groundwater against pollution and overexploitation, responding dynamically to the needs of an ever-increasing population, and responding effectively to the global climate and energy crises.

Lastly, the report highlights interlinkages between groundwater and human health, poverty alleviation and gender equality. To this end, improved knowledge and capacity development is not enough; to protect aquifers, we also need innovation, in terms of technical interventions, institutional and legal reforms, improved financing, and behavioural changes.

This remarkable publication, coordinated by UNESCO, was made possible thanks to the ongoing support provided by the Government of Italy and the Regione Umbria to UNESCO's World Water Assessment Programme. I also wish to thank the UN Water family for contributing its knowledge and skills.

For, when it comes to groundwater, many challenges and opportunities lie ahead. UNESCO is committed to addressing these, notably through its Intergovernmental Hydrological Programme. I therefore trust that this World Water Development Report will inspire decision-makers to adopt more focused approaches to developing, managing and governing groundwater – and, in doing so, make the invisible visible.

Audrey Azoulay

Audrey Azoulay

Foreword

by **Gilbert F. Houngbo**, *Chair of UN-Water* and
President of the International Fund for Agricultural Development

Beneath our feet, out of sight, groundwater is a resource most of us rarely think about. Yet, almost all of the liquid freshwater in the world is groundwater, providing critical support to drinking water supplies, crops, industries and ecosystems.

As this report makes clear, human activities over-use and pollute groundwater in many places; and in other locations, we simply do not know how much water is down there. The mismanagement of groundwater, and its frequent abuse either by contamination or over-exploitation, is a threat to the entire water cycle – and therefore a threat to human well-being and the survival of all life.

This year's United Nations World Water Development Report focuses upon the need to explore and protect groundwater, and shows that equitable and sustainable management of it will be central to surviving and adapting to climate change and meeting the needs of a growing population.

As ever, this publication is highly relevant both to an expert audience and to general readers seeking a better understanding of the part played by water in human societies and development. The experiences, information and analysis provided by UN-Water's Members and Partners help us understand the many ways in which groundwater is critical to healthcare, agriculture, jobs, the environment and many other domains.

The conclusion is clear: improving the way we use and manage groundwater is an urgent priority if we are to achieve the Sustainable Development Goals by 2030.

Decision-makers must begin to take full account of the vital ways in which groundwater can help ensure the resilience of human life and activities in a future where the climate is becoming increasingly unpredictable.

The 2022 United Nations World Water Development Report is the outcome of cooperation between various United Nations entities and partner organizations from the UN-Water 'family'. A richly diverse collection of expert professionals has produced a comprehensive yet clear and accessible analysis of this topic that identifies challenges and recommends solutions.

I am grateful to UNESCO and its World Water Assessment Programme for coordinating this edition, and to all colleagues who participated.

We must protect and use groundwater sustainably, balancing the needs of people and the planet. I am confident that this report will provide the reader with a better understanding of how to improve groundwater policies and I hope it will spur the urgent action that is sorely needed.

Gilbert F. Houngbo

Preface

by **Michela Miletto**, *UNESCO WWAP Coordinator*
and **Richard Connor**, *Editor-in-Chief*

Every past edition of the United Nation's World Water Development Report (WWDR) has offered a rather unique outlook on water. Some reports have focused on relatively technical subjects such as energy, wastewater, nature-based solutions or climate change. Other water-related topics covered in these reports, such as sustainable development, water and jobs, leaving no one behind, or valuing water, have been addressed primarily through socio-economic lenses. In some cases, we were able to base our work on a considerable amount of previously existing data, information, analysis and material, while in others, the knowledge base was considerably limited, compelling us to take a more creative approach in designing and drafting the report.

This latest WWDR is particularly unique: it is the first time that our report has focused on a specific element of the global water cycle – in this case, groundwater. In other words, the topic (or theme) of this year's report is more than just an angle or perspective through which to explore the role of water across various social, economic and environmental goals and objectives, it is about the resource itself. And more importantly, it concerns a critical freshwater resource that has remained 'under the radar' for far too long.

As the ninth in a series of annual, thematic reports, the 2022 edition of the WWDR seeks to explore the importance of groundwater for sustainable development and shed some light on the policy and management actions that need to be taken, not only to ensure the perenniality of the resource, but also to maximize the many opportunities it offers in a rapidly changing world of rising water demand and limited, often vulnerable, freshwater resources.

As highlighted throughout the report, groundwater already plays a vital role in supporting food and energy security, urban and (especially) rural settlements, and industry. It is an essential component for many healthily functioning ecosystems and offers exceptional prospects in terms of climate change adaptation and mitigation. The report also describes potential responses to overcome the challenges that currently impede progress in the governance and management of groundwater resources, namely in terms of data gathering and dissemination, legal and political frameworks, capacity-building, and financing.

Another unique aspect of this year's WWDR is the sheer number of authors and contributors, and the richness of on their inputs. Never before have we had such a tremendous level of support from such a broad field of recognized experts and practitioners from around the world, and we humbly believe that this is reflected in the quality and relevance of the report. We certainly made a lot of new friends – and reacquainted with several other ones – along the way! It is our sincerest hope that we will continue to foster such collaborative efforts for years to come.

Through working closely with of all these contributors, we have endeavoured to produce a balanced, fact-based and neutral account of the current state of knowledge, covering the most recent developments, and highlighting the challenges and opportunities that a greater attention to groundwater can provide. Although primarily targeted at policy- and decision-makers, water resources managers, academics and the broader development community, we hope this report will also be well received by non-specialists, and those who are engaged in the alleviation of poverty and humanitarian crises, in the pursuit of the human rights to water supply and sanitation, and the advancement of the 2030 Agenda for Sustainable Development.

This latest edition of the WWDR is the result of a concerted effort between the Chapter Lead Agencies listed in the acknowledgements. The Report also benefitted to a great extent from the inputs and contributions of several other UN-Water members and partners, as well as from numerous universities, research institutions, scientific associations and NGOs who provided a wide range of relevant material.

On behalf of the WWAP Secretariat, we would like to extend our deepest appreciation to the afore-mentioned agencies, members and partners of UN-Water, and to the writers and other contributors for collectively producing this unique and authoritative report during the second year of the COVID-19 pandemic, with all the additional difficulties the situation has imposed on each and all of us. Jac van der Gun deserves specific recognition for having generously shared his knowledge, wisdom and guidance throughout the report's publication process.

We are profoundly grateful to the Italian Government for funding the Programme and to the Regione Umbria for generously hosting the WWAP Secretariat in Villa La Colombella in Perugia. Their contributions have been instrumental to the production of the WWDR.

Our special thanks go to Ms Audrey Azoulay, Director-General of UNESCO, for her ongoing support to WWAP and the production of the WWDR, and to Mr Gilbert F. Houngbo, Chair of UN-Water and President of the International Fund for Agricultural Development.

We extend our most sincere gratitude to all our colleagues at the WWAP Secretariat, whose names are listed in the acknowledgements. The report could not have been completed without their professionalism and commitment.

Last but not least, we dedicate this report to the front-line healthcare providers and essential service workers whose tireless efforts allowed us to remain as safe as possible during the ongoing COVID-19 pandemic.

Michela Miletto

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Chapter Lead Agencies

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Executive summary

The purpose of this edition of the *United Nations World Water Development Report* (WWDR 2022) is to shine a spotlight on groundwater, calling attention to its specific roles, challenges and opportunities in the context of water resources development, management and governance across the world.

Groundwater – accounting for approximately 99% of all liquid freshwater on Earth and distributed over the entire globe, albeit unequally – has the potential to provide societies with tremendous social, economic and environmental benefits, including climate change adaptation. Groundwater already provides half of the volume of water withdrawn for domestic use by the global population, and around 25% of all water withdrawn for irrigation, serving 38% of the world's irrigated land. Yet, despite its enormous importance, this natural resource is often poorly understood, and consequently undervalued, mismanaged and even abused. In the context of growing water scarcity in many parts of the world, the vast potential of groundwater and the need to manage it carefully can no longer be overlooked.

The multiple services offered by groundwater

The capacity of groundwater systems to offer various services depends on their geographically varying properties and is dynamically influenced by ongoing natural and human processes.

These services include:

- *provisioning services*, which allow groundwater to be withdrawn for (human) water use purposes;
- *regulatory services*, which reflect the buffer capacity of aquifers to regulate the groundwater systems' quantity and quality regimes;
- *supporting services* on which groundwater-dependent ecosystems (GDEs) and other groundwater-related environmental features rely; and
- *cultural services* linked to leisure activities, tradition, religion or spiritual values, which are associated with particular sites rather than with aquifers.

Groundwater offers a number of additional opportunities, such as expanding geothermal energy generation, enhancing storage for improved water security, and adapting to the impacts of climate change.

The challenges

Groundwater storage depletion occurs when discharge exceeds recharge. Although climate variability and climate change can play a role, most cases of long-term groundwater storage depletion result from intensive abstraction. The rate of global aggregated groundwater storage depletion is considerable: for the beginning of the present century, the estimates are mostly between 100 and 200 km^3/year (accounting for roughly 15 to 25% of total groundwater withdrawals).

Groundwater pollution reduces the suitability of abstracted groundwater for drinking purposes and also affects groundwater-dependent ecosystems.

There are many sources of anthropogenic groundwater pollution: most of them are located at or near the land surface, but several other sources inject pollutants into the subsurface at greater depth below the surface. Agricultural pollution is widespread, it is a diffuse source that often includes large quantities of nitrate, pesticides and other agrochemicals. Groundwater pollution is a virtually irreversible process: once polluted, aquifer zones tend to remain with polluted water.

Groundwater governance

Groundwater *governance* processes enable groundwater management, planning and policy implementation. It takes place at multiple scales and geographic levels, including regional and transboundary scales. Groundwater *management* is action-oriented, focusing on practical implementation activities and day-to-day operations. It occurs more often at the micro- and meso-level.

Because groundwater is often perceived as a private resource (that is, closely connected to land ownership, and in some jurisdictions treated as privately owned), regulation and top–down governance and management are difficult. Governments need to fully assume their role as resource custodians in view of the common-good aspects of groundwater.

In Sub-Saharan Africa, where the opportunities offered by the vast shallow aquifers remain largely underexploited, only 5% of the area equipped for irrigation uses groundwater

Domestic laws and regulations regulate access to groundwater as well as human activities that impact the quality of groundwater. Additional relevant legal instruments include those that: provide access to water for basic needs as a matter of human rights; afford access to groundwater for livelihoods and small-scale productive uses; regulate land uses inimical to the natural groundwater recharge and discharge processes; and regulate the formation and functioning of associations of groundwater users for allocation, monitoring and policing responsibilities. Legal frameworks also need to include protection of discharge and recharge zones and of the area surrounding water supply wells, as well as sustainable yield norms and abstraction controls, and conjunctive use regulations.

In some jurisdictions, groundwater is regulated in conjunction with surface water, including rivers. In instances where there are conflicts between groundwater rights and surface water rights (for instance in the case of a stream that is drying up due to intense groundwater pumping nearby, and vice versa), a conjunctive management approach is warranted.

Point sources of pollution can be regulated through permits as well as through general effluent and/or ambient water quality standards. Non-point source pollution from diffuse or indistinct sources requires prevention measures: regulation of land uses and/or imposition of best agricultural and environmental practices.

Agriculture

Groundwater is a critical resource for irrigated agriculture, livestock farming and other agricultural activities, including food processing. In order to meet global water and agricultural demands by 2050, including an estimated 50% increase in food, feed and biofuel demand relative to 2012 levels, it is of critical importance to increase agricultural productivity through the sustainable intensification of groundwater abstraction, while decreasing the water and environmental footprints of agricultural production.

Where a perennial and reliable source of shallow groundwater exists, groundwater can be an important source for smallholder farmers. Regions heavily reliant on groundwater for irrigation include North America and South Asia, where 59% and 57% of the areas equipped for irrigation use groundwater, respectively. In Sub-Saharan Africa, where the opportunities offered by the vast shallow aquifers remain largely underexploited, only 5% of the area equipped for irrigation uses groundwater.

It is estimated that agricultural pollution has overtaken contamination from settlements and industries as the major factor in the degradation of inland and coastal waters. Nitrate, from chemical and organic fertilizers, is the most prevalent anthropogenic contaminant in groundwater globally. Insecticides, herbicides and fungicides, when improperly applied or disposed of, can pollute groundwater with carcinogens and other toxic substances.

Evidence suggests that laws and regulations to prevent or limit diffuse groundwater pollution from agriculture, and especially their enforcement, are generally weak. Policies addressing water pollution in agriculture should be part of an overarching agriculture and water policy framework at the national, river basin and aquifer scale.

Rural electrification has been a principal driver for groundwater development, especially where rural power grids have been extended into areas that would otherwise have relied on diesel fuel or wind energy. Advances in solar technology have witnessed the development of Solar-Powered Irrigation Systems (SPIS), adopted at scale to service farming operations. However, there is a risk of unsustainable water use if SPIS implementation is not adequately managed and regulated.

Human settlements

The groundwater dependence of innumerable cities appears to be intensifying, such that nearly 50% of the global urban population today is estimated to be supplied from groundwater sources. However, many urban poor live in peri-urban settlements, which are unplanned and lack legal status, and where public water infrastructure and services are not provided.

Groundwater provides the only feasible and affordable way to extend basic water access to unserved rural populations in much of the world

In developing economies, the use of private waterwells for urban self-supply has proliferated in recent years. The practice usually commences as a coping strategy in the face of irregular or inadequate piped water supply, and then continues in perpetuity as a cost reduction strategy to avoid paying higher water tariffs.

The impact of inadequate or inappropriate sanitation on groundwater is observed in urban areas where main-sewer coverage is low and most domestic faecal waste is discharged into pit latrines. Water utilities need to put a much more consistent emphasis on protecting their critical waterwell/springhead sources through restricting agricultural cropping and housing development in their groundwater capture zones, in the interest of safeguarding public health and reducing the cost of water supply.

Groundwater provides the only feasible and affordable way to extend basic water access to unserved rural populations in much of the world. This is especially the case in Sub-Saharan Africa and South Asia where the rural population is large but dispersed.

The coexistence of on-site sanitation and groundwater supply is a serious concern for shallow sources. Persistent contamination of rural groundwater supplies with pathogens is estimated to affect about 30% of the total installations. It will usually impact the marginalized the most (women and girls are often disproportionately more at risk of disease due to pathogens and toxins as a result of their exposure to wastewater).

The settlements, both temporary and permanent, of displaced people require special mention. These settlements often have a high population density but fall between the urban and rural categories. The construction of well-designed waterwells, in conjunction with appropriately cited and well-maintained sanitation systems, is vital in these cases.

Industry

Industries that withdraw groundwater include manufacturing, mining, oil and gas, power generation, engineering, and construction. Industries with a high groundwater dependency via supply chains include the apparel and food and beverage sectors. Various industrial processes make use of groundwater resources, in locations where surface water availability is limited in quantity, but also in situations where quality is important.

The oil, gas and mining industries, through their various activities, may have ample in-house data on the location and extent of aquifers and their properties

The discharge and infiltration into the ground of untreated or only partly treated industrial effluents can pollute groundwater. Human health and the environment can also be put at significant risk as a result of soil contamination and leaching from non-engineered and old industrial dumpsites and legacy mines.

Many production processes need a large amount of water for washing and cleaning their products at the end of production, to separate residues of processing chemicals. The use of groundwater for cooling purposes is very dependent on the location and type of industry and will therefore vary widely from country to country. Underground construction, such as tunnels, frequently require either temporary or permanent dewatering.

Mines in many cases require frequent or continuous dewatering in order to operate, and there is the risk of contaminating a local aquifer, which may be a source of drinking water. The disposal of the water also presents challenges for treatment if it is contaminated by the mining activities. However, the oil, gas and mining industries, through their various activities, may have ample in-house data on the location and extent of aquifers and their properties. Such data could be very useful to hydrogeologists, governments and water supply utilities.

The energy sector can also have profound effects on groundwater quality. Coal used in the generation of thermal electricity can significantly impact groundwater quality as a result of leaching through coal ash waste dumps. Fracking for natural gas, particularly in shallow aquifers, can also present considerable risks of groundwater contamination. Pollution sources include wastewater from formation water, flow-back water, and drilling and fracturing liquids.

The financial sector is now exerting its considerable influence over sustainable investing and this will have a knock-on effect, favouring clients in industry and energy who use groundwater sustainably, and encouraging others to do so.

Ecosystems

Groundwater-dependent ecosystems (GDEs) can be found across a variety of landscapes, ranging from high mountain valleys to the bottom of the ocean and even deserts.

Groundwater discharge supports the baseflows of streams and rivers, a crucial water source that determines their risk of falling dry during periods of drought. Terrestrial ecosystems depend on groundwater in all biomes around the world where it is accessible to plants. Water holes in arid environments are often purely groundwater-fed, and thus groundwater is crucial to sustaining the complex food webs of arid landscapes, such as savannahs. Riparian zones, wetlands and other surface water bodies often depend on groundwater.

GDEs also support critical ecosystem services. Aquatic and terrestrial GDEs provide habitat, support biodiversity, buffer floods and droughts, provide food, and offer cultural services. GDEs play critical roles in protecting aquifers from contamination by ensuring physical separation, by enabling biophysical processes like filtration, biodegradation and sorption of contaminants, and by facilitating and protecting natural recharge.

The shared well-being of groundwater, ecosystems and humans may be enhanced by groundwater management, conjunctive water and land management, nature-based solutions, and improved ecosystem protection. While groundwater management often focuses on groundwater or aquifers themselves, groundwater and ecosystems need to be managed together in order to ensure the continued provision of critical ecosystem services.

Climate change

Climate change directly impacts the natural recharge of groundwater through its influence on precipitation and on leakage from surface waters, including ephemeral streams, wetlands and lakes. Substantial uncertainty persists, however, in global projections of the magnitude of the impacts of climate change on groundwater recharge.

Developing water supplies that are resilient to climate change will, in many parts of world, involve the use of groundwater conjunctively with rivers, lakes and other surface water reservoirs

One observed and widespread impact of climate change influencing groundwater replenishment is the intensification of precipitation. In areas with inadequate sanitation provision, heavy rainfall events can flush faecal microbial pathogens and chemicals through shallow soils to the water table.

Global sea level rise (SLR) has induced seawater intrusion into coastal aquifers around the world. However, the impact of SLR alone on seawater intrusion is often small relative to that of groundwater abstraction. The impacts of climate change on groundwater may be greatest through its indirect effects on irrigation water demand via increased evapotranspiration.

Developing water supplies that are resilient to climate change will, in many parts of the world, involve the use of groundwater conjunctively with rivers, lakes and other surface water reservoirs. Groundwater-based adaptations to climate change exploit distributed groundwater storage and the capacity of aquifer systems to store seasonal or episodic water surpluses. They incur substantially lower evaporative losses than conventional infrastructure, such as surface dams.

The development of geothermal energy, a sustainable energy source, plays an important role in reducing CO_2 emissions. Deep aquifers can also be used for carbon capture and sequestration, the process of storing carbon to curb accumulation of carbon dioxide in the atmosphere.

Regional perspectives

Sub-Saharan Africa

Africa possesses large groundwater resources. While not all of this groundwater storage is available for abstraction, the volume is estimated to be more than 100 times that of the annual renewal of the region's freshwater resources. The development of groundwater has 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. About 400 million people in Sub-Saharan Africa still do not have access to even basic water services.

Most countries in Western and Central Africa have little groundwater storage but high annual rainfall and therefore regular recharge. Conversely, many countries in Eastern and Southern Africa have considerable groundwater storage despite very low levels of recharge. 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.

Only 3% of the total cultivated land in Sub-Saharan Africa is under irrigation, and only 5% of that is irrigated with groundwater. 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. 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, most notably in infrastructure, institutions, trained professionals and knowledge of the resource.

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. The share that groundwater makes up of the total withdrawal of freshwater also varies greatly from one country to another.

In many countries of Europe, groundwater is principally used for drinking water, which underscores the need to control water quality, given the potential health risks. The pollutants that most commonly cause poor chemical status in the European Union are nitrates as well as pesticides. While pollutants from agriculture dominate, industrial chemicals and substances related to mining also lead to chemical groundwater pollution in several river basin districts. More information is needed concerning such 'new' (or 'emerging') pollutants.

In addition to the need for collaboration among different water users within a given country, there is an increasing awareness of the transboundary nature of many groundwater resources, and, therefore, of the need for interjurisdictional cooperation.

Groundwater monitoring and expertise is commonly held by specialized institutions, while the implementation of water policy instruments 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.

Latin America and the Caribbean

Due to the relative abundance of surface water and the limited level of groundwater use, less than 30% of the freshwater abstracted in Latin America and the Caribbean comes from groundwater sources. In 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.

Most groundwater resources in the Arab region are non-renewable, and must be managed with a view to the fact that they are a finite resource

Throughout the region, there are shortcomings in the protection and monitoring of groundwater, giving way to its intensive exploitation and/or contamination, ultimately endangering its sustainability as well as its accessibility to the most vulnerable populations, who depend on these groundwater sources for their drinking water supply.

Groundwater plays an important role in the water supply systems of most Latin American cities, even though not always as the main source of supply. It also represents 50% of the water used by the industrial sector. In the Caribbean, where surface water tends to be relatively scarce, groundwater represents about 50% of the water abstracted.

As the importance of aquifers for the region´s ecosystems, social development and economic activities will only further increase in the near future, the region needs to move towards political processes that harmonize decision-making, monitoring and groundwater management both nationally and internationally.

Asia and the Pacific

The Asia-Pacific region is the largest groundwater abstractor in the world, containing seven out of the ten countries that extract most groundwater (Bangladesh, China, India, Indonesia, Iran, Pakistan and Turkey). These countries alone account for roughly 60% of the world's total groundwater withdrawal.

These socio-economic benefits of groundwater use are particularly crucial for the agricultural sector. The industrial and municipal sectors are also important users. While groundwater is abundant across most of the region, its 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.

Groundwater contamination from both anthropogenic and geogenic processes is an additional concern. The impacts of climate change on precipitation variability further exacerbate pressure on groundwater resources, particularly in areas with semi-arid to arid climates and on Small Island Developing States.

While management practices and institutional, legal and regulatory systems to address groundwater issues exist throughout the region, groundwater governance is challenging due to the unrestricted access regime in place in many countries. Improved groundwater governance, with popular support and enforcement capacity, is critically needed.

The Arab region

The Arab region is one of the most water-scarce in the world and groundwater is the most relied-upon water source in at least 11 of the 22 Arab states. 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 particularly alarming as groundwater is the primary source of water for vulnerable groups that are not formally connected or do not have access to public sources. Unsustainable agricultural practices, as well as industries and urbanization, are significantly impacting groundwater quality.

Most groundwater resources in the Arab 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. Unfortunately, only very few cases of groundwater cooperation exist in the region.

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

Building and updating the knowledge base

Groundwater data collected with public funds should be freely accessible

The UN *Summary Progress Update 2021 on SDG 6* raises the issue of the lack of groundwater data and groundwater monitoring initiatives, emphasizing that groundwater monitoring is a 'neglected area'.

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 recharge is usually estimated rather than directly measured. Highly vulnerable aquifers that provide services to people and the environment need to be monitored more frequently.

Scientific knowledge in hydrogeology and the methods and tools available are sufficient to address most groundwater management issues. The challenge lies more with the scarcity of reliable data for area-specific groundwater assessments and scenario analyses. Since all aquifers and their boundary conditions are unique, it is crucial to have groundwater assessments at field level to enable informed policies and management of groundwater resources.

Although often relatively expensive, monitoring is a wise investment: identifying problems at an early stage can be highly cost-effective, allowing mitigation measures to be introduced before serious deterioration of the resource takes place. Conventional monitoring programmes can be augmented by citizen science initiatives, which can also promote the integration of local knowledge into hydrogeological characterization and groundwater system assessments. Remote sensing techniques have also been used by the scientific community to improve monitoring and estimation of groundwater resources.

The sharing of data and information is often deficient, especially in low-income countries. Groundwater data collected with public funds should be freely accessible. 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.

In many low- and middle-income countries, hydrogeological capacity is missing, even when groundwater makes up the largest part of their managed water resources. This often comprises both technical and institutional capacity.

Policy and planning

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 groundwater system services and functions.

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

Any national 'groundwater management vision' needs to be 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. Groundwater policy should be contingent on the legal status and nature of ownership of groundwater (public or private), as well as on factors like the water users, the interrelated surface water features, and the land uses in aquifer recharge areas. 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.

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. Plans can be prepared as a cooperative effort between national ministries, provincial and local agencies, and other 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.

Groundwater management

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

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. However, not all management occurs through government. Communities and/or groundwater users themselves may independently choose to manage well siting and groundwater abstractions.

The most sustainable and cost-effective approach to managing groundwater quality is to ensure its adequate protection, thus avoiding contamination. This can be achieved through vulnerability mapping, development of groundwater protection zones and land use planning.

Particular attention should be given to the conjunctive management of surface water and groundwater resources and to the potential for 'nature-based' solutions. Integration with environmental management, land use management, and management of space and resources of the subsurface are all important issues within the purview of integrated management.

Managed aquifer recharge (MAR) is an integrated approach that allows 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 and recycled water, to be made available for productive use when needed. At the watershed scale, MAR can be used to maintain environmental water flows and their availability, creating lags in water discharges to a stream. The application of MAR has increased by a factor of 10 over the last 60 years, but there is still ample scope for further expansion, from the current 10 km^3/year to probably around 100 km^3/year.

Transboundary aquifers

Transboundary aquifers include a natural subsurface path of groundwater flow crossing an international boundary. Actions on the aquifer in one country, such as heavy abstraction or contamination, can have a significant impact on the other side of the border.

Frequently, transboundary aquifers are made part of broader water cooperation agreements developed for transboundary river basins

Transboundary aquifer management often suffers from a lack of institutional will and insufficient resources to collect the necessary information, especially at the local level. Coordinating, harmonizing and sharing data represents the first step in cooperation between neighbouring countries. These actions are essential to reaching an agreement about a reliable conceptual model of the aquifer, which in turn is a prerequisite for the formulation of management plans. The integration of gender considerations into transboundary cooperation generates opportunities for more socially equitable groundwater management.

International water law was initially developed for surface waters, but ever more frequently, transboundary aquifers are made part of broader water cooperation agreements developed for transboundary river basins. This illustrates the growing awareness of the importance of transboundary aquifers.

Scientific cooperation initiatives, in the framework of technical projects on transboundary aquifers, exist around the world. 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 and information, or when confidence is lacking.

Financing

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. 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. In some countries, there may be an abstraction fee or a groundwater tariff, but these fees and tariffs rarely reflect the true costs and value of the resource.

Governments need to assess and accept their potential role in promoting the sustainability of groundwater resources in accordance with the local conditions, 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 costs – and leverage private investment by funding initial exploratory and management initiatives.

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. This would allow to further leverage existing funding from official development assistance, from water supply and sanitation tariffs, and even from public–private partnerships. Fees and taxes in other sectors, such as in agriculture, can also help finance groundwater initiatives and reduce potential negative externalities.

In many countries, publicly funded activities in other sectors contribute to the depletion or pollution of groundwater 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. Reforming harmful subsidies and aligning them with groundwater policies should be part of the water financing agenda.

Moving forward

It is essential that countries commit themselves to developing an adequate and effective framework for groundwater governance

The General Assembly of the United Nations (UN), 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, and – since groundwater is an essential component of water supply and sanitation – to groundwater protection and aquifer recharge.

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). 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.

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.

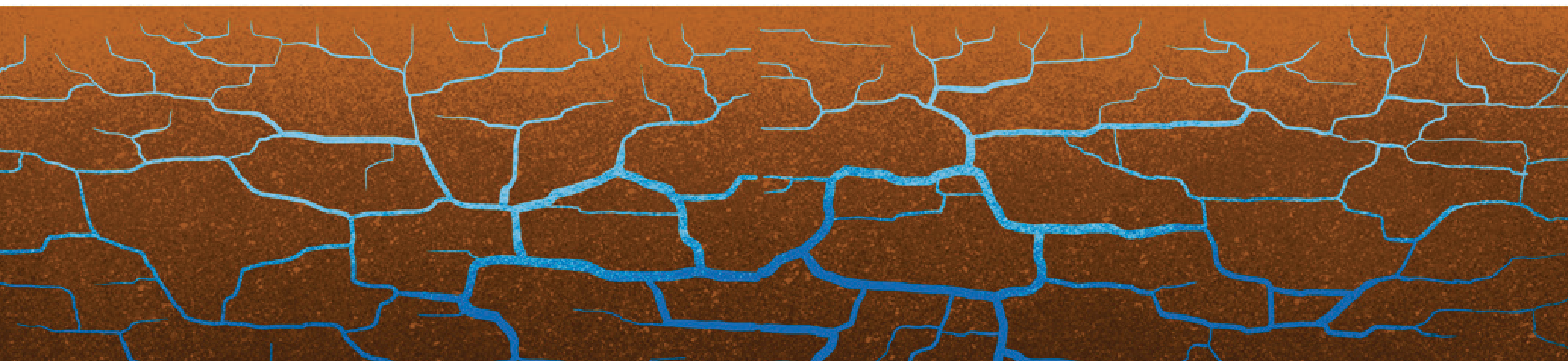
However, in spite of its overall abundance, groundwater remains vulnerable to overexploitation and pollution, both of which can have devastating effects on the resource and its availability. Unlocking the full potential of groundwater will require strong and concerted efforts to manage and use it sustainably.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

Prologue

State of groundwater resources

WWAP

Michela Miletto, Jac van der Gun and Richard Connor



As a prelude to the *World Water Development Report 2022*, this Prologue presents aggregated statistics, figures and other information on selected overall characteristics and the state of the world's water resources, as well as on observed trends. The numerical information aggregated at global, continental or regional scales is based on countless uncoordinated observations on variables that are difficult to assess, while documentation on their processing is usually lacking. Therefore, this information is unavoidably subject to significant uncertainty, even to the extent that different versions of the same variable are circulating. Despite these uncertainties, it is believed that the presented information will facilitate the understanding of the macroscopic setting and context of the groundwater themes discussed across the different chapters of the report, provided that the mentioned flaws are properly taken into account.

Freshwater volumes

Water is the most abundant liquid on Earth, but most of it is saline. Over the years, several scientists have published estimates of the global volume of freshwater. Shiklomanov and Rodda (2003) highlight the estimate by Garmonov published in Korzun (1974), according to which the global volume of liquid freshwater (less than 1% of all water on Earth in liquid, frozen or vapour form) is estimated to be 10.6 million km³, which is equivalent to a layer of water of 79 m (equivalent depth) over the entire land area of the globe, excluding Antarctica. Approximately 99% of this volume consists of groundwater, and only 1.4 million km³ of stored groundwater is 'modern', which means it entered the subsurface less than 50 years ago (Gleeson et al., 2016). More recent estimates of the global volume of freshwater include those of Kotwicki (2009): 11.1 million km³, and by Ferguson et al. (2021): 15.9 million km³ (only the fresh groundwater component). All estimates are partly based on rather arbitrary assumptions, therefore it is not possible to decide which estimate is the most realistic one. Evidently, these estimates are subject to a large margin of uncertainty.

Like freshwater volumes, the rates of freshwater renewal are also subject to considerable spatial variation

The freshwater volume is irregularly distributed over the continents, which is partly explained by differences in the size of the continents, partly by differences in the mean volume of freshwater per unit of area. A breakdown by Korzun (1974), based on Garmonov's estimate, is shown in Figure 1. At the scale of countries and smaller territories, the spatial variation in equivalent water depth is much more pronounced, with values ranging from zero to almost two thousand metres.

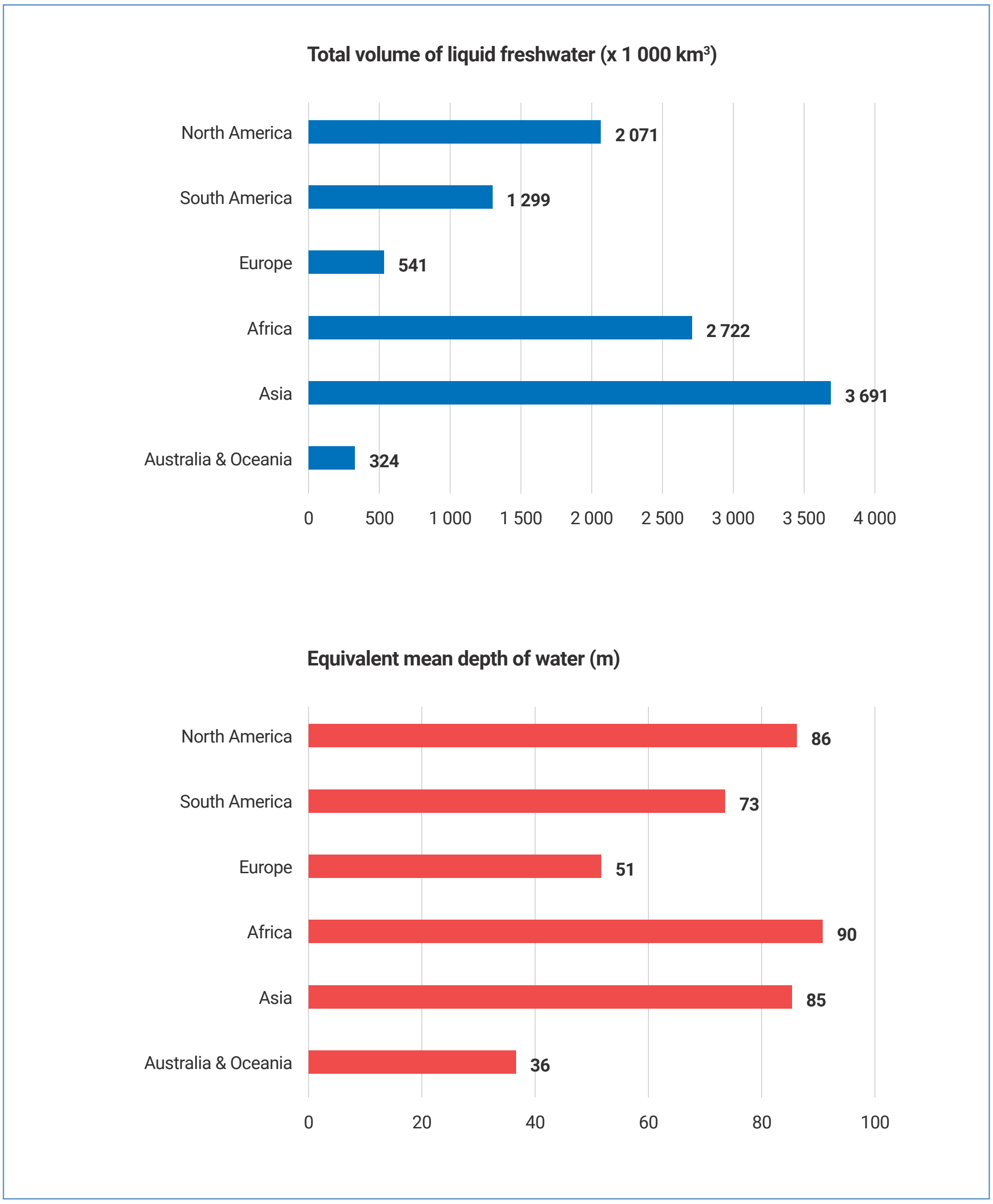
Variations of freshwater volumes over time, such as those caused by seasonal climatic variation, climate change and intensive exploitation, have during the time span of a human life no noticeable effect on the volumes shown in Figure 1. However, the same variations may, within the same time-frame, have drastic impacts on local or regional scales. Examples are: (a) shrinking lakes such as Lake Chad, the Aral Sea, Lake Urmia, the Great Salt Lake and Lake Poopó (Wurtsbaugh et al., 2017); (b) the disappearance of numerous springs around the world; declining flows in rivers like the Yellow River, the Ganges, Rio Grande, Congo and Murray-Darling rivers (Shi et al., 2019); and (c) steadily falling groundwater levels in intensively exploited aquifer systems, including the Ganges-Brahmaputra basin, the North China Plain and the Central Valley in California (Shamsudduha and Taylor, 2020).

Freshwater renewal

The rate of renewal defines the theoretical upper limit of sustainable water withdrawal. Freshwater renewal (essentially the water in the terrestrial part of the water cycle that is kept in motion), replaces volumes discharged from streams, soils and aquifers, and enables humans to withdraw water sustainably. Like freshwater volumes, the rates of freshwater renewal are also subject to considerable spatial variation. Even when aggregated to the level of continents, they show marked differences (Figure 2).

Figure 1

Estimated volumes of liquid freshwater present on the different continents

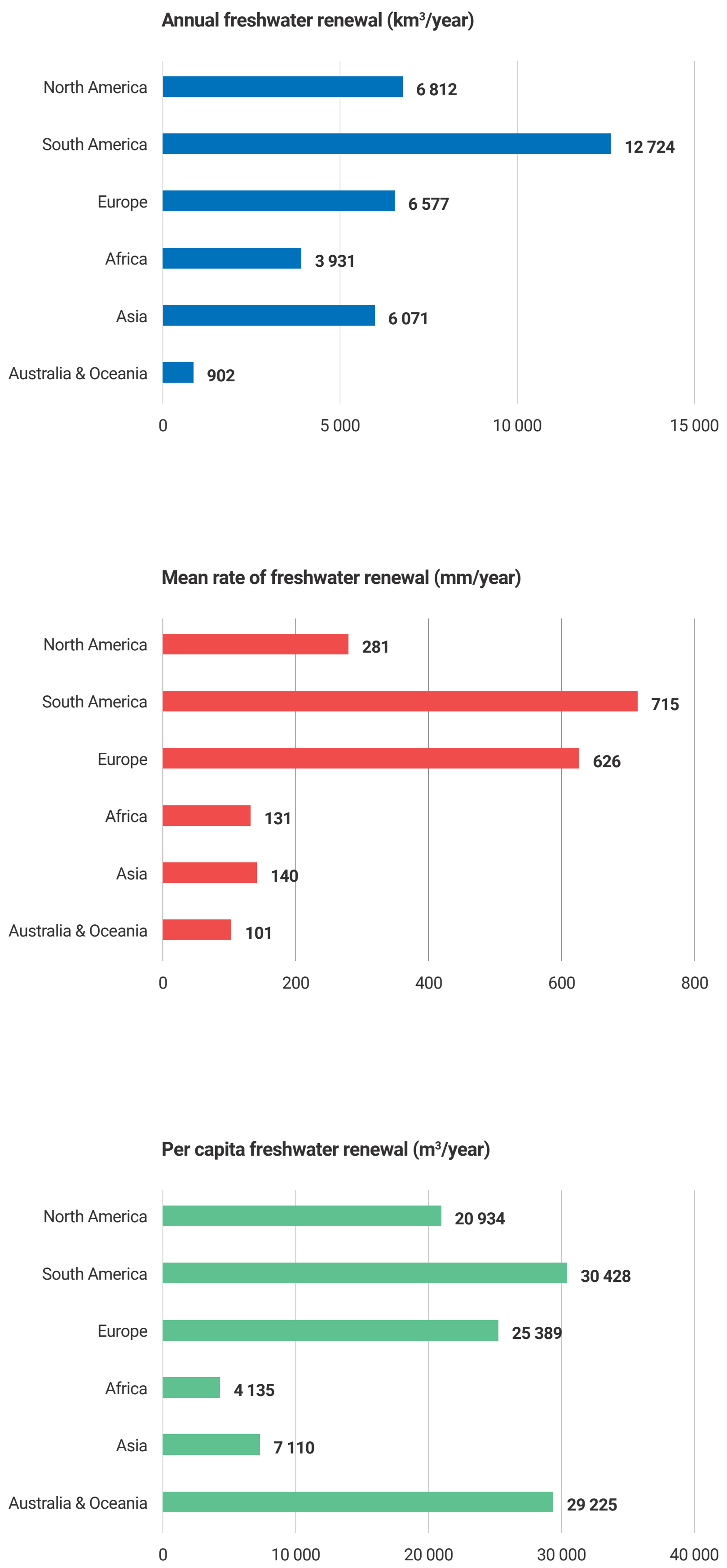


Source: Shiklomanov and Rodda (2003), based on data from Korzun (1974).

Obviously, the differences in the share of each continent in the global volume of freshwater renewal (mean value: 37,000 km³/year) are partly caused by variations in the size of the continents, but there are also significant differences in the rate of renewal per unit of area (water depth in mm per year). Average freshwater renewal depths for the comparatively wet continents South America and Europe are four to seven times higher than those for Asia, Africa, and Australia & Oceania, continents that each include vast arid and semi-arid territories. According to the data presented by Ritchie and Roser (2017), the mean annual freshwater renewal averaged over the total global land surface (excluding Antarctica) equals a water depth of 274 mm – only 0.35% of the average depth of stored freshwater, which implies a mean residence time of almost three hundred years. Africa and Asia have the lowest per capita freshwater renewal rates.

Figure 2

Estimated freshwater renewal on the different continents, 2015



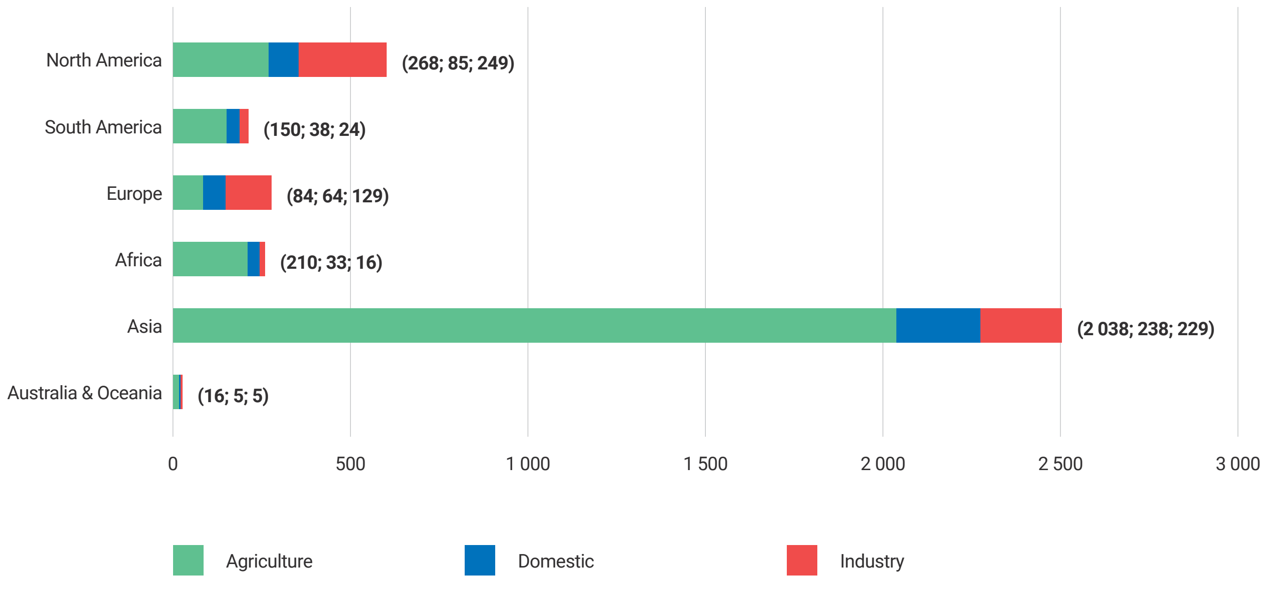
Source: Ritchie and Roser (2017), based on data from Aquastat.

Freshwater withdrawal, water stress and water scarcity

Freshwater withdrawal from streams, lakes, aquifers and human-made reservoirs (so-called 'blue water' sources) has increased strongly during the last century, and is still increasing in most parts of the world. Global freshwater withdrawal was probably around 600 km³/year in 1900 and increased to 3,880 km³/year in 2017, according to recent estimates (United Nations, 2021; Aquastat, n.d.). The rate of increase was especially high (around 3% per year) during the period 1950–1980, partly due to a higher population growth rate, and partly to rapidly increasing groundwater development, particularly for irrigation. The rate of increase is nowadays approximately 1% per year, in tune with the current population growth rate.

As shown in Figure 3, Asia has the largest share in global freshwater withdrawal (64.5%). It is followed by North America (15.5%), Europe (7.1%), Africa (6.7%), South America (5.4%) and Australia & Oceania (0.7%).

Figure 3 Freshwater withdrawal in 2017, aggregated by continent and by water sector use (km³/year)



Source: Based on data from Aquastat (n.d.).

Comparison with the renewal estimates (Figure 2) shows that at the global scale the freshwater withdrawal rate has reached 10.5% of the mean annual freshwater renewal rate. These percentages vary significantly between the continents: high for Asia (41.3%), low for South America (1.7%) and Australia & Oceania (2.9%), with in-between values in Africa (6.6%), North America (8.8%) and Europe (4.2%).

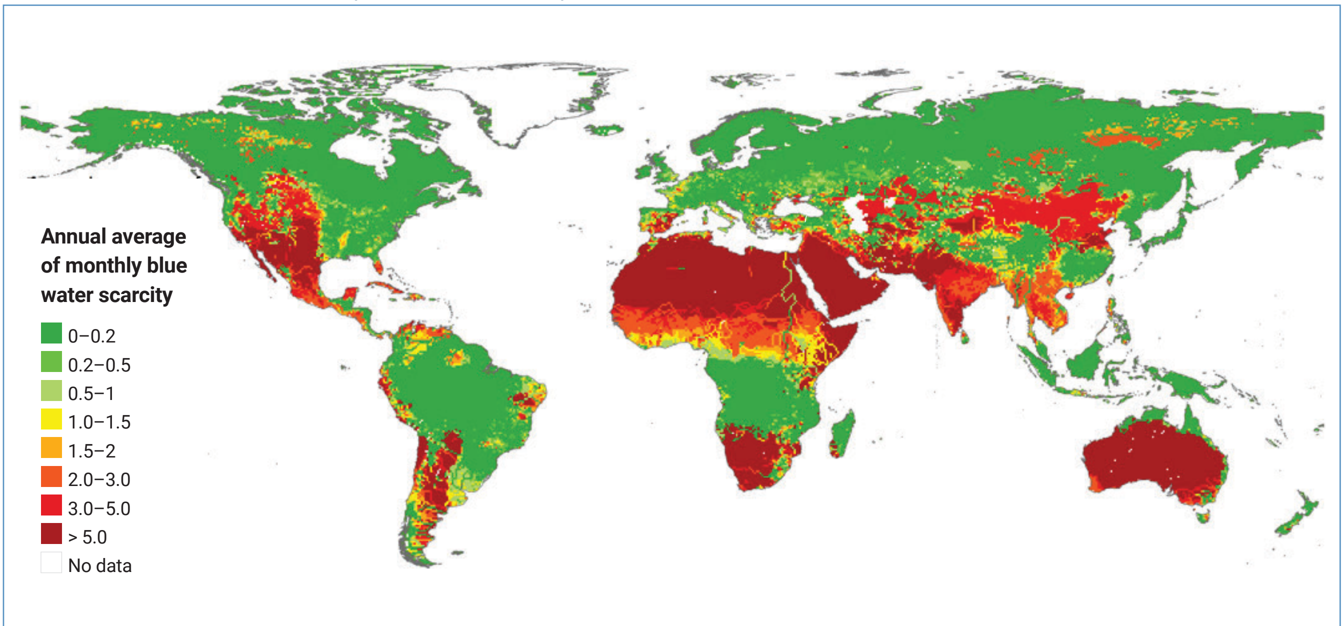
While the rate of increase in freshwater use has levelled off in most developed countries, it continues to grow in the majority of the emerging economies, as well as in middle- and lower-income countries. Globally, water use is expected to grow by roughly 1% per year over the next 30 years, driven by increasing demand in the industry and energy sectors as well as by municipal and domestic uses, mainly as a function of industrial development and improving water and sanitation service coverage, in combination with population growth, economic development and shifting consumption patterns (United Nations, 2021).

Withdrawal as a percentage of renewal is an often-used water stress indicator, but when applied to large aggregated areas and to mean annual data, it is rather ineffective for detecting zones that experience water stress. The indicator becomes more meaningful when used with a higher spatial resolution and taking into account seasonal variation, but it still has some flaws, notably as environmental flows and return flows of the non-consumed fraction of withdrawn water are ignored, while it often remains uncertain how the indicator scores need to be interpreted.

An estimated four billion people live in areas that suffer from severe physical water scarcity for at least one month per year

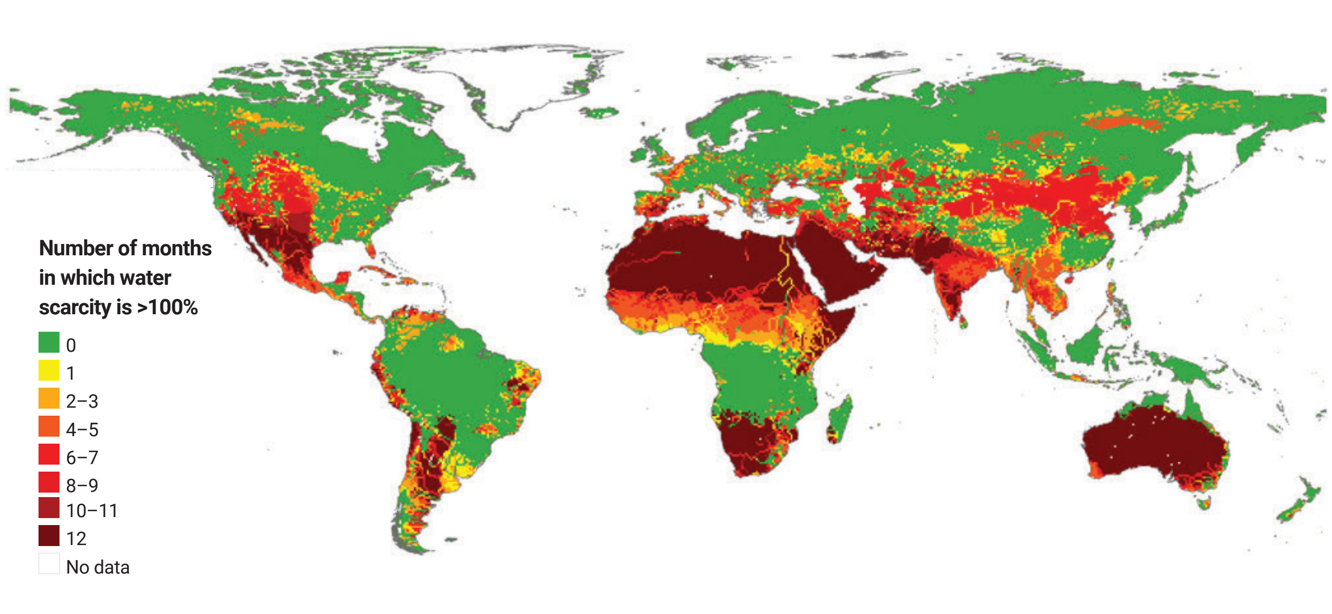
These shortcomings have been addressed in the blue water scarcity indicator, introduced by Mekonnen and Hoekstra (2016). This indicator is defined as the blue water footprint divided by blue water availability. Blue water footprint refers to 'blue water consumption' or 'net water withdrawal' and is equal to the volume of 'blue water' (= fresh surface water and groundwater combined) that is withdrawn and not returned to groundwater or surface water systems because the water evaporated or was incorporated into a product. Blue water availability over a given area is calculated as the sum of runoff generated in that area and received from upstream, minus the environmental flow requirements of all contributing areas, and minus the water footprint in all upstream contributing areas. Figure 4 shows the simulated annually averaged global pattern of blue water scarcity, while Figure 5 (based on simulations per calendar month) indicates the number of months per year in which blue water scarcity exceeds 1.0, indicating an unsustainable rate of withdrawal. An estimated four billion people live in areas that suffer from severe physical water scarcity for at least one month per year (Mekonnen and Hoekstra, 2016). Typical responses for areas where annual scarcity values exceed 1.0 include water transfers from neighbouring water-surplus areas (if available), or depleting stored water volumes of lakes, surface water reservoirs, and – above all – aquifers.

Figure 4 Annual average monthly blue water scarcity at 30x30 arc min resolution, 1996–2005



Source: Mekonnen and Hoekstra (2016, fig. 2, p. 3).

Figure 5 The number of months per year in which blue water scarcity exceeds 1.0, 1996–2005



Source: Mekonnen and Hoekstra (2016, fig. 3, p. 3).

Groundwater resources and their geographical distribution

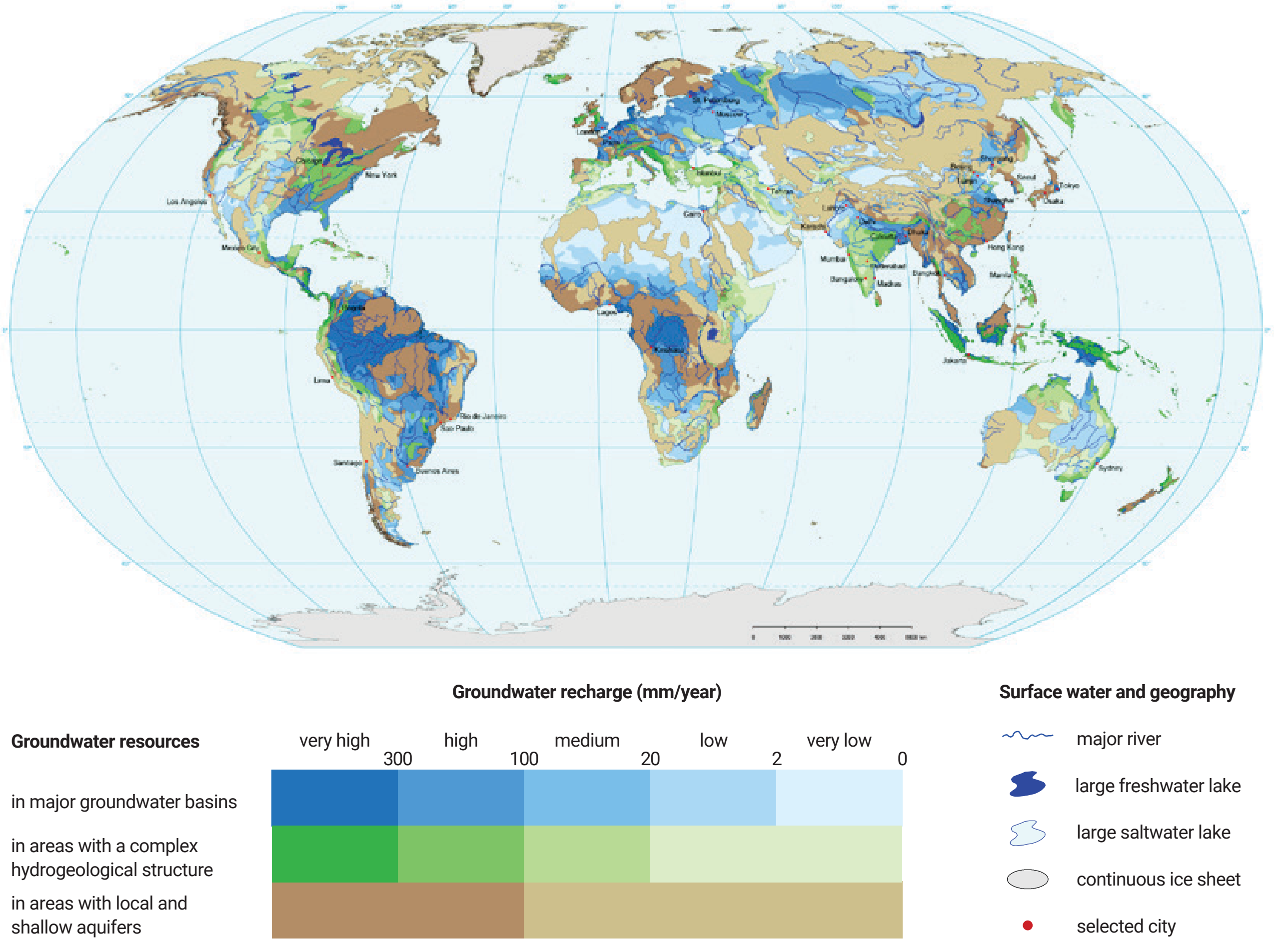
Large volumes of fresh groundwater are present below ground surface and distributed over the entire globe, but their abundance and the conditions for their withdrawal are subject to considerable spatial variation. In order to be productive, wells have to extend into geological formations that are characterized by comparatively high porosity and permeability (so-called 'aquifers', see Chapter 1), and filled with fresh groundwater. Hydrogeological maps show the patterns and boundaries of zones where such favourable formations are encountered (aquifers), alternating with zones dominated by formations that are unable to yield significant quantities of water to wells. The suitability of a certain location or zone for groundwater withdrawal depends furthermore on the rate of replenishment of the tapped aquifer (groundwater recharge) and on water quality. Recharge enables groundwater to be abstracted sustainably; if it is absent or minimal, then groundwater abstraction depletes the stored groundwater volume.

Large volumes of fresh groundwater are present below ground surface and distributed over the entire globe, but their abundance and the conditions for their withdrawal are subject to considerable spatial variation

Figure 6 shows a simplified hydrogeological map at the global scale. It shows major groundwater basins (blue colour) on all continents, part of them endowed with high to medium recharge rates, other ones (in arid and permafrost zones) not or only poorly recharged. These major groundwater basins contain the lion's share of all fresh groundwater stored on Earth and they present in general the most favourable conditions for groundwater abstraction. Areas with a complex hydrogeological structure (green colour) contain thick sequences of formations that also transmit significant quantities of groundwater (often stored and flowing in fissures rather than in pores), but their productivity tends to be less than that of the major groundwater basins, on average. The third main mapping unit (brown colour) represents the less favourable areas for groundwater development, but it should be noted that this is only a macroscopic characterization, not appropriate for local-scale assessments. Besides non-productive zones, this unit includes numerous relatively small and/or shallow aquifers that may be of enormous local or regional importance. For local projects, local-scale hydrogeological maps should be consulted.

Fresh and brackish groundwater does not only occur in the underground of continents and islands: it is also present offshore. Figure 7 shows the results of a recent inventory of such occurrences. Minor parts of these offshore fresh or brackish groundwater bodies may receive some contemporaneous recharge (by lateral inflow from a connected on-land groundwater system), but most of them are non-renewable resources. The feasibility and attractiveness of exploiting these offshore fresh and brackish water bodies for water supply in the future still has to be explored.

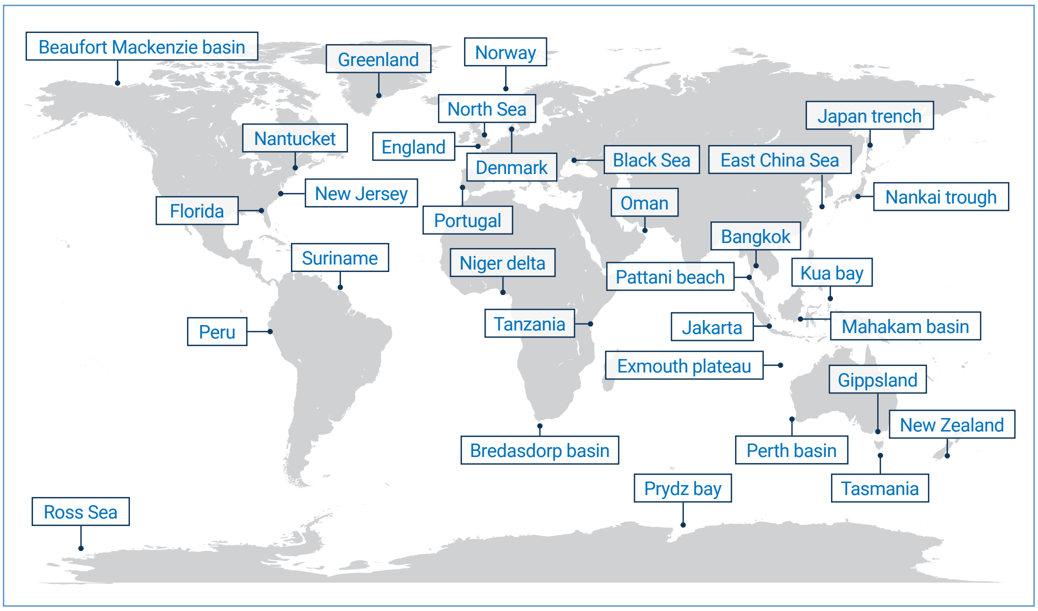
Figure 6 Groundwater resources of the world



Source: BGR/UNESCO (2008).

Figure 7

World map of known occurrences of fresh and brackish offshore groundwater



Source: Based on Post et al. (2013, fig. 1, p. 72).

Groundwater withdrawal and use

In response to quickly increasing water demands and catalysed by technical, scientific and economic progress, groundwater withdrawal has boomed during the 20th century in most countries of the world, reaching unprecedented levels at the beginning of the present century. Table 1 presents estimates of groundwater withdrawals during 2017, aggregated by region and by continent. According to this table, the total global groundwater withdrawal in 2017 was 959 km³, unevenly distributed across the globe.[1] It catches the eye that two-thirds of this quantity was withdrawn in Asia, with prominent shares in South and East Asia. North America is second in ranking by continent, with a share of 16% of the global groundwater withdrawal. Indeed, eight of the ten countries with the highest shares in global groundwater withdrawal (accounting for 75% of the total) are located in Asia (in descending order: India, China, Pakistan, Iran, Indonesia, Bangladesh, Saudi Arabia and Turkey), and two in North America (the United States of America (USA) and Mexico) (see Table 5.1). In spite of the fact that Africa accounts for about 17% of the global population (1.4 billion), its groundwater withdrawal is comparatively low, accounting for slightly less than 5% of the global total. Australia & Oceania, with its low population size, also has a very low share in global groundwater withdrawal.

In spite of the fact that Africa accounts for about 17% of the global population (1.4 billion), its groundwater withdrawal is comparatively low, accounting for slightly less than 5% of the global total

Comparison with estimates previously made for 2010 (Margat and Van der Gun, 2013) shows that the total global withdrawal rate has not significantly changed between 2010 and 2017. Nevertheless, at the regional level, percentages of change vary considerably. Although these percentages look rather pronounced for some of the regions, they do not yet allow to draw firm conclusions on trends, since the calculated differences may be caused by interannual climatic variation or even by inconsistencies in reporting by national agencies. After inspection of time series of annual records, it appears that groundwater withdrawal rates in most European countries have stabilized, or are even slightly declining. The same seems to be the case in Northern North America (i.e. Canada, USA and Greenland) and in South and East Asia. Apparently, groundwater withdrawal in the corresponding countries has reached intensities beyond which expanding is no longer desirable or feasible.

Table 1 shows also that, at the global level, groundwater withdrawal currently corresponds to 25% of the total freshwater withdrawal. The percentages vary between the continents: low for South America, a large part of which is endowed with abundant permanent surface water resources, and high for Australia & Oceania, where such surface water resources are scarce.

A breakdown of groundwater withdrawal by water use sector is presented in Table 2. It shows that 69% of the total volume is abstracted for use in the agricultural sector, 22% for domestic uses, and 9% for industrial purposes. These percentages vary between the continents. The Chapters 3, 4 and 5 of this report provide more information on the different human uses of groundwater, while Chapter 6 addresses in-situ groundwater services in support of ecosystems.

Area-specific natural constraints to groundwater withdrawal

Obviously, the absence of productive aquifers in a given area forms a primary constraint to the withdrawal of groundwater. Hydrogeological maps provide guidance on the occurrence or absence of such aquifers. However, there are more natural constraints to groundwater withdrawal; a few important ones are mentioned and briefly described below.

Groundwater quality deficiencies form a major constraint to groundwater withdrawal. Although most groundwater within a few hundred metres below the land surface is fresh, more than half of all groundwater under the globe's land surface is saline and therefore unsuitable for most types of water use. High groundwater salinity prevails in the deeper domains of sedimentary basins (paleo-salinity), but in many zones scattered over the world it is also observed at shallower depths, for instance in coastal areas and in zones with very shallow water table in arid climates (Van Weert et al., 2009). In addition, in some areas fresh groundwater does contain natural contaminants in excessive concentrations, for instance arsenic and fluoride.

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[1] Data that came available shortly before final editing of this report point to a global groundwater withdrawal of 978 km³ for 2018. The difference with the 2017 estimate lies within the margin of interannual variations and reporting inaccuracies.

Table 1 Groundwater withdrawals in 2017, aggregated by the world's major regions

Continent and region	Groundwater withdrawal (km³/year)	% change since 2010	% of total freshwater withdrawal
North America	156	0	26
Northern North America	113	-1	24
Central America	37.1	+12	38
Caribbean	6.5	-37	27
South America	27	+6	13
Northern and Eastern South America	7.9	-32	9
Andean countries	4.7	-22	11
Southern South America	14.7	+83	19
Europe	65	-6	23
Northern Europe	4.7	-3	20
Western Europe	15.2	+1	22
Eastern Europe	15.2	-24	18
Southern Europe	29.7	+1	31
Africa	45	+10	20
Northern Africa	26.2	+24	21
Western Africa	8.0	+9	28
Central Africa	2.1	-21	72
Eastern Africa	6.3	-6	13
Southern Africa	2.8	-16	14
Asia	657	-4	26
Northern Asia	3.1	-10	15
Central Asia	2.7	-85	2
Western Asia	63.7	-3	39
South Asia	401	-5	39
East Asia	132	-6	18
Southeast Asia	54.2	+54	11
Australia & Oceania	8	+21	31
Australasia	7.5	+30	29
Micro-, Mela- and Polynesia	0.6?	-36?	79?
World	959	-2	25

Source: Estimates based on Aquastat (n.d.), Eurostat (n.d.), and Margat and Van der Gun (2013).

Another constraint to groundwater withdrawal is depth below the land surface. If very deep boreholes have to be drilled to tap productive aquifers, or if groundwater levels are deep below the surface, then for most people and intended purposes the cost of well construction or of pumping may become prohibitive for abstracting groundwater. This constraint tends to enlarge differences in access between poor and wealthier segments of the local society.

Table 2 Breakdown of 2017 groundwater withdrawal by water use sector and by continent

	Groundwater withdrawal		Volumes by water use sector			Percentages by water use sector		
	(km³/year)	% of world	Agriculture	Domestic	Industry	Agriculture	Domestic	Industry
North America	156	16	97	48	12	62	30	7
South America	27	3	13	9	5	49	32	20
Europe	65	7	24	29	12	36	45	19
Africa	45	5	29	14	2	65	32	4
Asia	657	68	496	107	53	76	16	8
Australia & Oceania	8	1	4	4	0	48	48	3
World	**959**	**100**	**664**	**211**	**84**	**69**	**22**	**9**

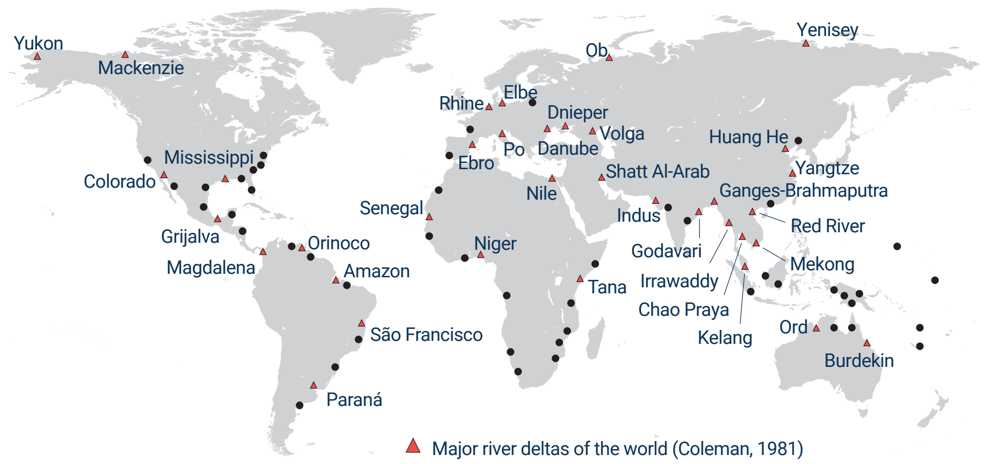
Source: Estimates based on Aquastat (n.d.), Eurostat (n.d.), and Margat and Van der Gun (2013).

Furthermore, near-shore groundwater withdrawal in coastal aquifers may trigger seawater intrusion, which will put an end to the local withdrawal of fresh groundwater. Sea level rise will similarly reduce groundwater withdrawal from low-lying coastal aquifers. Figure 8 shows global hotspots of zones vulnerable to seawater intrusion and to sea level rise. A somewhat similar physical condition constraining fresh groundwater withdrawal is the presence of saline or brackish groundwater underneath and hydraulically connected with shallow fresh groundwater. Fresh groundwater withdrawal in such areas (often also in coastal zones) tends to be hampered by upconing saline or brackish water.

Finally, groundwater-dependent ecosystems and shallow compressible sediment layers hydraulically connected to aquifers are additional components of the natural environment that may impose constraints on groundwater withdrawal, if ecosystem degradation and land subsidence have to be prevented. Global hotspots of land subsidence induced by groundwater withdrawal are shown in Figure 9.

Figure 8

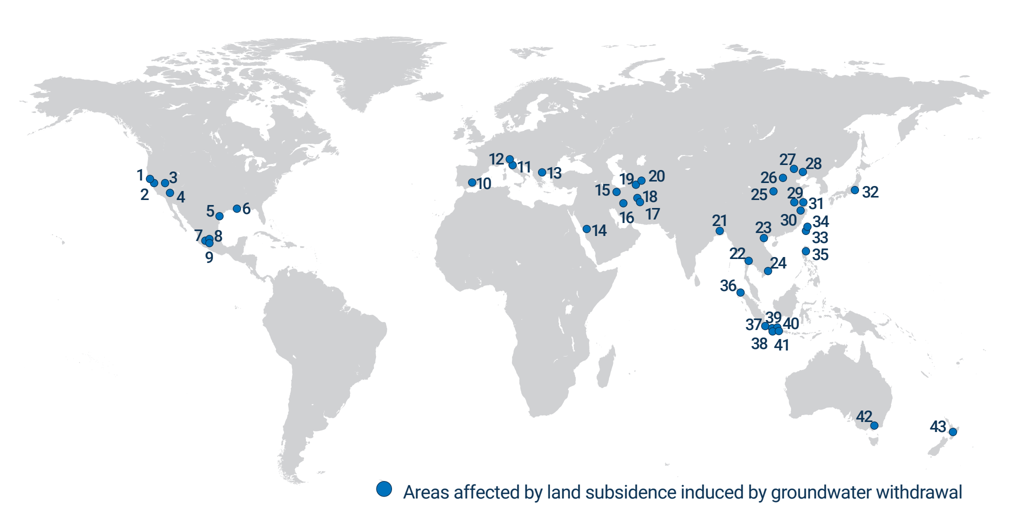
Global hotspots of groundwater vulnerability to seawater intrusion and sea level rise



Source: Based on Oude Essink et al. (2010, fig. 1, p. 2).

Figure 9

Global hotspots of land subsidence induced by groundwater withdrawal



Source: Based on Guzy and Malinowska (2020, fig. 1, p. 4).

Note: United States of America: 1. Santa Clara Valley; 2. San Joaquin Valley; 3. Las Vegas; 4. Eloy Basin; 5. Houston; 6. New Orleans. Mexico: 7. Celaya; 8. Zamora de Hidalgo; 9. Mexico City. Spain: 10. Lorca. Italy: 11. Ravenna; 12. Venice. Greece: 13. Saloniki region. Saudi Arabia: 14. Wadi Al-Yutama. Iran: 15. Tehran; 16. Yazd; 17. Rafsanjan; 18. Zarand; 19. Kashmar; 20. Mashad. India: 21. Kolkata. Thailand: 22. Bangkok. Vietnam: 23. Hanoi; 24. Ho Chi Minh. China: 25. Xian; 26. Taiyuan; 27. Beijing; 28. Tianjin; 29. Su-Xi-Chang; 30. Hangzhou-Jiaxing-Huzhou; 31. Shanghai. Japan: 32. Tokyo. Taiwan Province of China: 33. Yunlin; 34. Taipei. Philippines: 35. Manila. Indonesia: 36. Medan; 37. Jakarta; 38. Bandung; 39. Blanakan; 40. Pekalongan; 41. Semarang. Australia: 42. Latrobe Valley. New Zealand: 43. Wairakei.

Chapter 1

Introduction

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1.1 Purpose and scope of this report

The purpose of this edition of the *United Nations World Water Development Report* (WWDR 2022) is to shine a spotlight on groundwater, calling attention to its specific roles, challenges and opportunities in the context of water resources development, management and governance across the world.

Groundwater, accounting for approximately 99% of all liquid freshwater on Earth (Shiklomanov and Rodda, 2003), provides societies with tremendous opportunities for social, economic and environmental benefits, including potential contributions to climate change adaptation and to achieving the Sustainable Development Goals (SDGs). Its contribution to satisfying water demands is considerable. For example, groundwater provides 49% of the volume of water withdrawn for domestic use by the global population (Aquastat, n.d.; Margat and Van der Gun, 2013) and around 25% of all water withdrawn for irrigation, serving 38% of the world's irrigated land (Aquastat, n.d.; Margat and Van der Gun, 2013; Siebert et al., 2013). Yet, despite its enormous importance, this natural resource is often poorly understood, and consequently undervalued, mismanaged and even abused. In the context of growing water scarcity in many parts of the world, the vast potential of groundwater and the need to manage it carefully can no longer be overlooked.

Groundwater accounts for approximately 99% of all liquid freshwater on Earth

Groundwater is intimately interconnected and interacting with many other components of the Earth's physical environment. This can be observed in the water cycle, where atmospheric water and surface water upon percolating to the subsoil become groundwater, which – in turn – sooner or later either discharges into surface water bodies or into the sea, or returns to the atmosphere through evaporation. Similar transformations take place in the water use chain, an anthropogenic side-branch of the water cycle: when groundwater or surface water is withdrawn, this raw water is in some cases by treatment converted into potable groundwater, it is supplied to users, and the non-consumed part of it subsequently becomes wastewater that is discharged – treated or untreated – to groundwater or surface water systems. Groundwater also participates in numerous other natural cycles and processes, and it plays an important role in sustaining human health, livelihoods, economic development and ecosystems. Awareness of these interlinkages has led to the widely shared view that groundwater development and management should take place in integrated approaches. However, this does not detract from the critical need to properly understand the specific facets of groundwater and of the processes it is involved in. This report intends to contribute to this understanding.

This first chapter of the report presents basic concepts and terminology related to groundwater and aquifers[2] in the context of global perspectives and initiatives, and summarizes the main challenges and opportunities related to groundwater. The next chapter addresses legal and other institutional aspects of groundwater governance. The subsequent chapters describe groundwater from the perspective of the three main water use sectors in human society: agriculture (Chapter 3), human settlements (Chapter 4) and industry (Chapter 5), its interactions with ecosystems (Chapter 6), and its relation with climate change (Chapter 7). Chapter 8 presents different perspectives on groundwater from across five global regions. Finally, response options are described and discussed in terms of expanding the knowledge base (Chapter 9), groundwater policy and planning (Chapter 10), groundwater management (Chapter 11), transboundary aquifer resources (Chapter 12), and financing (Chapter 13). The report concludes with an outlook to moving forward in terms of the most prudent development, use, management and protection of the groundwater resources and creating the enabling conditions to do so (Chapter 14).

[2] See section 1.3 for a definition and characterization of aquifers.

1.2 Unique properties and characteristics of groundwater and groundwater systems

1.2.1 What is groundwater?

Many people consider groundwater to be synonymous with underground water, in other words all water below the land surface. Hydrogeologists and hydrologists, however, make a distinction between subsurface water in the saturated zone (where all interstices are completely filled with water) and that in the unsaturated zone (where the interstices contain both water and air). They reserve the term groundwater for the former only, thus to water below the water table.[3] This stricter definition of groundwater is adopted throughout this report.

1.2.2 Unique properties and related characteristics

Groundwater and surface water are closely interconnected and interacting. For many human uses, either of the two may be substituted by the other one. Nevertheless, some properties and characteristics markedly distinguish groundwater systems (see Box 1.1) from surface water systems:

- Groundwater is present in *pores, fissures and other voids within geological formations* and it does not exist without this lithological matrix.
- Groundwater is *invisible*, hidden to the naked eye.
- Groundwater is a *spatially distributed* resource. It is virtually ubiquitous and extends laterally under most of the land surface – as opposed to surface water in streams and lakes that covers only a minor part of the land area.
- Groundwater occurrences are not only of large lateral extent, but have also a *significant vertical dimension* (3D geometry). Groundwater may extend vertically from very close to the land surface to great depths, down to thousands of metres.
- Groundwater is generally *moving very slowly*, mainly because the subsurface lithological matrix offers a hydraulic resistance to flow many orders of magnitude higher than the hydraulic resistance experienced in open channel flow. Groundwater flow in karst formations, however, may be quite fast.
- *Large volumes of groundwater are stored* in the subsurface, exceeding annual groundwater replenishment by two orders of magnitude, on average.

Box 1.1 Groundwater systems

Groundwater system is a generic term that may refer to different conceptual images of specific three-dimensional portions of the saturated underground. Well known among these are the concepts of *aquifers* and *aquifer systems*, identified and delineated on the basis of perceived contrasts in hydraulic properties with adjoining parts of the subsurface. They are defined and addressed in some more detail in Section 1.3. Other examples are the *contributing subsurface segments of river basins* (with groundwater divides as boundaries), *groundwater flow systems* as defined by Tóth (1963) and *groundwater bodies* as introduced by the European Union in its Water Framework Directive (European Parliament/Council, 2006; European Commission, 2008). The delineation of the latter does not follow a standardized methodology, but one of the criteria for defining the boundaries is jurisdiction with regard to groundwater. These conceptual images are a simplification of reality, but they are helpful for analysing and understanding the state of groundwater, relevant groundwater processes, and the interactions with people, ecosystems and other external systems (see also Figure 1.1).

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[3] This implies a hydrostatic pressure equal to or greater than the local atmospheric pressure.

The delineation of aquifer boundaries is often difficult, in particular if the aquifer is lithologically heterogeneous, large in extent or deeply buried

As a result of the mentioned unique properties, groundwater systems in practice often show the following characteristics and features:

- Easy and *open access* to numerous people, leading to *common* pool characteristics.
- Often *poorly known* and understood, even by the local population.
- *Difficult and/or costly access* to exploration, assessment and monitoring activities. This constrains the development of sufficient and accurate knowledge on the local groundwater systems, necessary for adequate identification and analysis of opportunities and challenges, and potential responses.
- The large volumes of stored groundwater (groundwater reserves) form *huge water quantity buffers*, ensuring permanent availability of water in many regions with pronounced dry seasons and only intermittent or seasonally flowing streams.
- Within single large groundwater systems, *groundwater ages* commonly vary widely (from recent to tens of millennia old), while salinity and other quality parameters may also be subject to *significant variation*.
- Over time, *groundwater quality* may change due to long residence times and contact with the lithological matrix and subsurface biosphere.
- Compared to surface water systems, groundwater systems are usually *better protected against pollution* (due to the overburden's resistance to flow), but once polluted they are much more difficult to remediate. Shallow groundwater domains, in turn, are more vulnerable to pollution than deeper ones.

1.3 Aquifers, their main characteristics and the groundwater resources they contain

1.3.1 Aquifers: spatial units defined by hydraulic subdivision of the subsurface

The geological formations that make up the subsurface – sedimentary, igneous and metamorphic rocks – show an almost endless variation in properties. The category of hydraulic properties is most relevant for understanding flow and storage of groundwater. Therefore, hydrogeologists commonly look at the subsurface through a hydraulic lens and subdivide it schematically into spatial units that differ from each other in terms of their capacities to store groundwater (linked to total or drainable porosity or void ratio) and to transmit groundwater (linked to permeability or hydraulic conductivity). Spatial units that score comparatively high in both respects are called *aquifers*; they combine the functions of groundwater reservoir and 'highway' for groundwater flow.

Various *aquifer* definitions can be found in textbooks and other publications. They show differences in perspective (source of water supply versus 'neutral' groundwater flow) and some definitions seem to associate an aquifer exclusively or mainly with the lithological matrix (container) and not or less with groundwater in its interstices (content). Box 1.2 presents a simple but clear definition, to-the-point and compatible with the views of most groundwater professionals.

Box 1.2 What is an aquifer?

An aquifer is a saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients (Freeze and Cherry, 1979).

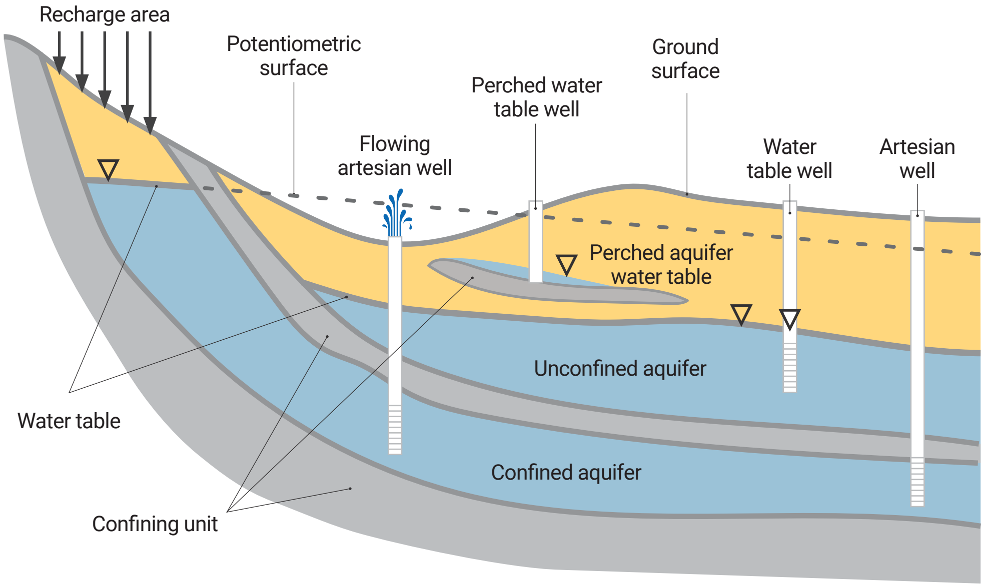
The delineation of aquifer boundaries is often difficult, in particular if the aquifer is lithologically heterogeneous, large in extent or deeply buried. It requires the involvement of competent hydrogeologists capable of properly interpreting the structure, continuity and properties of geological formations in the subsurface that usually only have been observed in a limited number of locations.

1.3.2 Other hydraulic units in the subsurface

Aquifers interact with other hydraulically distinct units in the subsurface, in particular with the unsaturated zone and with aquitards (see definition below). Figure 1.1 presents a hypothetical vertical cross-section in which aquifers and some other subsurface hydraulic units are shown.

Figure 1.1

Vertical cross-section showing aquifers, confining units and the unsaturated zone



Source: Based on Harlan et al. (1989, p. 9).

The *unsaturated zone* stretches from the land surface down to the water table. The interstices (pores or fissures) in the matrix of this zone are not entirely filled with water, but contain also air. Water in the unsaturated zone has a pressure lower than atmospheric pressure, due to matrix suction forces, which influences its hydraulic behaviour. The unsaturated zone plays a role in groundwater recharge by transmitting excess rainfall or surface water downward from the land surface to the saturated zone. In areas with shallow water tables, it facilitates the upward flow needed for groundwater to be discharged directly to the atmosphere by evaporation or evapotranspiration.

Aquitards are subsurface formations containing significant quantities of groundwater but incapable to transmit significant quantities to wells. Their permeability is low compared to that of aquifers, but on a regional scale they may yield substantial quantities of water to adjoining aquifers or transmit water between the aquifers it separates. Hydraulically, aquitards function as confining or semi-confining layers.

The remaining lithological units in the subsurface are hydraulically inactive and form barriers to groundwater flow, either because of very low permeability, or because interconnected interstices are lacking. Somewhat outdated terms for these confining units are *aquicludes* and *aquifuges*, respectively.

1.3.3 Aquifer types

Aquifers can differ and be classified on the basis of a variety of criteria, such as:

- *Size*: aquifers range in lateral extent from less than hundred to more than a million km², while their thickness may vary from less than ten to more than one thousand metres.
- *Lithology*: the most productive aquifers are composed of sand and gravels (unconsolidated), sandstones (consolidated), karstic limestones or certain volcanic rocks (e.g. basalts); weathered bedrock may form local aquifers, usually less productive.
- *Stored volumes (reserves)*: largest in thick and porous sedimentary aquifers, smallest in fissured bedrock aquifers.
- *Location with respect to land surface*: shallow aquifers (with their top less than a few tens of metres below surface) are likely to be more actively involved in the water cycle than moderately deep- or deep-seated aquifers; in addition, groundwater withdrawal becomes more expensive and technically challenging with increasing depth.
- *Unconfined or confined*: unconfined aquifers have a free water table that moves vertically with changes in storage, while in confined aquifers there is no free water table since the water pressure below the upper confining layer is everywhere exceeding atmospheric pressure. The change of storage in confined aquifers is not related to a moving water table, but is accompanied by elastic responses of stored water and the solid matrix to changes in pressure.
- *Recharge conditions*: many aquifers are abundantly recharged (hundreds of millimetres per year) and therefore contain renewable groundwater resources; others (mainly in dry or permafrost areas) are not significantly recharged, hence the water they contain is classified as non-renewable.
- *Domestic versus transboundary aquifers*: domestic aquifers are situated entirely within one single jurisdiction (national or subnational), while aquifers crossed by national or other jurisdictional boundaries are called transboundary.

Important aquifers usually have a name, for easy identification and communication.

Human activities such as groundwater withdrawal and artificial recharge produce shifts in the water budget

1.3.4 Hydrological regime of an aquifer

The principle of mass conservation implies that groundwater recharge is always balanced by groundwater discharge and change in storage. Consequently, human activities such as groundwater withdrawal and artificial recharge produce shifts in the water budget: the former leads to reduction of natural discharge and/or groundwater storage, the latter to the opposite.

1.3.5 Aquifer systems

Depending on area-specific conditions and on the scale of investigation or mapping, two or more stacked aquifers with intercalated and overlying aquitards may together be called an *aquifer system*, provided that they are interconnected components of one hydraulically continuous system. If, for instance in Figure 1.1, the confining unit between the two aquifers would be leaky (and thus would be an aquitard), then there is hydraulic connectivity between the two aquifers, which means that together with the aquitard they form an aquifer system. In practice, the distinction between aquifers and aquifer systems is somewhat arbitrary, because distinguishing between aquitards and low-permeability lenses, as well as between permeable and poorly permeable rocks, is subjective. With increasing complexity and size, the term 'aquifer system' tends to be preferred. The largest aquifer systems in the world, located in deep sedimentary basins, are up to few million square kilometres in lateral extent and thousands of metres deep. The deeper parts of most such aquifer systems are filled with saline water.

1.4 Brief history of groundwater development

Groundwater has been abstracted and used for human purposes since time immemorial. For a long time, this must have been limited to tapping water from springs and from shallow dug wells. Muscular energy of animals or humans was used to lift water from the wells to the surface. Over time, techniques have been developed to use this energy as efficiently as possible, such as the *shaduf* (early predecessor of the handpump), and the animal-driven *saqiyah* (modified Persian wheel) and *arhor* (Margat and Van der Gun, 2013; Yannopoulos et al., 2015). These techniques contributed to the development of small-scale groundwater-based irrigation, but the groundwater abstraction rates remained low in this early stage of development.

A major step forward was the invention and introduction of the *qanat* system, around 1000 to 800 BCE, a tunnel system that taps shallow groundwater and conveys it under gravity, thus without the need for external energy to bring groundwater to the surface. It is believed that *qanats* originated in Northwest Iran and from there spread over the Middle East, Northern Africa and Southern Europe, while they are also found in Central Asia, Western China and South America (English, 1968; Mostafaeipour, 2010). They have been – and still are in some countries – of great importance for irrigation and human settlements in arid regions.

Groundwater has been abstracted and used for human purposes since time immemorial

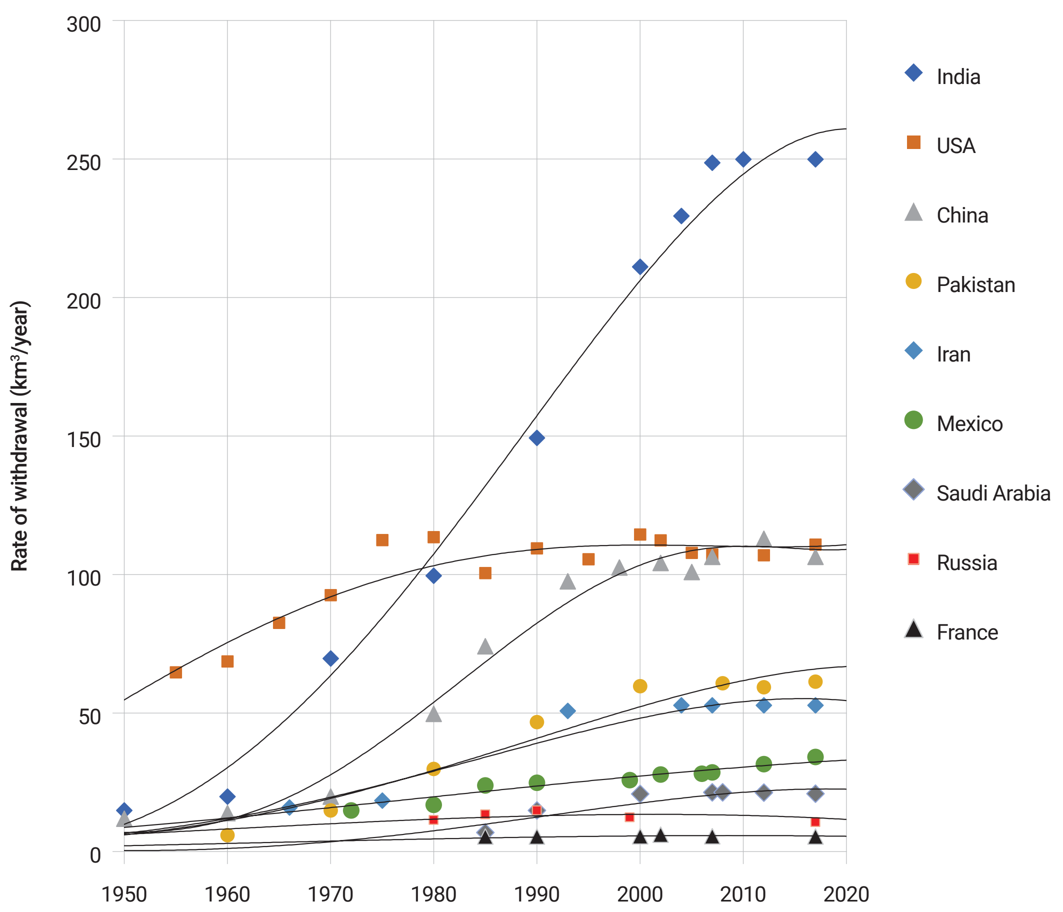
Windmills are another ancient energy-saving technique to bring water to the surface. It is not known since when they have been in use for pumping groundwater: most likely since the Middle Ages or earlier. They are currently still in use, in particular for cattle watering and small-scale irrigation (Yannopoulos et al., 2015; Glazema, 2003).

Although percussion drilling techniques were developed in China already one thousand years ago for the exploitation of deep brines (Kuhn, 2004; Han and Cheng, 2013), digging remained until recent times the common technique for constructing water wells across the world, restricting groundwater withdrawal to relatively shallow depths. Development of well drilling techniques, starting in the early 19th century, heralded a major revolution, although it took a long time before these techniques became sufficiently advanced and were widely applied around the world. They paved the way for exploring and exploiting deeper aquifers, and were also instrumental in discovering artesian aquifer zones where flowing wells could be constructed. At the beginning of the 20th century, the appearance of high-capacity power-driven pumps capable of pumping deep groundwater led to unprecedented increases in groundwater abstraction in response to ever-increasing water demands. Consequently, groundwater withdrawal boomed during the 20th century, starting during early decades in the USA, Mexico and several European countries, and in most other countries during the second part of the century or near its end.

Figure 1.2 illustrates the evolution of groundwater withdrawal during the period 1950–2020 for selected countries (countries for which sufficient data are available). It shows clearly the difference in timing of maximum growth between the USA and Asian countries like India, China, Pakistan and Iran. The total global groundwater withdrawal during 2017 is estimated at 959 km^3 (see Prologue), of which 68% corresponds to the nine countries shown in Figure 1.2. Assuming that the remaining countries in the world followed on average the same pattern of increase, it is estimated that the globally aggregated groundwater withdrawal was only 158 km^3/year in 1950, and that this increased over the successive decades by the following mean annual percentages: +3.7% (1950–1960), +4.8% (1960–1970), +3.9% (1970–1980), +3.4% (1980–1990), +1.8% (1990–2000), +0.8% (2000–2010) and –0.2% (2010–2017). Its share in total freshwater withdrawal has risen from 12% in 1950 to 25% in 2017. It can be observed that groundwater withdrawal rates have more or less stabilized in the USA, most European countries and China.

The uses, benefits and challenges of groundwater in the agricultural, domestic and industrial sectors are described in the Chapters 3, 4 and 5, respectively.

Figure 1.2 Evolution of total groundwater withdrawal in selected countries, 1950–2020



Source: Based on Margat and Van der Gun (2013, fig. 5.4, p. 128). Updated by the last author, using reported national data.

1.5 The multiple services offered by groundwater to humankind and to ecosystems

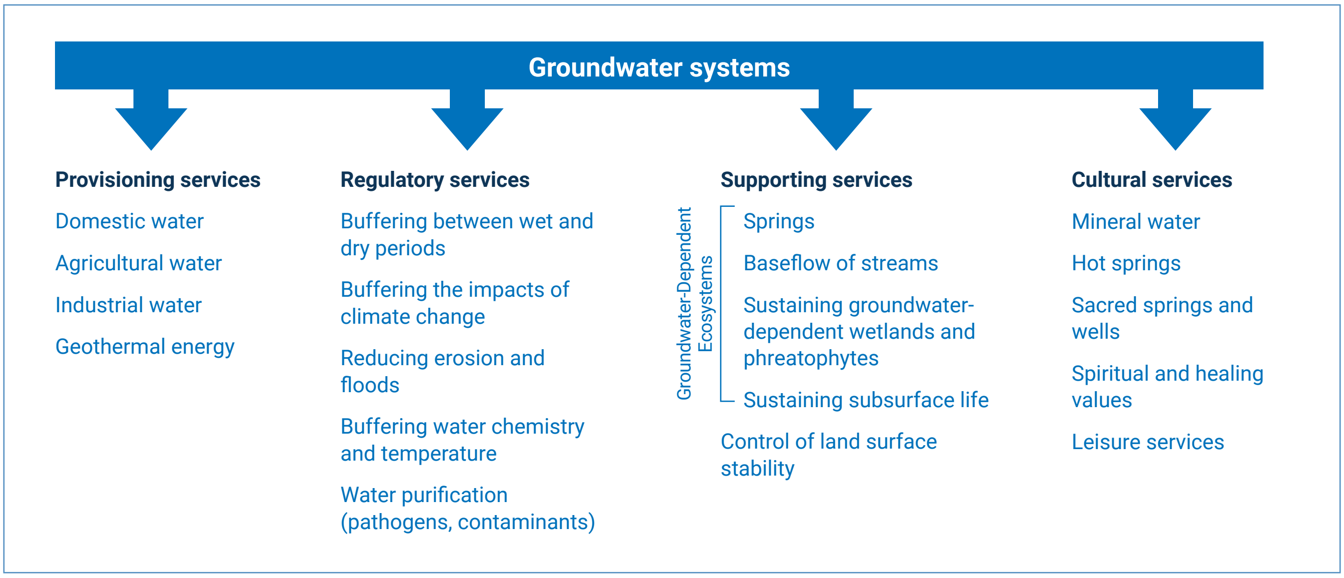
Groundwater withdrawal for human uses is very important, but it corresponds to only one category of the services offered by groundwater systems (provisional services). It should not be overlooked that groundwater offers many more services, as indicated in Figure 1.3. Most of the services mentioned in this figure are obvious, but a few explanatory comments are presented.

- *Provisioning services* allow groundwater to be withdrawn for water use purposes, but in some cases withdrawal is merely for extracting the geothermal energy it carries, after which the abstracted water is returned to the subsurface.
- *Regulatory services* are *in-situ* services that reflect the buffer capacity of aquifers (see Section 1.2); they mainly regulate the groundwater systems' water quantity and water quality regimes.
- *Supporting services* are *in-situ* services, too; they are focusing on groundwater-dependent ecosystems (GDEs) and other groundwater-related environmental features. Not only aquifers, but also aquitards may play an important role in this category, sometimes a main role (control of land subsidence).

- Finally, groundwater provides also *cultural services*; those linked to leisure activities, tradition, religion or spiritual values are associated with particular sites rather than with an aquifer. Indeed, groundwater has played an important role in cultures and religions across the world, from the caves and springs venerated by the Mayan peoples of Mexico to the dragon wells and sacred springs of China (Ray, 2020).

Provisioning services are potentially conflicting with the supporting services: the latter tend to become stressed under intensive groundwater withdrawal. Groundwater governance and management have to pursue an optimal balance between conflicting or competing services.

Figure 1.3 The multiple services offered by groundwater systems



Source: Based on Van der Gun (2019, fig. 5).

1.6 Global interconnections

Groundwater is basically a local resource, predominantly viewed by practitioners in a local context. Nevertheless, it is interconnected with its surroundings at different spatial scales, which implies that different perspectives are required to oversee and address the full range of relevant issues: not only the local perspective counts, but also aquifer-wide, national, transboundary, regional and global perspectives. Some important global interconnections regarding groundwater are briefly reviewed below.

1.6.1 Groundwater in the global water cycle, interacting with climate and other global systems

With its specific characteristics, especially its buffering capacity, groundwater puts its distinct mark on the global water cycle. However, the global water cycle and its water budget are not in a dynamic equilibrium: they are being modified by climate change and by increasingly significant human interferences, such as groundwater withdrawal and land use practices. In principle, the interaction is bi-directional, which implies that a modified water cycle will also produce feedback to the global climate. The last few decades have witnessed considerable progress in assessing and understanding these global-scale modifications and their repercussions. A new discipline has emerged: Global Hydrology. It uses hydrological models at a global scale, exploring large-scale hydrological patterns and processes, coupled with climate, land use or water use models, in order to obtain a better understanding of the Earth system. Coupling with other domains – food security, economics, energy and biodiversity – lies ahead (Bierkens, 2015).

1.6.2 Groundwater and Earth system resilience

As pointed out by Gleeson et al. (2020a), different processes within the global water cycle regulate climate and support ecosystems. Human activities – including groundwater withdrawal – currently are a major force disturbing these processes, potentially causing planetary-scale regime shifts that threat the stability of our planet as a suitable habitat for humans and ecosystems. It is important to explore how resilient our planet is to such regime shifts and how to control them.

1.6.3 Groundwater and sea level rise

Intensive groundwater withdrawal causes a reduction of stored terrestrial water, which produces a nearly equal increase of the volume of water in the oceans

Intensive groundwater withdrawal causes a reduction of stored terrestrial water, which produces a nearly equal increase of the volume of water in the oceans. Estimates of the corresponding annual global contribution diverge (Wada et al., 2010, 2016; Konikow, 2011; Bierkens and Wada, 2019), but there is no doubt that it forms a significant contribution to the total observed and predicted sea level rise, in addition to the climate change contributions. The main impacts of sea level rise are coastal inundation, flooding and increasing saline water intrusion.

1.6.4 Global degradation of groundwater-dependent ecosystems

Groundwater-dependent ecosystems are very vulnerable to intensive groundwater withdrawal. Continuously expanding groundwater withdrawal across the globe causes global-scale decline of baseflows, springs, artesian flows and wetlands, leading to loss of the biodiversity and to encroaching desertification in the longer run (see Chapter 6).

1.6.5 Groundwater and global trade

Global trade has enabled food and other commodities to be produced at large distance from where they are consumed or used. According to Hoekstra (2018), 22% of water use in the world is for producing export products. Consequently, large volumes of 'virtual water'[4] travel across the world, implying that a variable percentage of countries' water footprint of consumption lies outside their own territory (the 'external footprint'). International trade obviously yields economic benefits to exporting countries, but water savings in importing countries risk increasing water stress in exporting countries. For 2010, global groundwater depletion embedded in food production was estimated at 141 km³/year, of which 26 km³/year was exported (Dalin et al., 2017).

1.7 Groundwater in the context of global agendas and frameworks

1.7.1 UNESCO's Intergovernmental Hydrological Programme

The Intergovernmental Hydrological Programme's (IHP) major achievements with special focus on groundwater include the worldwide promotion of hydrogeological mapping (Gilbrich and Struckmeier, 2014), the establishment of a global initiative on transboundary aquifers (the Internationally Shared Aquifer Resources Management initiative, or ISARM), the World-Wide Hydrogeological Mapping and Assessment Programme (WHYMAP) and the establishment of the International Groundwater Resources Assessment Centre (IGRAC). The main objective of IHP's eighth phase (IHP-VIII 2014–2021) was to translate scientific knowledge into the action that is required for water security.

1.7.2 The 2030 Agenda for Sustainable Development

The UN Sustainable Development Goals (SDGs – Figure 1.4) are a call for action by all countries – poor, rich and middle-income – to promote prosperity while protecting the planet. The 17 SDGs were adopted by all UN Member States in 2015, as part of the

[4] The term 'virtual water' was introduced by Allan (1998, 2003) to indicate the water needed to produce agricultural and other commodities. International trade implies virtual water flows between countries.

2030 Agenda for Sustainable Development that defines a 15-year plan with 169 targets to achieve the SDGs (UNDESA, n.d.). Although only one SDG target makes explicit reference to groundwater in its wording (Target 6.6), no less than 53 targets appear to be interlinked with groundwater, including – but not limited to – all targets related to SGDs 6, 12 and 13. In the majority of the cases, there is synergy between achieving the target and trends or aspirations regarding groundwater ('reinforcing linkages'), but in some cases they are conflicting or of a mixed character (Guppy et al., 2018). Groundwater is a key resource for achieving the goals of the 2030 Agenda, which implies that adequate groundwater expertise and local hydrogeological knowledge are required for its successful implementation (Velis et al., 2017; IAH, 2017). There is a strong case for defining additional 'groundwater status indicators' for several SDG 6 targets, because groundwater is integral to these, but not adequately dealt with so far (IAH, 2017).

Figure 1.4
The Sustainable Development Goals

Source: UNDESA (n.d.).

1.7.3 Water, sanitation and hygiene (WASH)

Although only one SDG target makes explicit reference to groundwater in its wording (Target 6.6), no less than 53 targets appear to be interlinked with groundwater

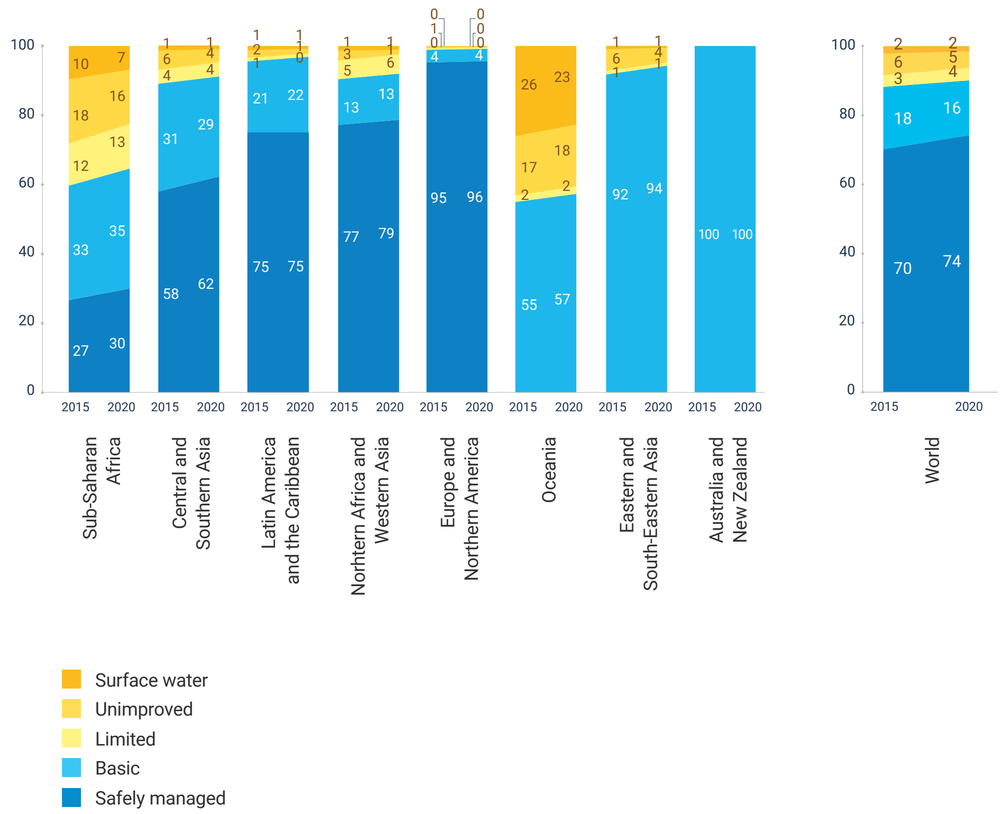
Reporting on the worldwide improvement of access to safe drinking water, sanitation and hygiene belongs to the missions of the World Health Organization (WHO) and United Nations Children's Fund (UNICEF), in cooperation with numerous other organizations. Their Joint Monitoring Programme (JMP) for WASH has reported on country, regional and global progress on drinking water, sanitation and hygiene since 1990.

Figure 1.5 shows the status and progress in regional and global drinking water coverage during the period 2015–2020. The percentage of the world population using safely managed drinking water services increased from 70% to 74%, but differences between and also within the regions are considerable. Similar statistics are available for sanitation services: use of safely managed sanitation services increased from 47% to 53% of the world population during 2015–2020. JMP reports furthermore that, by 2020, 71% of the world population had basic handwashing facilities with soap and water available at home (WHO/UNICEF, 2021). The latter facilities have gained importance since the outbreak of the Covid-19 pandemic, because handwashing is indicated to reduce the transmission of viruses strongly (Brauer et al., 2020).

JMP does not specify the share of groundwater in WASH services and their progress, but it is certainly considerable.

Figure 1.5

Regional and global drinking water coverage, 2015–2020 (%)



Note: Five SDG regions had estimates for safely managed drinking water services in 2020.

Source: Adapted from WHO/UNICEF (2021, fig. 2 and 3, p. 8).

1.8 Challenges related to groundwater

The capacity of groundwater systems to offer various services (as shown in Figure 1.2) depends on their geographically varying properties (See Prologue) and is dynamically influenced by ongoing natural and human processes. The latter lead to numerous groundwater-related challenges in all parts of the world, in particular in densely populated areas. The main types of these challenges are briefly described below. More details and potential responses are presented in several other chapters of this report, either in a thematic (Chapters 3–7), a regional (Chapter 8) or a governance/management context (Chapters 10 and 11). Addressing the challenges requires a good understanding of the underlying causal chain – from root causes (such as population growth, economic development and climate change) via stresses (e.g. groundwater withdrawal, influx of pollutants) to changes in groundwater state (groundwater quantity, water levels/pressures, water quality) and their impacts on humans, ecosystems and the environment.

1.8.1 Long-term groundwater storage depletion

Groundwater storage depletion, accompanied by declining groundwater levels, occurs when groundwater discharge (i.e. the sum of groundwater withdrawal and ‘unforced’ or natural discharge) exceeds groundwater recharge. Although climate variability and climate change can also play a role (by influencing groundwater recharge and water demands), most cases of long-term groundwater storage depletion result from intensive groundwater abstraction. Long-term groundwater depletion is observed in countless aquifers, predominantly located in semi-arid and arid zones, where it often forms a major threat to sustainable groundwater use for irrigation. The rate of global aggregated groundwater storage depletion is considerable: for the beginning of the present century, the estimates are mostly between 100 and 200 km³/year (Bierkens and Wada, 2019).

The potential impacts of groundwater level declines include:

- increasing costs, technical complexity and energy demands of groundwater abstraction;
- increasing water scarcity caused by wells, aquifer zones or entire aquifers running dry;
- degradation of groundwater-dependent ecosystems and other non-provisioning groundwater services;
- land subsidence in areas with highly compressible sediments or other geological formations prone to deformation in response to changes in water pressure;
- competition between groundwater-using sectors or between individual well users; and
- increasingly inequitable access to groundwater (including the loss of intergenerational equity).

Well-known large aquifer systems affected by significant long-term storage depletion are those of the Indo-Gangetic Plains, the North China Plain, the California Central Valley, the US High Plains and the Arabian Aquifer System. Most of the groundwater withdrawn from these aquifer systems is used for irrigated agriculture.

Land use, land use practices, artificial drainage and surface water management are other human activities influencing groundwater storage.

Groundwater pollution is a virtually irreversible process: once polluted, aquifer zones tend to remain with polluted water

1.8.2 Groundwater pollution

Groundwater pollution reduces the suitability of abstracted groundwater for drinking purposes and other human uses, while it may also affect groundwater-dependent ecosystems.

There are many sources of anthropogenic groundwater pollution: most of them are located at or near the land surface (agriculture, households, sewerage, landfills, industries and other urban sources, storage tanks, roads, canals, pipelines, etc.), but several other sources inject pollutants into the subsurface at greater depth below the surface (wells, oil and gas development, mining, subsurface disposal, and other subsurface human activities). Agricultural pollution is widespread; it is a diffuse source (non-point source) that often includes large quantities of nitrate, pesticides and other agrochemicals. In contrast, industries and households usually produce point-source pollution. The range of industrial pollutants is very large (numerous organic and inorganic substances, microorganisms, radionuclides) and varies according to the types of industrial products. Among the pollutants produced by households and found in sewerage, microbiological compounds and so-called 'emerging micro-pollutants' (e.g. PPCPs[5] and EDCs[6]) are distinctive (Lapworth et al., 2012).

As mentioned already in the Prologue, in addition to anthropogenic pollutants, geogenic pollutants (e.g. arsenic and fluoride) may also be present in the subsurface. Human action such as groundwater pumping may contribute to their release from the rock matrix and to their subsurface transport.

Groundwater pollution is a virtually irreversible process: once polluted, aquifer zones tend to remain with polluted water. Since most anthropogenic sources of pollution are located at or near ground surface, pollution is most often observed in shallow aquifers zones, in particular if a protecting low-permeability layer is absent. However, due to

5 PCCPs: Pharmaceuticals and Personal Care Products

6 EDCs: Endocrine Disrupting Compounds

steadily increasing human activities in the deeper subsurface domains (hydrocarbon development, fracking, subsurface storage, etc.) pollution is also encroaching into deeper zones, although this is somewhat less widespread. Groundwater pollution is a major issue in almost all areas characterized by high population density and/or significant agricultural or industrial production.

1.8.3 Groundwater salination

Fresh groundwater zones may become brackish or saline in several ways.

One of the mechanisms is related to flooding by seawater. Seawater inundating low-lying coastal land tends to infiltrate into underlying aquifers, replacing fresh groundwater by saline water. This happens either suddenly, during exceptional events (storm surges or tsunamis), or gradually, in tandem with the slow marine transgression caused by sea level rise. In terms of areal extent, only a very minor percentage of the Earth's land area is exposed to the risk of marine flooding, but these areas are often comparatively highly populated. Moreover, in view of predicted sea level rise, this phenomenon threatens to deprive low-lying islands of extremely flat topography (such as atolls in the Pacific Ocean) from sufficient freshwater resources for continued human habitation.

Fresh groundwater zones may become brackish or saline in several ways

Groundwater abstraction is another trigger of groundwater salination. It may induce sea water intrusion in coastal areas, and it may cause relatively stagnant brackish or saline groundwater to start moving in vertical or horizontal direction, towards the exploited fresh groundwater zone. Both mechanisms form significant threats to fresh groundwater resources, especially in coastal areas.

Another significant cause of groundwater salination is irrigation. After application, irrigation water is temporarily stored in the upper soil zone, from where crops withdraw it. This water uptake by crops is selective, in the sense that part of the dissolved solids remains behind in the soil. These salts are subsequently flushed down, either by rains during wetter periods of the year, or by an irrigation water surplus applied by the farmer to prevent soil salination. As a result, the dissolved solids content of shallow unconfined aquifers in irrigated areas tends to increase gradually, unless drainage provisions divert the mineralized water to surface water bodies. This groundwater salination mechanism is additional to the increase of dissolved solids in groundwater caused by downward-percolating agrochemicals.

1.8.4 Priority, allocation and access issues

In absence of any form of community or government control, it is unlikely that an optimal combination of groundwater services will develop in a given area, and that all inhabitants will share equally in the benefits from groundwater. This is due to factors such as incompatibility between groundwater services, competition between potential groundwater users, the open-access and common-pool characteristics of groundwater, and the lack of a level playing field.

In many areas, it can be observed that groundwater-dependent ecosystems suffer and degenerate as a consequence of uncontrolled intensive groundwater abstraction by individuals or companies in pursuit of short-term economic profits; that most groundwater is abstracted by the wealthier segments of the population, while relatively poor and landless people (including refugees and other migrating groups) often have no or very limited access to groundwater; that groundwater development for public domestic water supply often gets insufficient priority and therefore remains inadequate; and that those who enjoy the profits of groundwater withdrawal often ignore the associated negative externalities, at the expense of resource sustainability and future generations. Such issues tend to become burning challenges, in particular in water-scarce areas, and therefore need to be addressed in policies.

1.9 Opportunities for enhancing benefits from groundwater

The impressive volumes of groundwater withdrawn and used, and the widespread evidence of *in-situ* groundwater services demonstrate the enormous importance of groundwater for humankind and groundwater-dependent ecosystems. Although the current rates of groundwater withdrawal are unsustainable in several areas and thus will decrease sooner or later, there are also various opportunities left for enhancing benefits from groundwater. Such opportunities – that will contribute to achieving goals defined at local, national or supra-national levels (e.g. the European Union Groundwater Directive or the United Nations' SDGs) – are described below. Most of these opportunities focus on making more groundwater available to human society, which is needed to meet ever-increasing water demands driven primarily by population growth and climate change.

1.9.1 Tapping the unexploited groundwater potential

In contrast to intensively exploited aquifers, in several regions of the world there are also aquifers that are still exploited at very low rates, far below the maximum sustainable rates. These aquifers harbour an *unexploited groundwater potential*, available for being tapped and used. A global inventory of such aquifers is not yet available, but available information suggests that many of them can be found in sparsely populated regions of Sub-Saharan Africa (MacDonald et al., 2012; Cobbing and Hiller, 2019), the northern half of South America, the Russian Federation and Canada, among others (Margat and Van der Gun, 2013). The rates of withdrawal are in parts of these regions constrained by insufficient financial means for appropriate technical infrastructure rather than by low water demands or low availability of groundwater.

In contrast to intensively exploited aquifers, in several regions of the world there are also aquifers that are still exploited at very low rates, far below the maximum sustainable rates

1.9.2 Developing unconventional groundwater resources

Under conditions of increasing water scarcity, the development of unconventional groundwater resources may be considered. They may supplement scarce freshwater sources, but their development is usually less attractive than conventional groundwater withdrawal due to technical, environmental or financial feasibility constraints.

One of these unconventional resources is *brackish groundwater,* often present at relatively shallow depths. Brackish groundwater can be used directly, without any treatment, for purposes such as brackish aquaculture, cooling systems, operations in the oil and gas industry, and – if the mineral content is not too high – irrigation of salt-tolerant crops. For purposes that require water of lower mineralization, such as drinking water use, brackish groundwater can either be mixed with freshwater, or be desalinized. Especially in the Arab region and in the drier parts of the USA, there exists much interest in developing brackish groundwater (Stanton and Dennehy, 2017; Dawoud, 2019).

Deep-seated fresh groundwater (here defined as groundwater present in aquifers of which the top is deeper than 500 m below the surface) is only rarely tapped for water supply, thus can be classified as an unconventional groundwater resource. It is an interesting option if the corresponding deep-seated aquifer is substantially recharged. However, most deep-seated aquifers are likely to contain non-renewable groundwater resources only, which precludes sustainable groundwater development. Rather, these resources might be tapped temporarily as a buffering emergency resource during exceptionally dry periods, when other water sources run short (Van der Gun et al., 2012).

Already in antiquity, *offshore fresh groundwater* was a known phenomenon and submarine freshwater springs were used for drinking purposes at some locations (Taniguchi et al., 2002). Recent inventories have demonstrated that offshore fresh or brackish groundwater occurs in many parts of the world, either in submarine discharge zones of aquifer systems that are recharged on the neighbouring land (Taniguchi et al., 2002; Zhou et al., 2019), or as bodies of non-renewable groundwater originating from previous geological times (Post et al., 2013; see also Figure 7 of this report's Prologue). According to the cited references, the global aggregated discharge rate and stored volumes are considerable. Exploiting these unconventional groundwater resources, however, is not easy and is likely to be expensive.

The exceptionally wide occurrence of large volumes of groundwater, combined with the resource's unique buffer function, offers great potential for water supply security in climate change adaptation

1.9.3 Expanding geothermal energy development

As described in Chapter 7, groundwater offers in different ways opportunities for developing geothermal energy. Despite progress made in recent years, this branch of energy development is still in its infancy. There is ample room for expanding geothermal energy development globally, which will not only enhance the global benefits obtained from groundwater, but also make a significant contribution to the transition to cleaner energy and carbon neutrality.

1.9.4 Expanding anthropogenic replenishment of the groundwater buffer

Managed aquifer recharge (MAR) is an effective technical intervention that makes use of the naturally available storage capacity of the subsurface (see Box 7.1 and Section 11.5). Excess water that otherwise would be lost is temporarily stored and made available for beneficial use at a later moment in time. The application of MAR has increased by a factor of 10 over the last 60 years, but there is still ample scope for further expansion, from the current 10 km^3/year to probably around 100 km^3/year (Dillon et al., 2019). MAR ranks under the most effective groundwater management interventions.

1.9.5 Adapting to climate change and mitigating disasters

The exceptionally wide occurrence of large volumes of groundwater, combined with the resource's unique buffer function, offers great potential for water supply security in climate change adaptation (see Chapter 7). This provides widespread easy access and the possibility of reliable use when surface water sources fail (e.g. during prolonged periods of drought).

The ability of groundwater resources to buffer during short-term changes and shocks can also help mitigate the impacts of anthropogenic and natural disasters and emergencies, such as industrial accidents, droughts, floods, earthquakes and landslides, when surface water supply systems are directly affected (Vrba and Verhagen, 2011).

Chapter 2

Legal and other institutional aspects of groundwater governance

UNDP

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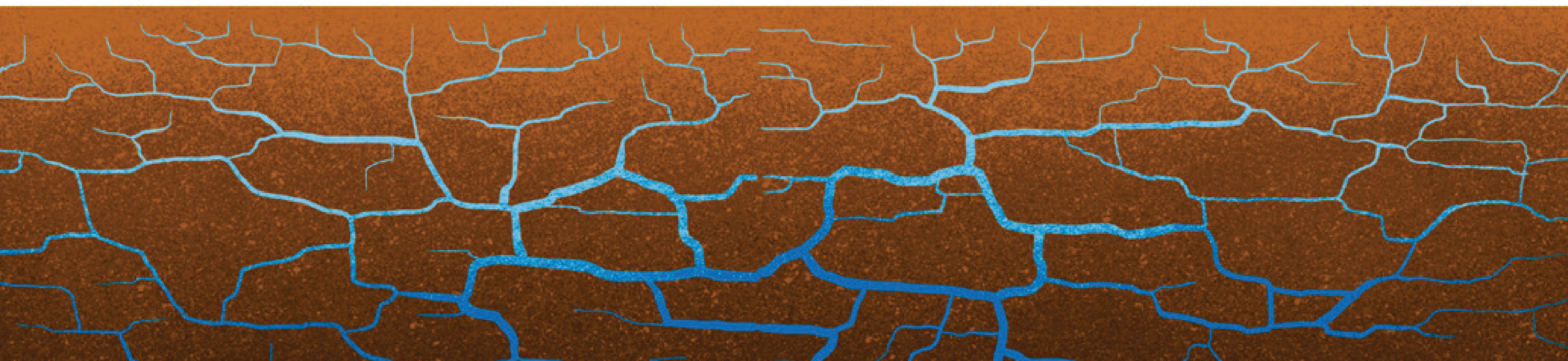


This chapter defines the linked concepts of groundwater governance and groundwater management, explaining how they differ from each other. Then, it describes the prevailing legal instruments for, and the institutional aspects of, groundwater management and governance.

2.1 Groundwater governance and management

Groundwater governance and management both address abstraction and allocation, use efficiency, and quality protection. While often used interchangeably, this report distinguishes between the two concepts (see Boxes 2.1 and 2.2, respectively). Groundwater *governance* processes set the conditions for and enable groundwater management, planning, and policy implementation. Principles for 'good' water governance include equitable access, accountability, transparency, stakeholder participation, inclusiveness, etc. Groundwater *management* is action-oriented: focusing on practical implementation activities and the 'nitty-gritty' of day-to-day operations, it emphasizes the results of decisions (Linton and Brooks, 2011).

Groundwater governance and management can be challenging because of the common-pool nature of most underground resources, along with information gaps and the diversity of stakeholders and their interests (Ross, 2016). Aquifer systems (the saturated rock or sediment medium, and the water contained in the saturated zone of the formation) act as 'hosts' of the resource, providing ecosystem services such as natural storage (green infrastructure) (United Nations, 2021; Puri and Villholth, 2018; UNGA, 2009). The hydrogeological, socio-economic, and politico-institutional realities of aquifer systems need to be considered alongside how they are used and managed. The time lag and invisibility of groundwater resources add to the complexity: negative impacts on groundwater may remain unseen for years, and physical limits of the aquifer are invisible to both users and decision-makers. As a result, the risks and problems associated with groundwater and aquifers are often not addressed proactively.

Box 2.1 Defining groundwater governance

Much effort has gone into identifying the core characteristics of groundwater governance. The most comprehensive effort has been carried out by the project '*Groundwater Governance – A Global Framework for Action*' (Groundwater Governance Project, 2016a, 2016b, 2016c). It defined groundwater governance as follows:

"*Groundwater governance comprises the promotion of responsible collective action to ensure control, protection and socially-sustainable utilization of groundwater resources and aquifer systems for the benefit of humankind and dependent ecosystems. This action is facilitated by an enabling framework and guiding principles*" (Groundwater Governance Project, 2016c, p. 17).

Drawing on this definition, governance has a set of four essential *components* or provisions:

1. an **institutional framework** characterized by representation and leadership, organizations and capacity, and stakeholder engagement and participation;
2. a comprehensive **legal framework**;
3. **knowledge** systems and more generalized **awareness** about issues; and
4. **policies, incentive structures and plans** aligned with effective governance.

The *guiding principles* of groundwater governance are:

- conjunctive management of surface water and groundwater;
- co-management of both quantity and quality of groundwater resources;
- co-governance of subsurface space and subsurface resources, which comprises the regulation of all activities and functions located in the subsurface space to ensure harmonized use and avoid undesirable and irreversible damage;
- 'vertical' integration in planning and management between local, district/provincial, and federal-level authorities, as well as international levels, as applicable; and
- (horizontal) policy coordination of other sectors that affect, or are affected by, groundwater.

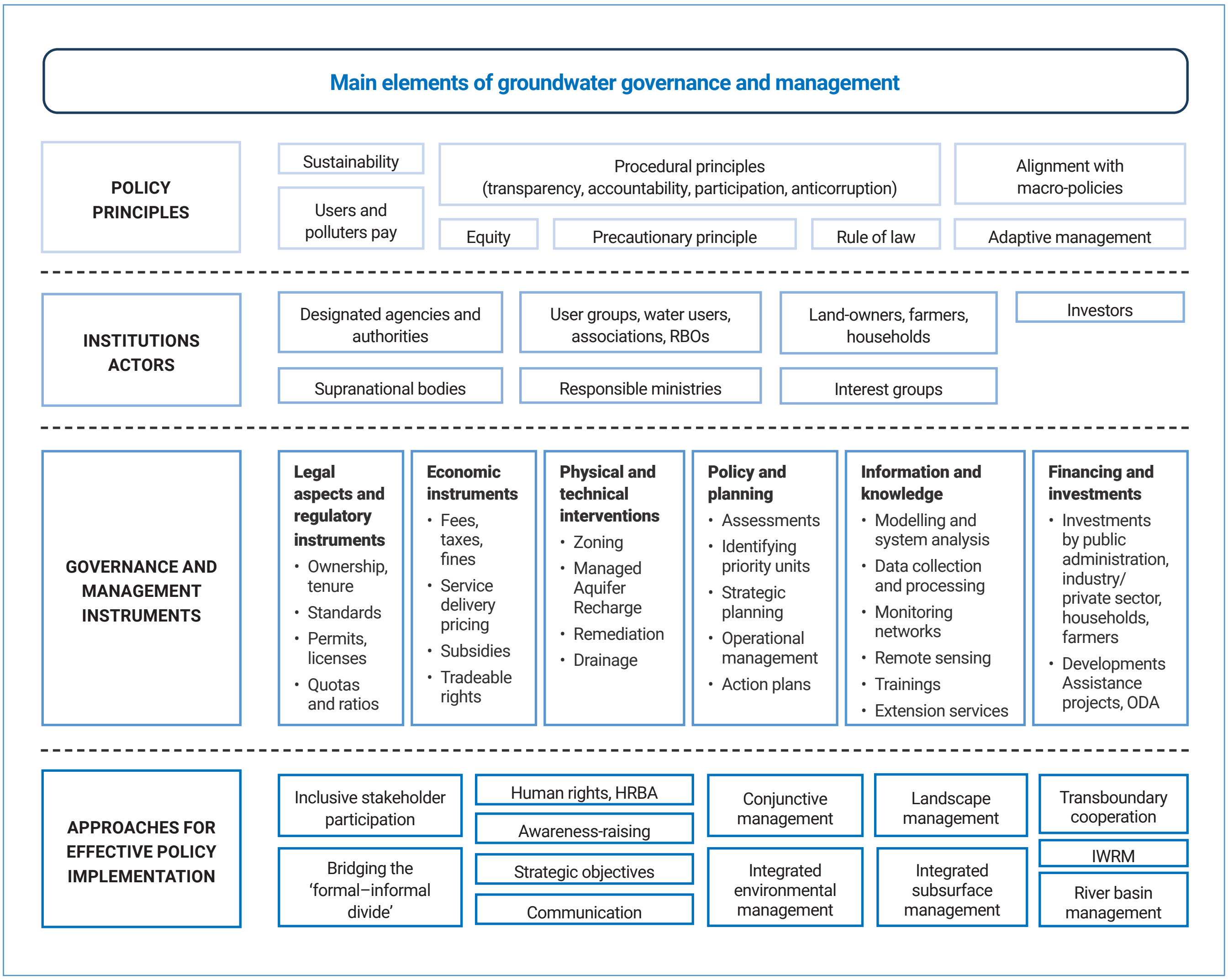
Box 2.2 Defining groundwater management

The Groundwater Governance Project (2016c, p. 17) defined groundwater management as "… *the activities undertaken by mandated actors to sustainably develop, use and protect groundwater resources*".

Management comprises measures, interventions, actions and activities that can be practical, technical and tangible to varying degrees, and that aim to "*control groundwater abstraction and to prevent the degradation of groundwater quality, typically with the objective of ensuring sustainable freshwater provision and preserving desired environmental and ecosystem conditions that depend on groundwater*." Technical management activities involve drilling and maintaining wells, installing water-saving technologies, etc. (see Chapter 11).

Groundwater governance and management occur within the broader policy environment of a country or basin, and are related to policy principles and planning, legal aspects, and implementation. Figure 2.1 suggests how overarching ideas and policy principles are translated, partially through laws and regulations, into management instruments. However, the methodologies and approaches for implementation are a critical filter or vehicle for the outcomes of the policy intensions.

Figure 2.1 Main elements of groundwater governance and management, from policy principles to implementation approaches



Source: Authors.

Because groundwater is often perceived as a private resource (that is, closely connected to land ownership, and in some jurisdictions treated as privately owned), regulation and top–down governance and management are difficult. In practice, decisions relating to individual wells are mainly exercised by (land-) owners, and it is often difficult for governments to quantify, allocate and regulate groundwater withdrawal and usage, particularly if their resources are limited. The corollary is that almost everywhere, groundwater governance and management must include public and private stakeholders, as well as local communities. At the same time, governments need to fully assume their role as resource custodians in view of the common/public good aspects of groundwater. Greater integrity and policies that enhance access for smallholders and women have a greater chance of contributing to the common good and achieving sustainable development.

2.2 Legal instruments

Legislation regarding groundwater resources defines binding and enforceable entitlements, and identifies rights and obligations that are subsequently operationalized through management decisions, including monitoring and enforcement. For instance, the European Union's Water Framework Directive (European Parliament/Council, 2000) and its Groundwater Directive (European Parliament/Council, 2006) have triggered a large number of management activities.

Laws and regulations that incorporate societal goals and policy objectives (see Chapter 10), and that set an enabling and regulatory framework for achieving those goals, are fundamental components of groundwater governance. They are also instrumental to the management of groundwater. Stable legal frameworks also enable governments and groundwater users to plan for resources management (see Chapter 10) over the long term and to deal with competing interests, including those of the environment and of future generations (Smith et al., 2016).

Domestic laws and regulations dictate access to groundwater as well as human activities that impact the quality of groundwater

Legal frameworks need to include protection of discharge and recharge zones and of the area surrounding water supply wells, as well as sustainable yield norms and abstraction controls, and conjunctive use regulations. Such frameworks would require data sharing to facilitate important processes, among other things the balancing of competing or conflicting interests among stakeholders, the reduction/elimination of inequalities in accessing and benefiting from the resource, and coordination with urban and rural land uses for management of the entire subsurface space (Groundwater Governance Project, 2016c).

Domestic laws and regulations dictate access to groundwater as well as human activities that impact the quality of groundwater (see Section 2.2.2). Additional relevant legal instruments include those that:

(a) Provide access to water for basic needs, as a matter of human rights. The human rights to water and sanitation, as well as the right to a safe, clean, healthy and sustainable environment, differ from water rights in that they are neither temporary nor subject to state approval, and in that they cannot be withdrawn. The General Assembly of the United Nations and the Human Rights Council recognize that equitable access to safe and clean drinking water and sanitation are human rights (UNGA, 2010; UNHRC, 2010). As such, groundwater resources need to be protected as part of the human right to a safe, clean, healthy and sustainable environment, which was recently recognized by the Human Rights Council (UNHRC, 2021). In places where water services are lacking or inadequate, households and communities' groundwater reliance is multiple times higher, with implications for states' duties to respect, protect and fulfil the right to safe drinking water in relation to resource protection. The role of the state ranges from advising end-users to protect 'their' groundwater resources, to supporting households whose wells have dried up due to recurrent drought (Grönwall and Danert, 2020).

(b) Afford access to groundwater for the livelihoods and small-scale productive uses of traditional communities, in fulfilment of customary law. Formal rules, however, may ignore customary law with the result that users are left without legal protection before formal water rights holders (Hodgson, 2016). Customary rules continue to play a significant role, for instance with respect to groundwater resources being perceived as belonging to the community, while rejecting the concept of individual rights. In much of Africa and Asia, customary water rights are intrinsically linked to land and embedded in land tenure systems (Mechlem, 2016; Meinzen-Dick and Nkonya, 2007). However, customary rules relating to water resources may be unfair or even discriminatory, and against the interests of women, children and minorities (Hodgson, 2016); where women and minority groups are denied formal land ownership, they may also be deprived of groundwater rights. The responsible governance of land tenure, fisheries and forests is inextricably linked with access to and management of other natural resources, such as groundwater (FAO, 2012).

(c) Regulate land uses inimical to the natural groundwater recharge and discharge processes, and to the environment-support function of groundwater in relation to, in particular, wetlands and oases.

(d) Regulate the formation and functioning of associations of groundwater users for allocation, monitoring and policing responsibilities at the common-pool groundwater level.

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; a handful of treaties and agreements have been concluded by countries with specific regard to transboundary aquifers and groundwater (see Chapter 12).

In the majority of jurisdictions today, public or government ownership of groundwater is the norm

2.2.1 Water rights – from private property rights to administrative entitlements

In the majority of jurisdictions today, public or government ownership of groundwater is the norm, and groundwater extraction and use are based on administrative entitlements such as individual permits, licenses or concessions that, in many jurisdictions, are time-bound and qualified as to volumes and rates of extraction (Salman and Bradlow, 2006; Nelson and Quevauviller, 2016; Groundwater Governance Project, 2016c; Burchi, 2018a). However, in some jurisdictions with sizeable populations, such as India, Pakistan, the Philippines and more than half of the states in the USA, groundwater rights are tied to land ownership and groundwater is regarded as private property (Closas and Molle, 2016; Tarlock and Robinson, 2019).

The Groundwater Governance Project has stressed the importance of bringing the resource into the public domain, despite the legal and practical challenges this may entail, thus enabling the state to assign use rights and to regulate extractions in line with the societal goals of sustainability, equity and efficiency (Groundwater Governance Project, 2016c). The transition of groundwater from the private to the public domain, however difficult in view of the political overtones, can be accomplished successfully (as has been the case in jurisdictions like Argentina, the Australian states of New South Wales and Victoria, Germany, Italy, Morocco, South Africa, Tanzania, Uganda and Zimbabwe) through legislation or through the pronouncements of the highest courts (Burchi, 1999, 2012, 2018a; Burchi and Nanni, 2003; Salman and Bradlow, 2006). In Spain, on the other hand, the attempt to switch from private to public groundwater ownership decreed by the 1985 Water Law stranded eventually, despite a favourable ruling of the Supreme Court, and the pre-1985 private owners can still enjoy usufructuary rights. New rights are, however, allocated under public property. This illustrates problems of gaining acceptance for such ownership transitions (Closas and Molle, 2016).

In some jurisdictions, groundwater is regulated in conjunction with surface water, including rivers. In others, it forms part of framework laws. More and more countries are strengthening their legal framework regarding groundwater, ranking it on a par with surface water regimes, protecting quantity as well as quality, and involving stakeholders to balance both private and public interests (Mechlem, 2016). Box 2.3 shows an example from Australia, where 'share-based' allocations and abstraction rights were introduced in order to manage groundwater withdrawals. The use of such resource extraction regulation can better balance the habitat and environment-support function of groundwater and aquifers with productive uses and other needs (Burchi, 2018a; Smith et al., 2016).

Box 2.3 Shifting from 'volume-based' to 'share-based' water abstraction rights in New South Wales (Australia)

The Australian state of New South Wales introduced a Bulk Access Regime by virtue of the Water Management Act (2000). The quantum of groundwater extracted from aquifers has shifted from a volumetric allocation to a variable share in the available groundwater from a given aquifer. Relevant extraction licences are made up of two parts: a 'share component', which entitles the licence holder to a share in the available groundwater from the aquifer; and an 'extraction component', which entitles the licence holder to take groundwater at specified times, rates and at specified locations from the given aquifer. The former is the linchpin of this sophisticated management and governance regime, and is determined on the basis of water sharing rules (including of surface water) and water sharing plans negotiated in a participatory manner in cyclical ten-year aquifer management plans (see Chapter 10) (Burchi, 2018a).

Illegal emission and discharge of substances into water bodies or into the ground, or unlawful treatment of wastewater, in a way that cause major harm or risks to groundwater systems and/or human health, may be considered an offence or crime

It is worth noting that in some instances there are conflicts between groundwater rights and surface water rights, for instance in the case of a stream that is drying up due to intense groundwater pumping nearby, and vice versa. A conjunctive management approach holds promise to deal jointly with groundwater and surface water rights, as has been done in New South Wales, in Australia (Box 2.3).

2.2.2 Regulating pollution

Point sources of pollution – industrial discharge of wastewater (notably including injection wells), solid waste handling that can affect groundwater resources, and municipal sewers – can be regulated through permits as well as through general effluent and/or ambient water quality standards. Direct discharge of hazardous or toxic waste to groundwater has been outlawed in some jurisdictions (Burchi, 2018a). Non-point source pollution from diffuse or indistinct sources requires prevention measures: regulation of land uses and/or imposition of best agricultural and environmental practices. Just as for point-source pollution, these measures include: prohibiting or limiting certain polluting and water-using activities; limiting the use of pesticides, herbicides and fertilizers (especially to reduce nitrogen and phosphorus build-up); restricting certain cropping patterns; reducing animal grazing intensity; reclaiming land; and managing drainage (Mechlem, 2016).

Illegal emission and discharge of substances into water bodies or into the ground, or unlawful treatment of wastewater, in a way that cause major harm or risks to groundwater systems and/or human health, may be considered an offence or crime. Sanctions and penalties may be stipulated for discharges without a permit or in violation of one, under criminal, civil or administrative law. Enforcement efforts and the prosecution of polluters, however, are often challenging due to groundwater's invisible nature.

2.3 Institutional aspects

Groundwater *governance* takes place at multiple scales and geographic levels, including at regional (such as the European Union) and transboundary scales. In contrast, groundwater *management* occurs more often at the micro- and meso-level. A variety of social/institutional, organizational, financial, and technical arrangements, as well as commonly accepted rules, practices and norms, shape access to groundwater. It is on the micro- and meso-level that attention should be focused to address the needs of the poor (Cleaver et al., 2005).

There is a diversity of stakeholders/actors in groundwater-related institutions, representing the public and private sectors, (regional) water authorities or committees, utilities, river basin organizations, communities, informal groups, and society at large. Part of the role of these institutions is to implement policy and law, to translate decisions into actions and ensure that regulations, governance procedures and mandated enforcement are carried out (Smith et al., 2016) on the basis of acquired information and knowledge about the groundwater systems. Government agencies commonly have the mandate for multilevel groundwater governance and management activities, but in practice their role may vary considerably from a top–down regulatory approach to a permissive, 'laissez-faire' position (Kemper, 2007). The assigned or allowed roles (or focus) of stakeholders can also be very different. For instance, local norms and institutions may influence divisions of labour and functions, which in turn shape the sourcing and allocation of water. Further, community organisations can be faction-ridden, gender-segregated and exclusionary (Cleaver et al., 2005). Where groundwater users operate as individuals or communities (including self-supply in urban areas, as well as farmer-led irrigation schemes), there may be few, if any, formal institutions through which governance can extend.

Performance of public agencies varies in practice from virtually inactive to proactive and effective, depending on the enabling framework (including regulations); the level of awareness of the importance of groundwater and of political commitment; budgetary allocation and, consequently, management capacity; leadership; and/or mandates. An additional factor is commercial and political pressures to over-exploit groundwater, alongside the overall political situation and the position of the government in the eyes of the local population (including mutual trust or the lack thereof).

A national government unit can ensure both vertical integration between the national and local level, and horizontal cooperation across different levels and at the interface with other sectors. At the river basin or aquifer system level, stakeholder organizations can play important roles in coordinating groundwater planning and management. Because groundwater is perceived (often incorrectly) as a local resource, decentralized organizations (including municipalities) have a critical role. However, an aquifer can extend beneath more than one river basin, which complicates river basin and aquifer governance and integrated water resources management. Governments should endeavour to seek the systematic engagement of stakeholders with the objective to create permanent mechanisms for stakeholder involvement. This can be in the form of water users associations and other fora (Groundwater Governance Project, 2016c).

According to the Groundwater Governance Project (2016c), the vision for a 'Global Framework for Action' involves effective institutions with the capacity to look ahead and plan, to be inclusive and legitimate in the eyes of the stakeholders, and to come to credible and verifiable commitments, with the following components:

- sound organizational design with adequate capacity for policy-making and public administration of resource use and pollution protection;
- mechanisms for permanent stakeholder engagement and participation to foster socially responsible attitudes and actions on groundwater as a common-pool resource;
- procedures for cross-sector coordination and co-management to allow groundwater issues to be adequately addressed in the policies and practices of linked sectors; and
- institutions for the management of groundwater resources that traverse intranational and international boundaries (where relevant).

Institutions, by themselves, are not enough to properly govern intra- and international groundwater/aquifers. They need to be accompanied by national (and sometimes subnational) policies (see Chapter 10) and laws to guide these institutions in their work.

River basin organizations seldom contemplate groundwater, partly due to a lack of knowledge and capacity in aquifer assessment and partly because of a historical institutional separation of surface water and groundwater. As a result, river basin planning becomes incomplete. In several parts of the world, though, cooperation has started and this suggests some emerging best practice, modelled on approaches used in transboundary river basin management (Groundwater Governance Project, 2016c).

Chapter 3

Groundwater and agriculture

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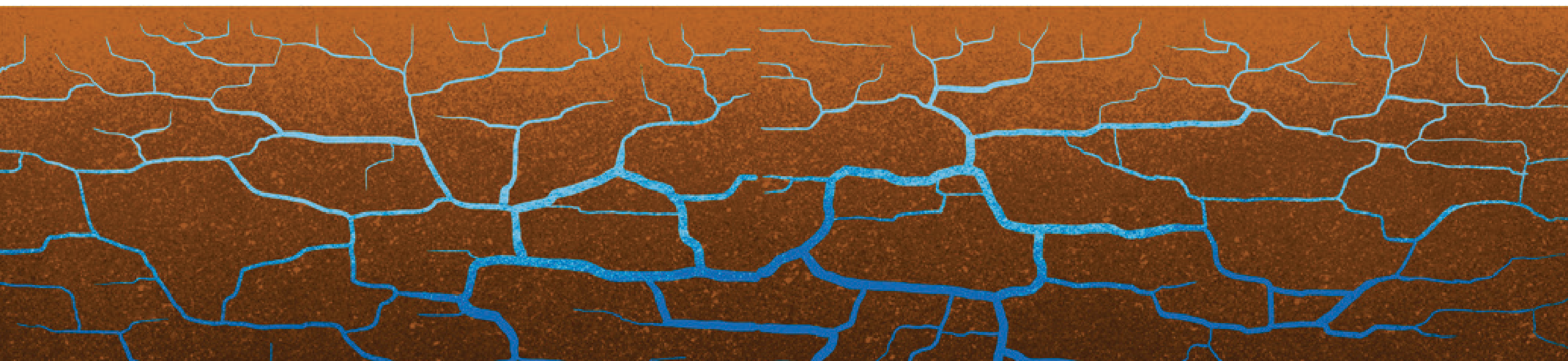

3.1 Introduction

This chapter provides an overview of the role of groundwater in agriculture, the sector with the largest use of the resource at a global level. As population and income growth drives demand for more intensive and higher-value food production, for which groundwater is well suited, irrigated agriculture, livestock and related industrial uses, including food processing, are becoming increasingly reliant on this resource (FAO, 2020).

3.2 Groundwater use in the agricultural sector

3.2.1 Importance of groundwater for agriculture

Groundwater is a critical resource for irrigated agriculture, livestock farming and other agricultural activities, including food processing. Global groundwater withdrawals in 2018 were estimated to be approximately 978 km³ per year for all sectors, including agriculture (Aquastat, n.d.; Eurostat, n.d.; Margat and Van der Gun, 2013). Approximately 70% of global groundwater withdrawals, and even more in arid and semi-arid regions (Margat and Van der Gun, 2013), are used in the agricultural production of food, fibres, livestock and industrial crops (FAO, 2020). An estimated 38% of the lands equipped for irrigation is serviced by groundwater (Siebert et al., 2013). In the broader context, irrigated agriculture still accounts for 70% of freshwater withdrawals (FAO, 2020), and an estimated 90% of all water evaporation (Hoogeveen et al., 2015). Water use for food processing is also significant, up to 5% of global water use (Boretti and Rosa, 2019). These numbers highlight the overall water-intensive character of food production.

Groundwater is a critical resource for irrigated agriculture, livestock farming and other agricultural activities, including food processing

Groundwater abstraction has played a major role in accelerating food production from the 1970s onwards (FAO, 2020; Shah et al., 2007), especially in semi-arid and arid areas with limited precipitation and surface water. At the same time, it has sustained local to regional economies that are dependent on groundwater for livelihoods, economic growth and food security.

In order to meet global water and agricultural demands by 2050, including an estimated 50% increase in food, feed and biofuel relative to 2012 levels (FAO, 2017), it is of critical importance to increase agricultural productivity through the sustainable intensification of groundwater abstraction, while decreasing water and environmental footprints of agricultural production, which can be achieved, for example, through agro-ecology (Snapp et al., 2021) and better food policy and economic instruments (FAO, 2021).

To understand the diverse and dynamic impacts of agricultural groundwater use across the globe, Shah et al. (2007) distinguish between four types of socio-ecologies:

- arid agricultural systems, such as in the Middle East and North Africa, where groundwater is also increasingly in demand for higher-value non-agricultural uses;
- industrial agricultural systems, such as those in Australia, Europe and the western USA, where groundwater supports commercial precision agriculture[7] and attracts relatively high financial resources for its management;
- smallholder farming systems, such as in South and increasingly Southeast Asia as well as the North China Plain, where groundwater irrigation is the mainstay of 1–1.2 billion, mostly poor farmers; and
- groundwater-supported extensive pastoralism, such as in much of Sub-Saharan Africa and Latin America.

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[7] Precision agriculture comprises the use of information and communication technology tools, including global positioning systems, satellites, drones, sensors and aerial images that provide farmers with site-specific information to make management decisions (Lowenberg-DeBoer and Erickson, 2019). Determining soil and crop conditions, while minimizing impacts on wildlife and the environment, is at the root of precision farming. Although concentrated in high-income countries, some precision tools have great potential in low-income countries. Many of these applications have been limited to large-scale farming, but there are opportunities for small-scale farmers as well (FAO, 2020).

In regions where a perennial and reliable source of shallow groundwater exists, including in previously rainfed areas, groundwater has been and continues to be an important source for smallholder farmers (Villholth, 2013a; Shah, 2009; Giordano, 2006). It represents a relatively accessible, local, on-demand and perennial source of water for agricultural practices, which translates into reduced poverty, better food security, and improved livelihoods. Evidence from Asia two decades ago indicates that the proliferation of groundwater access promoted greater interpersonal, interclass, gender and interregional equity in access to irrigation when compared to large canal irrigation projects (Shah et al., 2007; Deb Roy and Shah, 2003; Van Koppen et al., 2002). Studies in Africa, Asia and Latin America show that when poor farmers attempt to improve their livelihoods through smallholder agriculture or livestock farming, groundwater and small pumps are commonly involved, which benefit women in particular (Villholth, 2013a; Shah et al., 2007; Van Koppen, 1998).

3.2.2 Regional comparison of groundwater-sourced irrigation

The area of land equipped for irrigation (including full control, equipped wetlands and spate irrigation) globally has more than doubled since the 1960s, from 139.0 Mha in 1961 to 325.1 Mha in 2013 (Table 3.1). Regional variation in the extent of the irrigated area is pronounced. Asia accounts for 72% of the global area equipped for irrigation, predominantly in South and East Asia, and 41% of its cultivated area is irrigated. Sub-Saharan Africa has the least irrigation development: the irrigated area accounts for 3.4% of the regional cultivated

Table 3.1 Irrigated areas per region and globally, including groundwater share

Continent and region	Total area equipped for irrigation from surface or groundwater (Mha) (Faostat 1961–1996; Aquastat 1997–2013)		Irrigated area as % of total cultivated area (Faostat)		Groundwater irrigation (2013) (Aquastat)	
Year	**1961**	**2013**	**1961**	**2013**	**Area equipped (Mha)**	**% total irrigated area**
Africa	**7.4**	**15.6**	**4.4**	**5.8**	**3**	**19.2**
Northern Africa	3.9	7.4	17.1	25.6	2.5	34.6
Sub-Saharan Africa	3.5	8.2	2.4	3.4	0.4	5.4
Americas	**22.7**	**52**	**6.7**	**13.1**	**23.7**	**45.5**
Central America and the Caribbean	17.4	1.7	6.7	13	0.6	33.8
North America	0.6	34.3	5.5	14.9	20.1	58.7
South America	4.7	16	6.8	10.5	3	18.5
Asia	**95.6**	**232.6**	**19.6**	**40.9**	**89.7**	**38.7**
Central Asia	9.6	13.2	16.2	28.5	1.1	8
East Asia	7.2	73.9	13.4	56	21.3	28.9
South Asia	36.3	98.0	19.1	45.7	55.5	56.6
Southeast Asia	34.5	22.8	29.7	20.7	0.6	4.6
Western Asia	8	24.7	11.7	40.6	11.2	45.2
Europe	**12.3**	**21.4**	**3.6**	**7.3**	**7.1**	**14**
Eastern Europe and Russian Federation	8.7	4.8	5.8	3.6	0.25	10.1
Western and Central Europe	3.6	16.6	1.9	13.5	6.8	40.7
Oceania	**1.1**	**3.2**	**3.2**	**6.8**	**0.8**	**24.9**
Australia and New Zealand	1.1	3.2	3.2	6.9	0.8	24.9
Pacific Islands	0.001	0.004	0.2	0.6	0.0004	10
World	**139.1**	**324.8**	**10.2**	**20.6**	**124.7**	**38.4**

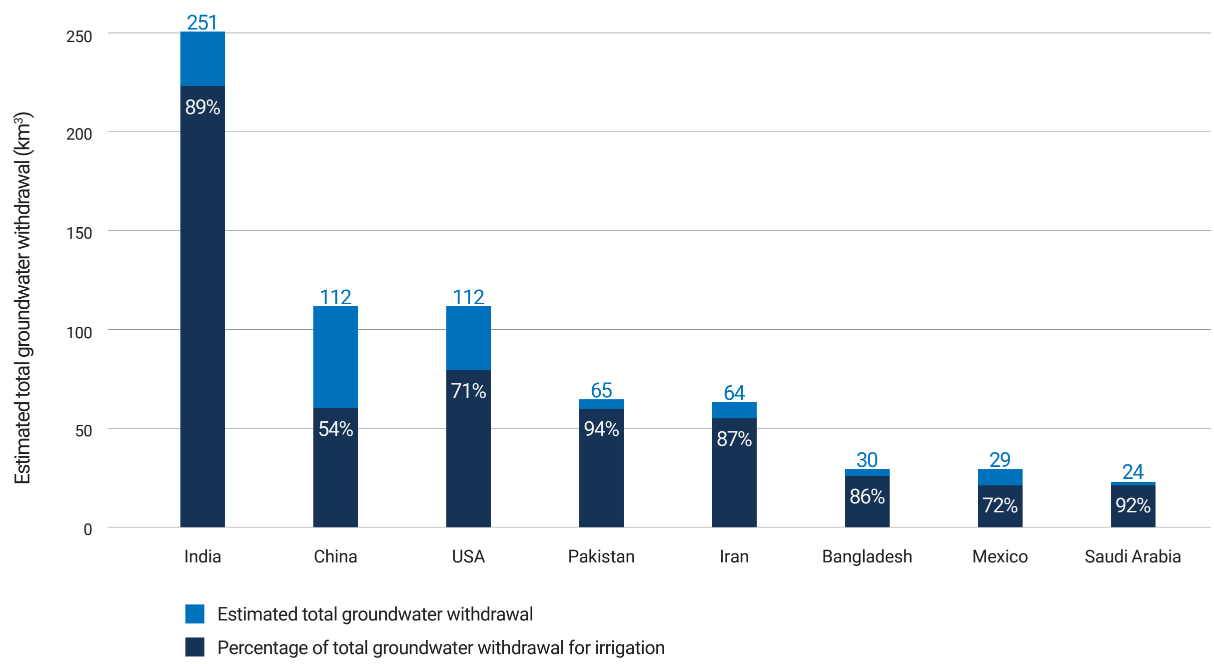
Source: Data from Aquastat (n.d.) and Faostat (n.d.).

area, while in West Asia it accounts for 41%. Regions heavily reliant on groundwater for irrigation include North America and South Asia, where 59% and 57% of the equipped area use groundwater, respectively, while in Northern Africa it is 35% and in Sub-Saharan Africa only 5% (see Section 8.1.3).

3.2.3 Country comparison of groundwater-sourced irrigation

Countries with the largest area under irrigation include China (73 Mha), India (70 Mha), the USA (27 Mha) and Pakistan (20 Mha) (Aquastat, n.d.). The proportion of total groundwater abstraction used for irrigation varies significantly in these countries. India, as the largest groundwater user globally, at an estimated 251 km³ per year abstracted, uses 89% of its groundwater abstraction for irrigation. China is relatively less reliant on groundwater, with an estimated 54% of total groundwater abstraction going into irrigation on average, but with significant geographic disparities, with the North China Plain (see Section 8.4.4) being more critically reliant on groundwater compared to the southern regions (Liu et al., 2010). Other countries, such as Bangladesh, Iran, Mexico, Pakistan, Saudi Arabia and the USA, are also heavily reliant on groundwater for irrigation, with amounts of groundwater abstraction for irrigation ranging from 71 to 94% (Margat and Van der Gun, 2013) (Figure 3.1).

Figure 3.1 Estimated total groundwater withdrawal and the percentage for irrigation for selected countries in 2010



Source: Based on data from Margat and Van der Gun (2013).

3.2.4 The extent of conjunctive water use

Conjunctive use[8] of groundwater and surface water in agriculture is significant. It typically supports intensification within existing surface water irrigation areas, like in South Asia, where it enables perennial cropping and salinity control (Shah, 2009). The evolution of conjunctive use is typically not managed or planned, but rather a coping mechanism for farmers when established surface water systems fail to secure perennial freshwater access. There is little

[8] Conjunctive water use refers to combined use of surface and groundwater to meet crop water demand (Shah et al., 2006).

consistent reporting of conjunctive use (Siebert et al., 2010), but census data in the USA (Dieter et al., 2018), China and India (Evans and Dillon, 2018; Ministry of Water Resources of India, 2017) indicate continued expansion.

3.2.5 Economic contribution of groundwater to agriculture

The economic contribution of groundwater in agriculture has been estimated at about US$210–230 billion per year globally, with gross productivity of US$0.23–0.26 per m³ abstracted (Shah et al., 2007). Water productivity, in terms of crop yield per unit of water applied, is generally higher, up to a factor two, for groundwater than for surface water. This is primarily due to groundwater being available on demand, its proximity to fields, and the fact that it is normally self-managed. This allows farmers to invest more heavily in other crop inputs, like fertilizers, pesticides and seeds, making their farming activities more attractive, more lucrative and less risky (Bierkens et al., 2019; Smilovic et al., 2015; Shah, 2007). However, the overall economic contribution and water productivity may appear low in comparison with other water-using sectors due to a combination of relatively high water consumption per unit of production and low agricultural commodity prices. In the context of economic growth and increased urbanization, this often results in agriculture having to give up water for urban and industrial uses, due to their generally higher value added per unit of water use (Molle and Berkoff, 2009).

3.2.6 Groundwater for livestock

The volumes of groundwater used for livestock[9] drinking water are small in comparison to the volumes used to irrigate fodder crops for livestock (Shah et al., 2007). The irrigated production of fodder accounts for 98% of water (surface and groundwater) used for livestock, with the remaining 2% of water being used for drinking and cooling (Mekonnen and Hoekstra, 2012). Globally, an estimated 264 km³ of surface and groundwater per year is used for fodder production, equating to about a fifth of total agricultural water consumed and less than a third of water used for food crops (Heinke et al., 2020).

Rangeland under human-managed permanent meadows and pasture, mostly rainfed, covers almost 33 million km² of the Earth's surface, an estimated 70% of all agricultural land (Faostat, n.d.). The total number of livestock more than tripled, from 7.3 billion units in 1970 to 24.2 billion units in 2011 (FAO, 2018a). Intensification of livestock production is associated with a concentration of feed and water demand, especially in industrial farming, often associated with intensified pressure on land and in-situ water resources, for example in irrigated fodder cultivation under zero-grazing systems (IPES-Food, 2018).

Many arid and semi-arid rangelands depend entirely on access to groundwater to sustain drinking water for cattle. Groundwater well structures encourage stocking ratios higher than the rangeland carrying capacity in terms of natural vegetation for grazing, and also concentrate livestock around boreholes. The environmental sustainability of rangelands can be severely disrupted by the introduction of boreholes with power-driven pumps (Shah et al., 2007). In Somalia and northern Kenya, boreholes have enhanced water security, while also encouraging overstocking, resulting in disputes over water and pasture rights as well as the exclusion of vulnerable communities (Gomes, 2006).

Pastoralism plays a crucial role in supporting livelihoods across large parts of Sub-Saharan Africa (Giordano, 2006). While groundwater abstraction may be less intensive in livestock rangelands, land degradation due to livestock may have significant impacts on the recharge of groundwater and the quality of the same (Meglioli et al., 2013).

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[9] Livestock is used in a broad sense to cover all domestic animals regardless of age, location or purpose of breeding. Non-domesticated animals are excluded under this definition unless they are kept or raised in captivity. Livestock included are large and small quadrupeds, poultry, insects (bees) and larvae of insects (silkworms) (FAO, 2018a).

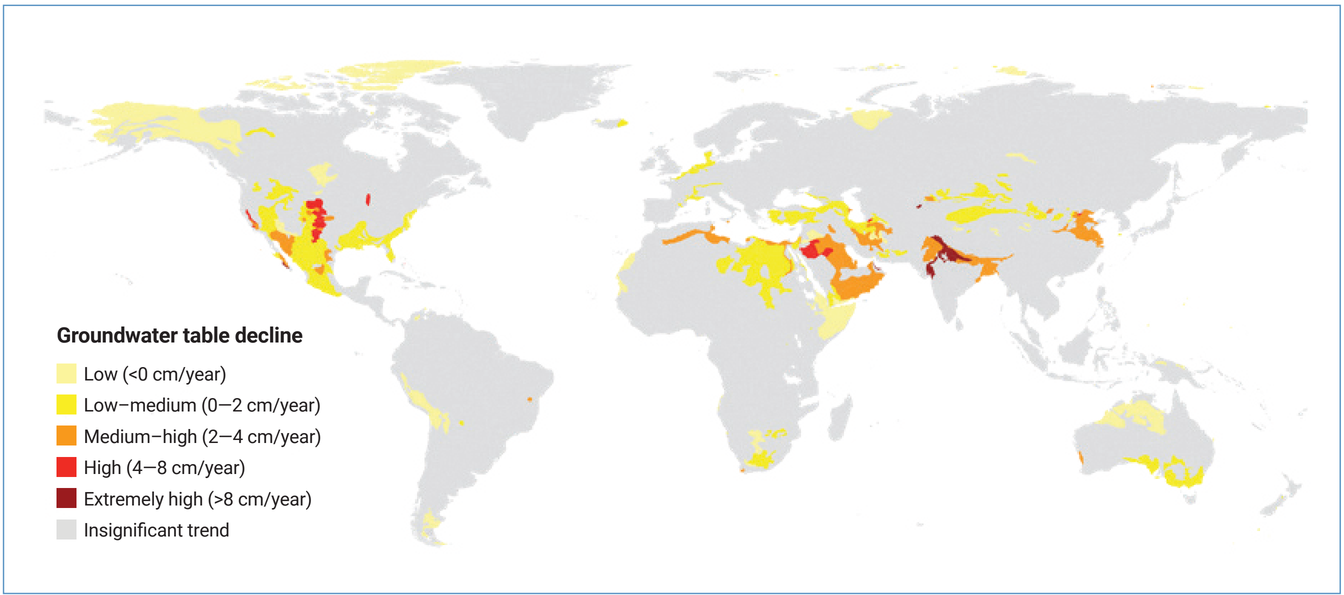
3.3 Impacts of agriculture on groundwater quantity

3.3.1 Groundwater depletion attributed to irrigation

Depletion of groundwater is often attributed to agricultural withdrawals. Depletion leads to a multitude of externalities, including drying up of groundwater-dependent wetlands and watercourses via reduced baseflows (see Chapter 6) and compaction of compressible earth layers, with ensuing land subsidence, downward migration of low-quality groundwater, and saline intrusion into aquifers and surface water systems along coastal plains.

Terrestrial observations and satellite data have demonstrated, or made plausible, that numerous aquifers are being exploited at rates that are inducing rapid depletion and associated social and environmental externalities. This includes several of the world's 37 major aquifer systems (Konikow, 2011; Gleeson et al., 2012; Scanlon et al., 2012a; Richey et al., 2015; Gong et al., 2018; Shamsudduha and Taylor, 2020) (Figure 3.2). High abstraction rates for irrigated agriculture are concentrated in arid and semi-arid regions, where population growth and expansion of irrigated areas have led to rapid growth in water demand.

Figure 3.2 Groundwater table decline in a selection of the world's major aquifers



Note: Groundwater table decline indicates the average yearly decline of the groundwater table over the study period (1990–2014).

Source: WRI (2019). Attribution 4.0 International (CC BY 4.0).

Groundwater exploitation has been driven by supply-push factors, such as its capacity to provide flexible, on-demand irrigation to support wealth-creating agriculture (Shah et al., 2007; Gleeson et al., 2012) and the easy availability of inexpensive pumps, drilling technologies and energy, often underpinned by government support and subsidy programmes. Demand-pull factors have also contributed, arising from the need to provide more food to increasing urban and rural populations.

The most notable depletion due to agricultural withdrawals occurs in continental aquifers associated with plains and coastal margins. Localized depletion in minor alluvial, coastal, deltaic and island aquifers (which are not shown in Figure 3.2) can also be partially attributed to agricultural withdrawals, leading to groundwater scarcity and pollution as well as saline intrusion, which threaten the potable water supply and limit agricultural production (Margat and Van der Gun, 2013).

Aquifers that are decoupled from contemporary recharge, notably those located in arid groundwater-dependent areas, present special and particularly alarming cases of groundwater depletion, as stored groundwater is permanently removed while the aquifer receives no or insignificant natural replenishment under the current climate (Bierkens and Wada, 2019) (Box 3.1).

Such non-renewable aquifers, receiving a negligible rate of recharge on the human timescale, require long-term strategies for planned depletion, in which alternative measures to secure basic water supply, while transforming the economy to a less water-intensive one, are essential. The time horizon over which to achieve such goals is a critical planning parameter, but it is associated with large uncertainty, as the absolute storage capacity and the economic feasibility of abstraction of finite aquifers remain uncertain (Foster and Loucks, 2006). Many parts of renewable aquifers are likely subjected to irreversible depletion as well, as refilling them from natural recharge, or even enhanced recharge, is infeasible. This may be because of compaction and subsidence of the aquifers, or because the natural refilling of the aquifers would be impossible owing to the extended time that would be required, let alone the external water resources needed to refill them artificially.

Unabated groundwater depletion in agricultural areas is becoming an issue of increasing concern regionally and globally

Unabated groundwater depletion in agricultural areas is becoming an issue of increasing concern regionally and globally, as it threatens to undermine food security, basic water supply, environmental integrity and climate resilience. This vexing issue sees limited progress, requiring increased management and governance capacity at multiple integrated levels and in intersectoral approaches (OECD, 2016) (see Chapters 2, 11 and 12).

Box 3.1 Groundwater depletion in Egypt

A notable development in the last decade is the proliferation of high-capacity and efficient borewells that are able to access groundwater hundreds of metres deep. Egypt began intensive groundwater development for irrigation in the 1960s through the New Valley project, tapping non-renewable groundwater resources of the Nubian Sandstone Aquifer system in the Western Desert of the country (Powell and Fensham, 2016). Subsequent projects and plans have accelerated the rate of irrigation expansion supplied by intensive groundwater abstraction. For instance, the Developing Southern Egypt project, 1997–2017, included the creation of 216,000 ha of irrigated area in the Toshka area in the southeast of the Western Desert. The project used surface water from the Nile River and groundwater from the Nubian Sandstone Aquifer, through borewells reaching depths of 200–1,200 m. From 1997 to 2006, groundwater levels dropped by up to 13.8 m in parts of the aquifer. Further plans to irrigate an additional 10,500 ha solely from groundwater through 50 borewells is expected to lead to further lowering of groundwater levels by 15 m (Sharaky et al., 2018). Critical surface expressions of the aquifer, in terms of artesian desert springs and oases, that have supported ancient civilizations and livelihoods, are now compromised as a result of this intensification of water and land use (Powell and Fensham, 2016).

Groundwater models that incorporate land use changes and estimates of withdrawals and recharge are used to track groundwater depletion (Konikow, 2013). Verifying the scale and magnitude of depletion trends using remote sensing by monitoring water storage changes in the Earth’s crust, through NASA’s Gravity Recovery and Climate Experiment (GRACE) satellite mission, remains challenging (Famiglietti, 2014). This is largely due to the coarse resolution of the gravity anomalies used to infer water storage changes (Vishwakarma et al., 2021). Modelled estimates suggest that between 2000 and 2009, global groundwater depletion for all uses was in the order of 113 km^3/year (Döll et al., 2014), while other models suggest volumes in the order of 304 km^3/year for 2010, of which about 75% was attributed to agriculture (Dalin et al., 2017; Wada, 2016). In practice, quantifying aquifer storage depletion at the global scale is still conjectural, as boundary, recharge and leakage conditions remain dynamic and uncertain. However, models increasingly include measured piezometric heads as a valuable indicator of storage changes, providing more certainty in estimates of depletion of local and regional aquifers (Haacker et al., 2016).

It is increasingly recognized that the virtual water embedded in crop products and their global redistribution via international trade is critical for understanding and managing sustainable water abstraction levels globally (Chapter 1). It is estimated that about 11% (or 25 km³/year) of global groundwater depletion is embedded in international crop trade (Dalin et al., 2017), supporting food security and economic growth, but also significantly contributing to large-scale depletion of aquifers overlaid by productive land. Wheat, maize, rice, sugarcane, cotton and fodder are the principal crops contributing to groundwater depletion. These crops are also heavily traded, indicating highly unsustainable water footprints[10] (of which groundwater is a large share) from intensive export of crops for food, fodder and fibre consumption by humans and livestock (Mekonnen and Gerbens-Leenes, 2020). Five countries account for about 70% of the unsustainable water footprint: China, India, Iran, Pakistan and the USA. Of the total unsustainable water footprint, 90% was for food and fodder crops, while 10% was for fibre crops, rubber and tobacco (Mekonnen and Gerbens-Leenes, 2020).

3.4 Agricultural lands with shallow groundwater tables

Shallow groundwater tables can present both opportunities and constraints for cultivation. On the one hand, shallow water tables can be problematic to agriculture due to the risk of waterlogging resulting from rainfall or irrigation in areas with inadequate natural or artificial drainage. This can lead to progressive soil salinization, notably in dry regions. On the other hand, shallow controlled water tables can be favourable to agriculture as they ensure continuous water availability for optimizing crop yields, even during extended dry periods. Smallholder farmers throughout Africa and Asia are reliant on seasonal and perennial shallow groundwater for cultivation (Pavelic et al., 2013; Pavelic et al., 2012; Shah, 2009).

While most inhabited arid and semi-arid areas of the world, including areas that used to have a good water endowment (Box 3.2), are experiencing groundwater depletion today, evidence shows that other regions, for instance Northern Europe, under current climate scenarios are facing net groundwater accumulation, seasonally or over several years, through longer periods of sustained higher-than-normal rainfall, potentially leading to waterlogging and flooding. This can cause significant challenges for agriculture and calls for proactive shallow groundwater management, like in the United Kingdom (Macdonald et al., 2008). The Netherlands is naturally prone to flooding and is constantly managing groundwater levels through artificial drainage and pumping (Zeeberg, 2009). In large parts of the Netherlands, shallow water tables have for centuries been artificially controlled, keeping groundwater tables close to crop/vegetation-optimal levels. Similarly, other low-lying countries like Denmark are reliant on widespread artificial sub-surface tile drainage in regions with clayey soil, which controls groundwater levels and keeps the soil and cropping conditions workable whilst protecting infrastructure, including roads (Kidmose et al., 2013).

3.5 Impacts of agriculture on groundwater quality

3.5.1 Agricultural groundwater pollution

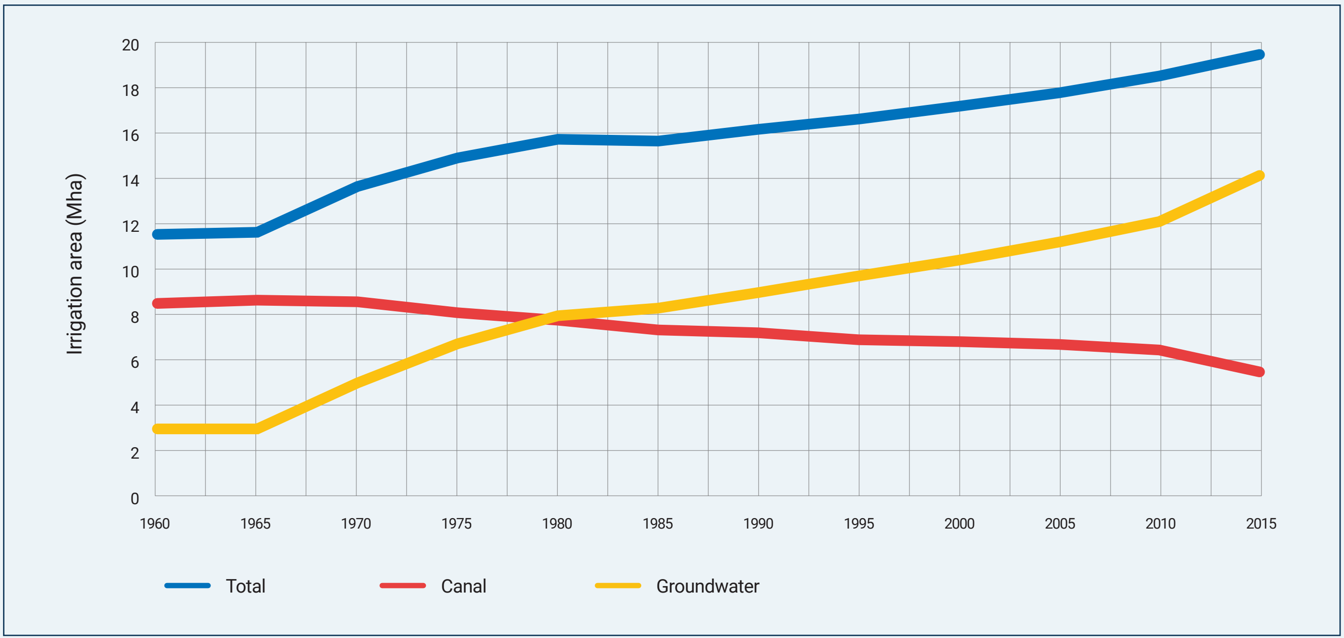
It is estimated that agricultural pollution has overtaken contamination from settlements and industries as the major factor in the degradation of inland and coastal waters (FAO, 2018a). The principal pollutants from agriculture are nutrients, pesticides, salts, sediments, organic carbon, pathogens, metals and drug residues. Nitrate, from chemical and organic fertilizers, is the most prevalent anthropogenic contaminant in groundwater globally (FAO, 2018a), notably leading to eutrophication of surface waters (Smolders et al., 2010). In the European Union, 38% of water bodies are under significant pressure from agricultural pollution (WWAP, 2015); in the USA, agriculture is the principal source of pollution of rivers; and in China, agriculture is responsible for a large proportion of surface and groundwater pollution by nitrogen (FAO, 2013).

10 The water footprint is considered 'unsustainable' if it is above the available renewable blue water and violates the environmental flow requirements (Mekonnen and Gerbens-Leenes, 2020).

Box 3.2 Surface water irrigated agricultural lands with shallow water table – the case of Pakistan

The Indus basin aquifer in Pakistan holds in storage at least eighty times the volume of freshwater held in the country's three largest dams. Yet the country is on the brink of a severe groundwater crisis (Lytton et al., 2021). Pakistan is the fourth-largest user of groundwater, responsible in 2010 for 6.6%, and in 2017 for 6.4% of the global groundwater abstraction (Margat and Van der Gun, 2013; Aquastat, n.d.), whilst occupying 4.6% of the total groundwater-irrigated area of the world (Bhutta and Smedema, 2007). The extensive use of groundwater in the country started in the 1960s, when large drainage wells were installed under government-funded Salinity Control and Reclamation Projects (SCARPs) to control waterlogging and salinity problems in 2.6 Mha of the irrigated lands, particularly in the Punjab province (Qureshi, 2020). Over time, shallow groundwater use was increasingly adopted by farmers as a way to expand irrigated areas, crop production and incomes, while coping with droughts. More secure water access helped increase crop yields by 50–100%. By 1980, the area irrigated by groundwater had surpassed the area irrigated with surface water (see graph below), while substantial parts of the cultivated land are in effect irrigated conjunctively, by combining the two, partially to control the generally higher salinity in groundwater. In short, Pakistan has over a period of 60 years turned from a surface water-dependent country to a groundwater-dependent country, and from a groundwater surplus country to a country with significant issues of groundwater overdraft, exacerbated by increasing salinity issues due to the use of poor-quality groundwater for irrigation. Approximately 21% of the irrigated area is affected by salinity, threatening the country's food security, as irrigated land is responsible for more than 90% of its total grain production (Qureshi, 2020).

Historical development of groundwater- and surface water-irrigated areas in Pakistan



Source: Qureshi (2020, fig. 4, p. 6).

Types of pesticides commonly used in agriculture include insecticides, herbicides and fungicides (Schreinemachers and Tipraqsa, 2012). When improperly applied or disposed of, they can pollute soil and water resources with carcinogens and other toxic substances, while their degradation products can be hazardous to the terrestrial and aquatic biosphere, as well as to human health (Tang et al., 2021; Sharma et al., 2019). The global market in pesticides is worth more than US$35 billion per year (FAO, 2018a). Contamination with organic micro-pollutants, like pesticides, in agricultural areas is less documented in emerging economies. However, where the issues have been investigated in vulnerable socio-economic environments with intensive agriculture, results have shown the presence of contaminants in excessive concentrations (Wentworth et al., 2021), indicating an emerging environmental and health hazard of critical concern.

Excessive accumulation of salt in groundwater through brackish drainage and seawater intrusion (Mateo-Sagasta and Burke, 2010) has increased with irrigation expansion, further exacerbated by climate change. Irrigation can mobilize salts accumulated in dryland soils, which are then transported by drainage water to aquifers and other receiving water bodies (FAO, 2018a). Major water salinity problems in agricultural land have been reported in Argentina, Australia, China, India, Pakistan, Sudan, the USA and many countries in Central Asia (FAO, 2018a; Shahid et al., 2018; Thorslund and Van Vliet, 2020). Estimates indicate that between 20–23% and 25–33% of the global land area under cultivation and irrigation, respectively, are saline and hampered in terms of agricultural productivity (Shahid et al., 2018; Jamil et al., 2011), principally in arid and semi-arid regions.

Evidence suggests that laws and regulations to prevent or limit diffuse groundwater pollution from agriculture, and especially their enforcement, are generally weak

The use of antibiotics for intensive livestock farming has increased with the growing global demand for meat (Manyi-Loh et al., 2018). It is largely unregulated in developing countries, with China as the leading registered producer and consumer of antibiotics within livestock farming (Maron et al., 2013). While antibiotics protect animals from infections, they also generate antibiotic-resistant bacteria that can be pathogenic to humans and that are very difficult to treat (Prestinaci et al., 2015). They are typically transmitted to the environment, including groundwater, through animal waste. A widespread prevalence of antibiotic-resistant bacteria has been documented at the global level (Manyi-Loh et al., 2018), with groundwater contamination reported in China (Xiao et al., 2016), Kenya (Wahome, 2013), South Africa (Carstens, 2013) and the USA (Li et al., 2015).

3.5.2 Economic, health and environmental impacts

The global environmental and social costs of agriculture-derived surface and groundwater pollution are estimated to exceed billions of dollars annually (OECD, 2012a). In the USA, pesticide contamination of groundwater and eutrophication of freshwater are estimated to cost US$1.6–2 and US$1.5–2.2 billion per year, respectively (Pimentel, 2005; Dodds et al., 2009). The global annual cost of salt-induced land degradation in irrigated areas is estimated at US$27.3 billion through the loss of crop production (Qadir et al., 2014).

Groundwater pollution from agriculture has direct negative impacts on human health. For instance, high levels of nitrates in water can cause methaemoglobinemia (blue-baby syndrome) in infants (Majumdar, 2003; Knobeloch et al., 2000). Whereas water quality standards for pollutants are generally stricter in terms of protecting human health than for the environment, nitrate is an example where the levels required to protect water bodies from eutrophication are lower than for methaemoglobinemia (Hinsby et al., 2008). Pesticide accumulation in water and the food chain, with demonstrated ill effects on ecosystem and human health, led the multilateral Stockholm Convention on Persistent Organic Pollutants to ban certain persistent pesticides (such as DDT and many organophosphates) in 2001 (Tang, 2013). However, a number of banned pesticides are still used in least developed countries, causing acute and likely chronic health effects (Ngowi et al., 2012).

3.5.3 Pollution control in the agricultural sector

Evidence suggests that laws and regulations to prevent or limit diffuse groundwater pollution from agriculture, and especially their enforcement, are generally weak (Groundwater Governance Project, 2016a). There has been more progress in groundwater laws and regulation than in effective implementation and enforcement, which represents a significant obstacle to sustainable groundwater management. In many countries, regulations are poor or non-compliance is pervasive, with groundwater pollution continuing largely unchecked. Attempts to regulate diffuse pollution through pollution fines have not worked, as it is difficult to identify polluters (OECD, 2017a). Economic instruments for pollution control of surface and groundwater are increasingly employed. These include taxes, 'set-asides' (the conversion of agricultural land to natural uses) and payments to limit production or the intensity of land use. Taxes include polluter payments, dedicated environmental taxes, and taxes on technologies, products and inputs that have adverse ecological consequences (e.g. pesticides), according to the level of hazard, or conversely subsidies on environmentally friendly technologies. Well-known approaches for reducing pollution, such as 'the polluter pays principles' are possible, through green taxes on pesticides and fertilizers, for example, but they are not often applied, are priced too low to act as deterrents, or have unintended distributional impacts, as poor farmers will be hit harder by such taxes (OECD, 2011; 2017a).

A combination of pollution control measures, including regulation, economic incentives, as well as information, awareness campaigns and data dissemination, is considered to work more effectively than regulations alone (OECD, 2008). Policies addressing water pollution in agriculture should be part of an overarching agriculture and water policy framework at the national, river basin and aquifer scale. Policies to promote information and awareness to change farmer behaviour and incentivize the adoption of Best Management Practices (FAO, 2018a) for agriculture are important to preventing pollution at the source (Liu et al., 2018). For instance, benchmarking can promote behavioural change among farmers by showing them how they perform in comparison to other farmers, in terms of the application of fertilizers and pesticides. Promoting Corporate Social Responsibility within the private sector is also advocated (FAO, 2018a).

3.6 Groundwater and energy linkages in irrigation

Groundwater abstraction and energy use are closely interrelated. Rural electrification has been a principal driver for groundwater development in India (Shah, 2009; Smith and Urpelainen, 2016). Concentration of groundwater development is notable when rural power grids are extended into areas that would otherwise rely on diesel generation or wind energy, such as evidenced in Ethiopia, Kenya and South Africa (Villholth, 2013a). Conversely, power utilities can face significant losses in revenue when declining groundwater levels and rising irrigation costs lead to diminishing pumping, as evidenced in the central USA (Rhodes and Wheeler, 1996).

Advances in solar technology have witnessed the development of Solar-Powered Irrigation Systems (SPIS), adopted at scale to service farming operations. These range from large-scale commercial operations, e.g. in Australia, to small-scale farmers in areas with relatively shallow groundwater, notably in remote locations producing high-value crops, such as in Afghanistan (FAO, 2018b). The proliferation of SPIS, either as grid-connected or off-grid solutions, can be attributed to the declining cost of solar panels over the last decade, in addition to government subsidy programmes, which have made such technology a viable option, particularly for small-scale farmers (FAO, 2018b). SPIS provide reliable, affordable and climate-smart energy for irrigation (Box 3.3). However, there is a risk of unsustainable water use if SPIS implementation is not adequately managed and regulated (FAO, 2018b). Once the systems are installed, there is no cost per unit of power and thus no financial incentive for farmers to save electricity for groundwater pumping. SPIS can therefore lead to over-abstraction of groundwater, and low field application efficiency. In some cases, farmers sell water to their neighbours at a profit, increasing overall groundwater withdrawals (FAO, 2018b; Closas and Rap, 2017). The linkage between energy subsidies and groundwater pumping for irrigation are well established, for instance with evidence from India (Scott and Sharma, 2010) (Box 3.4), Iran (Jamali Jaghdani and Kvartiuk, 2021) and Mexico (Scott, 2013).

Box 3.3 Energy and irrigation in Sub-Saharan Africa

Sub-Saharan Africa is characterized by poor energy infrastructure and low levels of electricity access, which correlate with low levels of agricultural development, including development of groundwater. In stark contrast, the continent has among the highest levels globally of solar energy availability (IEA, 2019a). Agriculture is largely rainfed, but as a result of population growth and climate change, there is a clear need to expand food production to ensure food security and build resilience. Groundwater resources across the region are generally underutilized, so that there is a high potential to sustainably expand small-scale irrigated agriculture if affordability and other constraints can be overcome (Altchenko and Villholth, 2015). The cost of small-scale SPIS have reduced significantly in recent years and are beginning to enter the market, particularly in East Africa where distributors and supply chains are better developed (Efficiency for Access, 2019). Diesel-driven pumps are cheaper to purchase but costlier to run than solar energy devices, and they generate high greenhouse gas emissions. It is anticipated that the mix of energy supply for small pumps across the region will depend on factors such as farmers' crop choice and the future price of diesel and appropriate solar technologies (Xie et al., 2021). With growing demand, better governance and co-management of groundwater and energy will be required to ensure sustainable resource use.

Box 3.4 Groundwater and energy in India

India is the world's largest user of groundwater. It has an annual draft of around 251 km³, 89% of which is used for irrigation (Margat and Van der Gun, 2013 – Figure 3.1), withdrawn through an estimated 20 million wells and tubewells. An estimated 60% of the irrigated area in India is served by groundwater (Shah, 2009). Groundwater-led irrigation was instrumental in the success of the Green Revolution in India from the 1960s. However, it has become apparent that gains in irrigated agricultural production have progressively led to a significant decline in groundwater levels in parts of the country, particularly in northwestern and peninsular southern India (Shah, 2009). Currently, India's water crisis can be largely traced to the expansion of groundwater irrigation, a trajectory set on course by India's food and electricity policy since the late 1970s. The food policy guaranteeing cheap food to consumers dictates the need to keep input prices low, including the level of electricity tariffs for pumping groundwater. Reduced electricity tariffs or free electricity to agriculture, as exist in many Indian states, coupled with assured state or government procurement of crops, encourage farmers to grow water-intensive crops, such as sugarcane, including in semi-arid regions with low natural recharge. This is responsible for unprecedented groundwater depletion in large parts of India (Mukherji, 2020).

Groundwater overwithdrawal in India can be traced to a lack of coherence between water, energy and food policies. Hence, solutions to India's groundwater problems should be positioned within a broader water–energy–food nexus context (Shah et al., 2012). Indirect management of groundwater through electricity policies have been attempted in many states in India. This has ranged from metering agricultural electricity connections and charging farmers near-commercial rates for irrigation (e.g. in the state of West Bengal – Mukherji et al., 2009); to rationing electricity to farmers to a limited number of hours in a day, made possible by bifurcation of electric feeders into agricultural and domestic feeders (e.g. in the states of Gujarat, Karnataka and Punjab – Shah et al., 2008; Mukherji, 2017). Both these measures, the pricing and the rationing of electricity, are meant to reduce demand for groundwater by giving price and scarcity signals, respectively (Sidhu et al., 2020). More recently, concerns about high carbon emissions from India's groundwater pumping and about the mounting subsidy burden on the electricity utilities, have led to pilots of Solar-Powered Irrigation Systems (SPIS). Grid-connected SPIS are being promoted to incentivize farmers to pump less groundwater while selling electricity back to the grid rather than using it for pumping groundwater (Shah et al., 2018), but evidence of whether grid-connected SPIS actually reduce groundwater pumping is still not available. Estimates of greenhouse gas emissions from groundwater pumping relative to the total national emissions from energy use range from 0.5% in China (Wang et al., 2012) and 3.6 % in Mexico (Scott, 2013) to 8–11% in India (Rajan et al., 2020). Compounding the situation, methane embedded in deep anoxic groundwater, released as groundwater is pumped to the surface, may also add to this budget (Kulongoski and McMahon, 2019).

Chapter 4

Groundwater for human settlements

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4.1 Introduction

4.1.1 Scope of topic

The chapter gives an overview of groundwater supply for domestic uses (including drinking water) in both urban and rural settings, and is intimately linked with the United Nations Sustainable Development Goals (SDGs) 3 and 6 for 2030. Water supply can be provided by public utilities, commercial operators, individual householders and community organizations. While the major part of urban water is generally supplied by water utilities, private urban self-supply from groundwater has grown markedly in many developing country cities. The role of groundwater in rural water supply is the other major focus of the chapter, noting that waterwells[11] are often the only year-round reliable source of village drinking water. The chapter also examines the hazards of groundwater use and the issue of groundwater pollution due to inadequate urban and rural sanitation.

4.1.2 Brief historical evolution

Since the earliest times, humankind has met its need for good quality water from subterranean sources (Margat and Van der Gun, 2013). Springs, the surface manifestation of underground water, played a key role in social development, and the first waterwells were sunk initially in parts of Asia, the Middle East and Ethiopia to depths of up to 50 metres.

Groundwater exhibits numerous benefits as the basis for water supply development by public utilities

During the 20th century, there was a major boom in waterwell construction for urban water supply. Major advances in waterwell drilling, pumping technology, energy access and geological knowledge allowed for faster drilling of deep boreholes, and for the extraction of larger quantities of water. Shallow wells, installed with affordable technology and fitted with handpumps, were developed for community supplies in rural areas. Groundwater thus became a key natural resource supporting human well-being and economic development – but one that was still widely misunderstood, undervalued, poorly managed and inadequately protected (IAH, 2015).

4.1.3 Data on groundwater abstraction

Global groundwater withdrawals were estimated to have exceeded 900 km^3/year by 2010, with waterwells and springheads providing some 36% of potable water supply (Döll et al., 2012; Margat and Van der Gun, 2013). The groundwater dependence of innumerable cities appears to be intensifying, such that nearly 50% of the global urban population are believed today to be supplied from groundwater sources (Foster et al., 2020a). In the case of the European Union (EU) and USA, groundwater provides the public water supply for 310 and 105 million people, respectively. However, comprehensive national statistics on groundwater pumping for human settlements are patchy (Table 4.1).

The social value of groundwater should not be gauged solely by volumetric withdrawals. This is because groundwater use brings major economic and health benefits, possibilities to scale on demand, high drought reliability, generally good quality requiring minimal treatment (IAH, 2015), and time saved by women and girls in locations where they are the main water fetchers. However, very high rates of urban population growth are generating unprecedented demand for water supply and sanitation, creating an enormous challenge for urban planning.

[11] The term waterwell is used generically here to cover all forms of dug wells, shafts, boreholes, borewells, tubewells, galleries and adits used for water abstraction.

Table 4.1 Selected country data on urban groundwater abstraction

Country	Population (millions)	Urban population (millions)	Utility water supply (Mm^3/year)	Utility groundwater supply (Mm^3/year) and proportion	Selected cities with major groundwater use
Brazil	209.3	178.2	16 740 **	3 164 (19%)	Natal, Ribeirão Preto, São Luís do Maranhão
Chile	16.4	14.7	1 267	498 (39%)	Santiago, Coquimbo, Concepción
Costa Rica	4.9	4.0	652	522 (80%)	San José, Puntarenas, Liberia
Mexico	129.2	102.1	14 230 *	7 000 (49%)	Mexico City, Mérida, San Luis Potosí, León
Paraguay	6.4	3.9	362 *	272 (75%)	Asunción, Villarica
USA	324.5	270.7	58 390 *	21 001 (36%)	Miami, Tampa, Phoenix, Oklahoma
Côte d'Ivoire	24.3	12.2	321 **	n/a	Abidjan, Bouake
Ethiopia	105.0	21.3	810 *	n/a	Addis Ababa, Dire Dawa
Kenya	49.7	13.2	495 **	n/a	Mombasa, Nakuru
Senegal	15.9	7.4	98 *	n/a	Dakar, St. Louis
Tanzania	42.9	9.9	328 **	n/a	Dodoma, Arusha, Tanga
Zambia	17.1	7.3	290 **	60 (21%)	Lusaka, Kabwe
India	1 339.2	455.3	56 000 **	13 328 (24%)	Lucknow, Chennai, Chandigarh, Indore
Pakistan	197.0	70.9	9 650 **	2 934 (30%)	Islamabad, Lahore, Rawalpindi, Multan
China	1 409.5	817.5	79 400 *	7861 (10%)	Tianjin, Beijing, Handan, Shenyang
Indonesia	964.0	145.2	23 800 **	21 420 (90%)	Jakarta, Semarang, Yogyakarta
Viet Nam	95.5	33.4	1 206 *	555 (46%)	Ho Chi Minh City, Da Nang, Hanoi
Bangladesh	164.7	59.3	3 600 **	2 603 (72%)	Dhaka, Khulna, Chattogram
Denmark	5.8	5.1	230	230 (100%)	Copenhagen, Odense, Aarhus, Aalborg
France	67.0	53.9	1 774	1 064 (60%)	Paris, Caen, Limoges, Le Mans, Poitiers
Germany	83.1	64.1	1 606	1 188 (74%)	Hamburg, Berlin, Munich, Hanover
Hungary	9.7	7.0	257	244 (95%)	Budapest, Miskolc
Italy	60.3	42.6	1 391	1 210 (87%)	Rome, Milan, Turin, Perugia
Netherlands	17.4	15.8	489	298 (61%)	Utrecht, Eindhoven, The Hague
Poland	37.2	22.8	576	357 (62%)	Warsaw, Wrocław, Poznań, Cracow
UK	66.8	55.5	3 558	1 245 (35%)	Portsmouth, Hull, Cambridge, Brighton

Note: ** / * private self-supply from groundwater is a major or significant issue, respectively.

Source: Based largely on UNICEF/WHO (2019) data for 2017, which often underestimate groundwater abstraction and provide no data on private in-situ waterwell use.

Table 4.2 Summary of the benefits of groundwater sources to water service utilities

Groundwater assets	Water supply benefits
• Widespread distribution, with direct access in many outlying districts • Natural quality is generally excellent, requiring minimal treatment (except where affected by anthropogenic pollution or by natural contamination – Foster et al., 2020b)	• Development usually involves low capital and few recurrent costs (except in a few hydrogeological settings), which can be staged in cases of rising demand
• Huge natural reservoirs that can be used for long-term water storage • Buffered against rainfall variability unlike surface water sources	• High level of water supply security in drought and river pollution episodes

Source: Foster et al. (2020a).

4.2 Urban water supply

4.2.1 Public systems

Groundwater exhibits numerous benefits as the basis for water supply development by public utilities (Table 4.2), with its typically high natural quality requiring only precautionary disinfection before entering distribution systems (Box 4.1).

Urban centres underlain and/or surrounded by high-yielding aquifers usually have better public water service levels and lower water prices – because of the potential to expand water supply production incrementally in response to rising demand at modest cost (IAH, 2015). Thus, most settlements located in favourable hydrogeological settings will initially have significant dependence on groundwater for their water supply (Figure 4.1) and significantly increased water supply security during extended drought or surface water pollution incidents (Foster et al., 2018).

Box 4.1 An example of successfully managed urban groundwater abstraction in Hamburg (Germany)

Hamburg has a population of some 2.2 million served by a municipally owned water utility. In 1964, after a long transition, it switched from filtered river water to groundwater for its water supply. Today, it operates about 470 waterwells pumping some 120 million m³/year from the shallow alluvial aquifer and a deeper formation. Nine of the corresponding capture areas have legal status as groundwater protection zones, but three are located outside the city's jurisdiction and their protection has to be negotiated with neighbouring authorities. In some cases, conflicts have arisen since the shallow aquifer is vulnerable to agricultural and industrial pollution, while the deeper aquifer is threatened by salinization from adjacent salt domes.

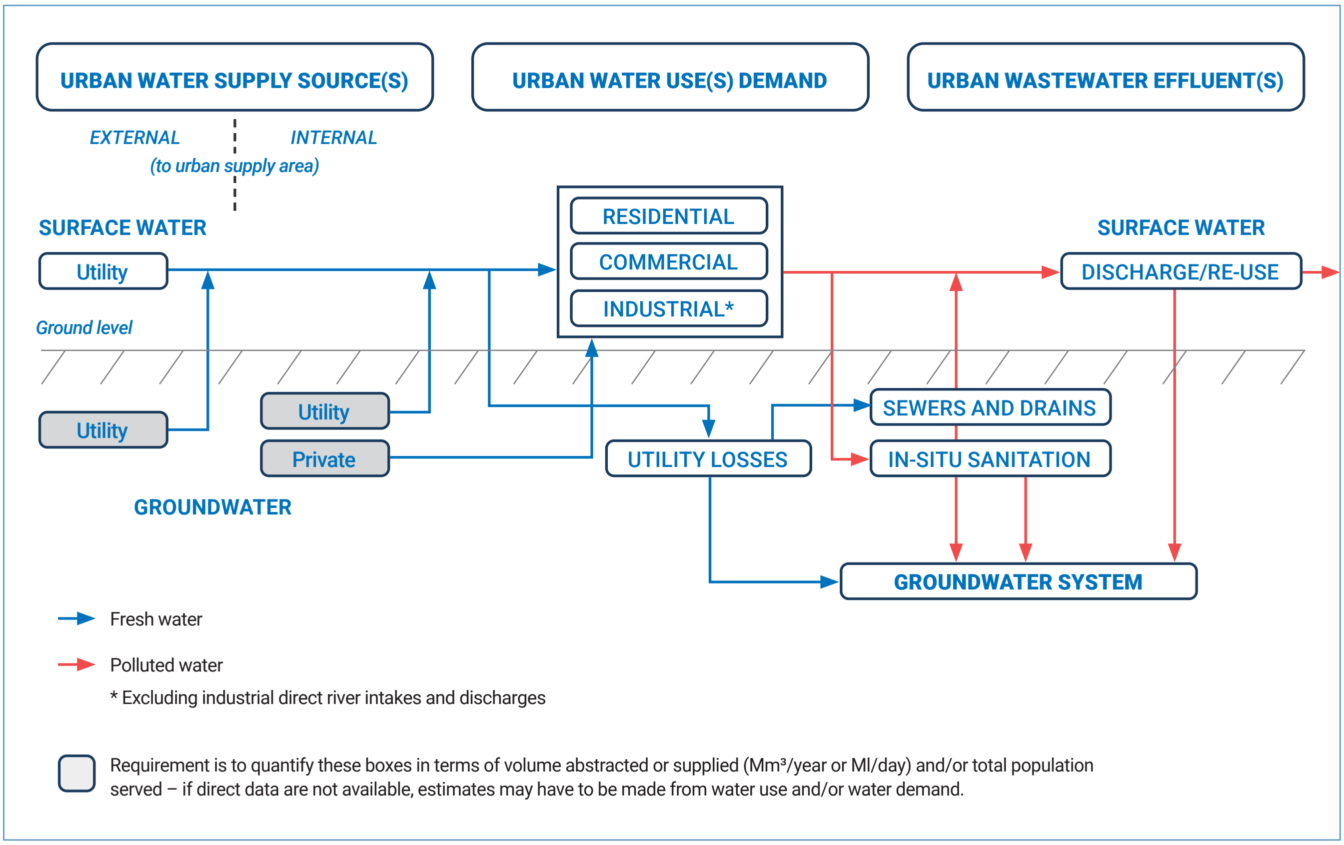
The water utility thus maintains its own network of about 1,400 monitoring boreholes, which provide a full and dynamic picture of groundwater quality. The data are stored in a digital information system, which also contains groundwater level data. In cooperation with the government geological agency, a numerical groundwater model has been elaborated covering 4,500 km² with over 3,000 production waterwells and calibrated with over 7,000 monitoring boreholes. This is used for wellfield management decision-making, water rights applications, interaction with industrial groundwater abstraction, refinement of groundwater protection areas and control of any serious pollution.

Source: Foster et al. (2020a).

Indirectly, groundwater contributes to urban poverty reduction by allowing water utilities to develop sources at much lower cost and allow lower connection charges. However, many urban poor live in peri-urban settlements, which are unplanned and lack legal status, and city planners often impede the provision of public infrastructure (power and water services) to such areas (IAH, 2015).

Looking forward, the widespread presence of groundwater resources will allow rapid development of utility waterwells as the 'hub' of new decentralized systems of water service provision for the fast-developing outer urban districts with populations of 20,000–50,000 (IAH, 2015). Such systems could minimize infrastructure costs, energy use and water losses, with deep waterwells generally being well suited to be their water sources. In order to reduce subsurface contaminant loads from in-situ sanitation, waterwell construction should be combined with the separation/recovery of urine to serve as fertilizer and the recovery of faeces for energy generation (i.e. valuing wastewater as a resource). Moreover, a special effort will be needed on the ground to control other sources of urban groundwater contamination (such as petrol stations, small-scale motor shops, garages and dry-cleaning laundries).

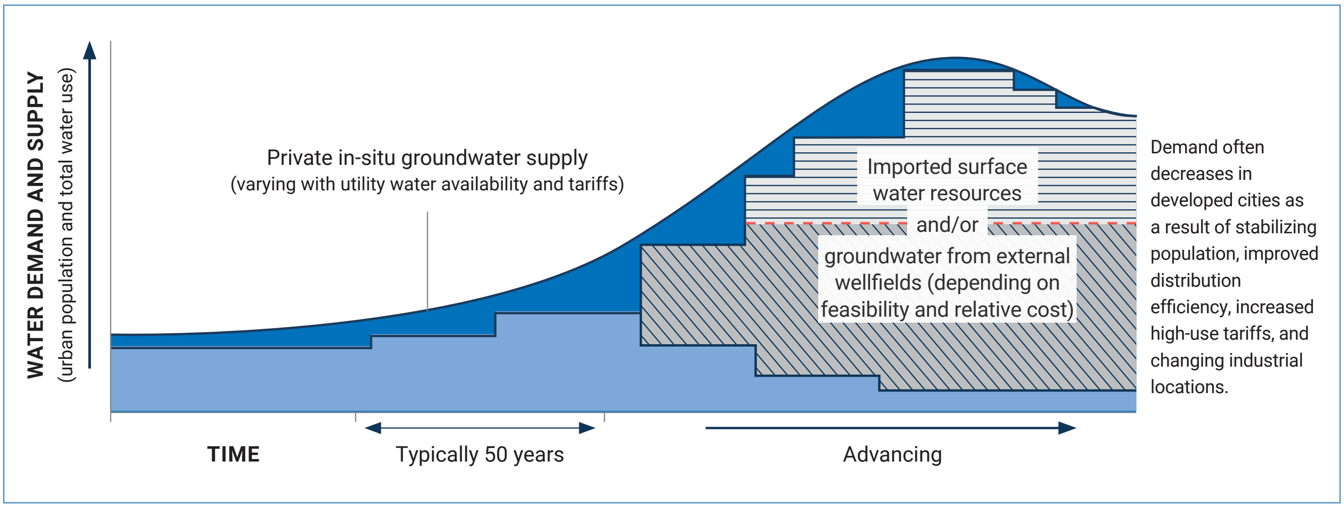
Figure 4.1 Schematic overview of urban water sources and their use and interaction



Source: Adapted from Foster and Hirata (2012, fig. 1, p. 22).

Within the limits of larger cities, there is often not enough groundwater available to meet the water demand sustainably (Figure 4.2). Where high-yielding aquifers are present in the immediate hinterland, the development of 'external wellfields' is an attractive option, compared to long-distant import of surface water resources. The capture area of these wellfields should be protected against pollution and overexploitation by land use controls and waterwell regulation, respectively.

Figure 4.2 Typical trend in the evolution of urban water supplies



Source: Adapted from Foster and Hirata (2012, fig. 2, p. 22).

The presence of major aquifers in the vicinity of cities can enhance urban water supply resilience, because they provide a 'natural buffer' against variability of river flows and surface reservoir levels, as a result of the very large volume of groundwater held in storage (Foster et al., 2020a; 2020c). The water stored in aquifers is also naturally protected from evapotranspiration losses and less vulnerable to pollution than surface water.

Box 4.2 Planned conjunctive use scheme to conserve a critical aquifer in Lima

Lima extends across the hyper-arid outwash fans of the Rímac and Chillón Rivers. Groundwater recharge arises from riverbed infiltration (recently enhanced), irrigation canal seepage, excess irrigation to agricultural and amenity land (reducing), and leakage from water supply mains and sewers. During the 1960s–1980s, the city grew rapidly to over 8 million and its water demand increased to more than 2,000 Ml/day in 1997. The waterworks on the Rímac River were expanded to a capacity of 860 Ml/day, although maximum production is not possible at times of extreme concentrations of suspended solids or during periods of drought. Of the total water supply in 1997, 1,050 Ml/day was derived from groundwater (including 720 Ml/day from 380 utility waterwells) with a resultant water table decline of 1–5 m/year, resulting in costly side effects.

Major studies were made to optimize conjunctive use through the concerted micro-measurement of domestic water use to reduce wastage, the reduction of groundwater abstraction in defined critical areas, additional Andean surface water transfers to the Rímac River of up to 260 Ml/day, improved flexibility of water distribution to allow most users to be supplied by either source, and riverbed recharge enhancement over 6 km of the Rímac River. Institutional arrangements empowered the water utility to act on behalf of the government. The success of the conjunctive use scheme is witnessed by the recovery of 5–30 m of the water table between 1997 and 2003 (following a decline of 10–40 m in the preceding 10 years), with water utility abstraction reducing from 265 Mm³/year in 1997 to 135 Mm³/year by 2009, while maintaining the capacity for higher production in the short term.

Source: Adapted from Foster et al. (2010a, Box B, p. 10).

Managed conjunctive use of groundwater and surface water can enhance water supply security, and has been successfully implemented in a wide range of cities, such as Lima

Managed conjunctive use of groundwater and surface water can enhance water supply security, and has been successfully implemented in a wide range of cities, such as Lima (Box 4.2). A recent project in Delhi captures excess monsoon river flow to recharge the aquifer supplying drinking water to the city, which is another form of conjunctive use.

In Brazil, for example, cities supplied with only surface water were almost twice as likely to be impacted by the major 2013–2017 drought as those with significant groundwater use (Foster et al., 2020a). In 70 Indian cities and towns, groundwater provides a 48% share of the urban water supply (Alam and Foster, 2019), but in Chennai (Box 4.3), for example, water supply security has been undermined by excessive aquifer exploitation. The inherent prejudice of some water utility staff for developing and operating large surface-water reservoirs can result in failure to make strategic use of local groundwater resources, which was an aggravating factor in the recent Cape Town water supply crisis (Olivier and Xu, 2019).

4.2.2 Private and community self-supply

The term self-supply is used to refer to water supply investments that are financed by users themselves (Foster et al., 2010b; Oluwasanya et al., 2011; Foster and Hirata, 2012; Coulibaly et al., 2014). In developing economies, most self-suppliers use groundwater and share their supply with neighbours (Sutton and Butterworth, 2021), and self-supply from groundwater provides a rapid solution in areas where it is technically feasible to those who can afford it.

Investments in private waterwells unlock significant finance for water supply access, and documented evidence as well as recognition of this phenomenon is growing (Foster et al., 2010b; Grönwall, 2011; Butterworth et al., 2013; Sutton, 2017, Grönwall and Danert, 2020). Nevertheless, private groundwater use tends to pass under the radar of official in-country water supply statistics (Danert and Healy, 2021), or the phenomenon is not recognized at all by the government (IAH, 2015).

Box 4.3 Groundwater helps survival in severe water supply crises in Chennai (India)

Chennai has a population of 8.6 million and had to face an acute water supply crisis in 2017–2019 when its main reservoirs almost dried up as a result of a persistent drought. By June 2019, their combined reserves had shrunk to 0.1% of total storage capacity and the water utility could only supply 520 Ml/day, mainly from local groundwater, against a total demand of 830 Ml/day. The city has more than 420,000 private waterwells, but the water table has fallen significantly over large areas, causing saltwater intrusion due to long-term aquifer overexploitation and limited recharge in the recent poor monsoons.

These pressures forced Chennai to deploy some 5,000 tankers with a capacity of 9,000 l each, making 5–6 trips per day to supply groundwater from surrounding rural areas to the water utility, totalling 200–300 Ml/day. However, a local history of poor water resource management has fuelled conflicts between urban and rural populations.

Source: Alam and Foster (2019).

The use of private waterwells for urban self-supply has 'mushroomed' in recent years, especially in South Asia, Latin America and Sub-Saharan Africa

The use of private waterwells for urban self-supply has 'mushroomed' in recent years, especially in South Asia, Latin America and Sub-Saharan Africa (Foster et al., 2010b; Grönwall et al., 2010; Alam and Foster, 2019). The practice usually commences as a 'coping strategy' in the face of irregular or inadequate piped water supply, and then continues in perpetuity as a 'cost reduction strategy' to avoid paying higher water tariffs. It is a proven way of unlocking household-level investment in access to water.

Private waterwell construction costs in most hydrogeological settings will be in the range of US$2,000–20,000, but are considerably higher (US$30,000–45,000) where deep boreholes (of 200–300 m) are required. In the latter case, private waterwell ownership will remain the preserve of the wealthy and it is not a 'pro-poor' proposition. While the practice reduces the pressure on water utility supplies, it can also have serious impacts on utility cash flows and investment cycles (Foster et al., 2018). There is a clear need for some regulation of urban waterwell self-supply, and without regular quality monitoring, it will always be risky, but nevertheless users appear to be superficially content with their supplies.

Research into urban self-supply from groundwater has revealed that:

- in India, an estimated 340 million dwellers depend primarily on self-supply sources from groundwater (Sutton and Butterworth, 2021), and many medium-sized cities are highly dependent on domestic self-supply from groundwater, which can amount to 40–60% of water-supply provision (Alam and Foster, 2019);
- domestic self-supply from groundwater in Brazil amounts to about 35% of total supply to São Paulo in drought conditions (despite not being recognized by the authorities and the city not being underlain by a major aquifer) and nationally there are at least 2.5 million private waterwells which represent 6–7 times the annual investment in water supply by government agencies (Foster et al., 2020a).

The case of Nigeria is particularly significant in view of its very large and rapidly growing urban population and high levels of self-supply. By 2009, some 38–43 million of the total urban population (75–80 million) were estimated to be dependent on private waterwells, despite the fact that the coverage of public water supply also expanded. In the city of Lagos alone, about 20% of the 18–20 million population are served by utility water supply, with about 50% owning private boreholes and another 30% obtaining water from these sources (Healy et al., 2017).

Informal slum settlements and the poorer peri-urban communities can only gain access to groundwater in those case where:

- community-based organizations use social capital and political connections to secure funding for non-reticulated waterwells from government programmes;
- non-governmental organizations provide non-reticulated waterwells to collection standposts; or
- low-cost dug wells can be constructed to tap exceptionally shallow water-tables, with the handicap of being much more vulnerable to faecal and chemical pollution (Grönwall, 2016; Lapworth et al., 2017).

In addition, the settlements of marginalized and displaced people, both on a temporary and permanent basis, require special mention. These settlements often have a high population density but fall between the urban and rural categories. The construction of well-designed waterwells is vital in these cases. Good examples are the Turkish cities receiving large numbers of Syrian refugees and the Rohingya refugee camps in Bangladesh. Such settlement areas source water from deep waterwells constructed by aid or relief agencies (Box 4.4).

Box 4.4 Deep waterwell provides clean water for Rohingya refugees in Bangladesh

In recent years, approximately 1 million Rohingya refugees have migrated to a settlement near Cox's Bazaar, just north of the Myanmar border with Bangladesh. Despite high local rainfall, providing clean water to these displaced people is difficult, since the shallow aquifers in the area are contaminated by human excreta. The challenge was overcome by drilling a deep waterwell tapping into the Tipam Sandstone Aquifer at depths of 100–300 m. Energy to pump the water up is generated by 187 solar panels. After precautionary chlorination, the water is stored in 6 tanks of 95,000 litres each, for gravity-fed distribution to the inhabitants.

Source: IOM (2019).

4.2.3 Urban use drivers and trends

The present-day drivers of urban groundwater use are the accelerating rates of urbanization, increasing per capita water use, higher ambient temperatures and reduced river-intake security due to water pollution and climate change, and the relatively low cost of waterwell construction and operation (IAH, 2015). Another practice that requires mention is the import of private tanker supplies to urban areas from waterwells that are mainly located in neighbouring rural areas.

In tropical Africa, the regional trend is that the rate of improving urban water supply has actually decreased between 1990 and 2015 (Banerjee et al., 2008). The urban population that remains 'unserved' with improved water supply can be usefully divided (Oluwasanya et al., 2011) into:

- those (70–80%) who are living physically close to the existing infrastructure but are not willing or able to be connected, because of either prohibitive connection costs and/or the insecurity of tenure at their dwelling place;
- those (20–30%) who live outside the existing infrastructure area, where the capital cost for the water utility to extend its coverage is too high, given the poor prospect of capital cost recovery unless subsidized supply is guaranteed; and
- the remainder, whose continuity and reliability of utility water supply are so poor that they have to make regular recourse to alternative solutions (such as expensive bottled water or unreliable water tankers).

4.3 Rural water supply

4.3.1 Improved village water sources

The nature of groundwater makes it highly suited to dispersed water supply for populations living in rural areas, and it is often the most cost-effective way of providing a secure water supply to villages. This is especially the case in Sub-Saharan Africa and South Asia where the rural population is large but dispersed. Groundwater will continue to be the predominant source of household water for the rural population in developing nations (Foster et al., 2008). Community hand-pump waterwells began to be adopted in the 1980s, during the United Nations International Drinking Water and Sanitation Decade, and led to a steady increase in access to safe water for rural people in low-income countries (Arlosoroff et al., 1987).

The volumes of water needed to meet the demands of rural villages are small and can readily be provided by small-diameter boreholes, dug wells or sometimes springheads, with water abstraction by handpumps or small motorized pumping equipment of low capacity (0.2–1.0 l/sec). Such water supplies are not normally reticulated to dwellings, although there is a widespread tendency for people to want to drill and operate private waterwells on their own premises. Hand-pumped water supplies can be abstracted from most rock types with the right expertise, but reticulated supplies for large villages (> 1.0 l/sec) can be more challenging to develop.

Groundwater provides the only feasible and affordable way to extend basic water access to unserved rural populations in much of the world

The use of groundwater includes both so-called ‘improved sources’ of adequate sanitary completion and also a large number of unimproved sources (Table 4.3), whose microbiological quality is at significant risk from the direct ingress of polluted surface water. The proportion of improved sources is steadily increasing, owing in no small measure to the application of guidance provided via the Rural Water Supply Network.[12]

A recent study in Ethiopia, Malawi and Uganda found that more than 90% of rural groundwater supplies had the inorganic quality that made it suitable for drinking, although there are particular geological areas where elevated arsenic and fluoride levels are a hazard. One of the greatest benefits of groundwater is its resilience to climatic variation. Groundwater is not reliant on the last 1–2 years of rainfall, but integrates rainfall over years and decades. Research into the performance of rural groundwater supplies in Ethiopia during the recent drought of 2015–2016 found that boreholes equipped with handpumps outperformed every other water supply (MacDonald et al., 2019).

4.3.2 Rural use statistics

Statistics on rural groundwater use are largely derived from estimates of rural population and per capita domestic water use for non-reticulated supply. While in northern Europe, water utilities provide reticulated supplies to many villages, no such services exist in the rural areas of most countries in the world, and groundwater plays a key role in meeting this water demand reliably.

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[12] www.rural-water-supply.net/en

Table 4.3

Drinking water service ladder with groundwater use

Category	Definition	Source examples
Improved private source	• Immediately available drinking water from improved water source • Free from faecal and priority chemical contamination	• Private borehole of sound sanitary completion on household premises • Reticulated/piped water supply from protected borehole
Basic community source	• Community drinking water from an improved source • Collection time under 30 minutes for a roundtrip, including queueing time	• Borehole or springhead of sound sanitary completion close to the households
Limited source	• Drinking water from an improved source • Collection time greater than 30 minutes for a roundtrip, including queueing	• Distant and congested borehole or springhead of adequate sanitary completion
Unimproved source	• Drinking water from unprotected source	• Unprotected dug well or springhead

Source: Based on WHO/UNICEF (2017).

Private waterwells also play an important role in providing for domestic use around the world (Healy et al., 2020). For example, Mali has over 170,000 private traditional family waterwells and it is estimated that in Ethiopia, Malawi and Zambia, more than 85% of households rely on private waterwells for their drinking water supply (Sutton and Butterworth, 2021).

4.3.3 Future challenges

Rural community groundwater supplies are not without their challenges. Recent research in Ethiopia, Malawi and Uganda has shown that less than 50% of water boreholes were functioning reliably and about 25% were contaminated with pathogens (MacDonald et al., 2019). The reasons are complex and include engineering and design issues, along with deficient long-term maintenance and management of the water service.

Groundwater provides the only feasible and affordable way to extend basic water access to unserved rural populations in much of the world

Emerging solutions involve prioritizing maintenance of existing services, increasing the quality of materials, and improving the design and construction through awareness-raising and capacity-building. Persistent contamination of rural groundwater supplies with pathogens is estimated to affect about 30% of the total installations. Although disinfection treatment is possible, it is rarely feasible at village level. The coexistence of on-site sanitation and groundwater supply is a serious concern for shallow sources, particularly in more densely populated villages. Inadequate quality of borehole construction is a pervasive issue, which allows the direct ingress of contaminated surface water (Danert et al., 2020).

Groundwater provides the only feasible and affordable way to extend basic water access to unserved rural populations in much of the world. Still, 11% of the global population lacks access to basic water services (UNICEF/WHO, 2019) and delivering sustainable groundwater services to these people is a major priority. The shallow borehole equipped with a shallow handpump still has a major role to play in the rapid upscaling of village water services, and needs to be accompanied by an improved attention to maintenance. The ultimate objective is household access to water, which would see a gradual move from community handpumps to reticulated systems, but again mainly based around groundwater. The use of solar energy for pumping has the multiple potential benefits in terms of water security and net zero emissions. But this shift relies on boreholes being able to supply higher yields (>100 m^3/d) sustainably, which will require substantial investment in understanding hydrogeology for appropriate borehole siting.

4.4 Environmental concerns

4.4.1 Threats to sustainability

The main challenges to the sustainable use of groundwater for urban supply are:

- absolute resource constraints in the case of the larger cities;
- frequent quality degradation caused by: inadequate in-situ sanitation, leaky storage of hydrocarbon fuels, casual disposal of industrial and municipal effluents, and uncontrolled solid-waste dumps (IAH, 2015; Lapworth et al., 2017);
- a tendency to overexploit groundwater resources within urban areas where the water utility is a major abstractor, which can be accompanied by land subsidence impacting the urban infrastructure and saline-water intrusion; and
- presence of elevated levels of natural trace contaminants (e.g. arsenic and fluoride) in some groundwater locally, especially in South Asia and East Africa (Foster et al., 2020b).

Urban settlements are often developed on coastal plains, and the population of coastal zones worldwide is predicted to grow to 1 billion in the coming decades. In coastal areas, the over-exploitation of groundwater resources seriously exposes aquifers to large-scale saline-water intrusion, a phenomenon that will be further exacerbated by climate change-induced sea level rise.

Environmental problems associated with groundwater exploitation can be divided into those relating to:

- land subsidence due to compaction of aquitards and aquifer materials, causing serious settlement of building foundations and increased flood risk in coastal cities, as a result of the overexploitation and falling water table of urban aquifers (e.g. in Bangkok and Beijing); and
- groundwater flooding, causing inundation or uplift of buried structures (deep basements, transportation tunnels, etc.), arising from water table rebound following the cessation of groundwater pumping from urban aquifers.

Other specific issues, like the conservation of wooden-pile foundations, require a policy that aims to keep urban water tables in shallow urban aquifers within a specified limited range.

Box 4.5 Major groundwater dependency but with significant hazards in Lusaka

Lusaka has grown rapidly from 0.5 million in 1978 to 2.8 million in 2018. It has long been dependent on local groundwater for its water supply. In 2018, the water utility operated 228 waterwells to provide about 140 Ml/day, with a river treatment plant providing a further 80 Ml/day. The water utility is still plagued by high water losses and poor revenue collection, but has taken a ‘pro-poor initiative’ by drilling stand-alone boreholes to supply water kiosks at a subsidized tariff of US\$0.25/m^3 (40–70% of the normal tariff).

In addition, there are thousands of private waterwells with a total abstraction of up to 300 Ml/day. In low-income peri-urban areas, most households still rely on shallow dug wells where the water table is less than 3 metres deep, but the dolomitic limestone formation they tap into (while high-yielding) is very vulnerable to pollution from urban wastewater and industrial effluents. Pit latrines are the predominant form of sanitation, and in these ground conditions, they form a serious hazard to groundwater quality and cause the frequent cholera outbreaks. Some large-scale projects to extend the main sewer network and wastewater treatment capacity are underway, but in the unplanned peri-urban slums these are difficult and costly to implement.

Source: Adapted from Foster et al. (2020c, Box 1, p. 126).

Increased rainfall intensity arising from climate change has in some areas resulted in exceptional rates of groundwater infiltration, as well as perched aquifers, giving rise to subsurface flooding in areas that have not previously experienced this problem.

There are, of course, broader environmental concerns arising from intensive groundwater abstraction for whatever purpose. The reduction in discharges to rivers as baseflow, as well as to dependent wetlands, is principal amongst these.

4.4.2 Urban sanitation and drainage issues

Urbanization greatly modifies the 'groundwater cycle' – with some benefits and numerous threats. Urban sanitation and drainage arrangements exert a major influence on groundwater recharge rates and quality.

The most serious problems arise in urban areas where main-sewer coverage is low and most domestic faecal waste is discharged into pit latrines

Careful consideration of groundwater resource sustainability and pollution vulnerability are required when planning urban sanitation and drainage. Where unconfined groundwater systems are in use for urban water supply, it will also be important to route stormwater drainage from roofs and paved areas to soakaways so as to maximize groundwater recharge. However, transitioning from in-situ sanitation to sewered systems in established urban areas is not widely feasible in developing cities because the dense population affords little space and the cost is often prohibitive. Given these constraints, in-situ sanitation is increasingly accepted as the norm, and its design and management have improved to ensure safe faecal sludge handling and disposal (Peal et al., 2020).

The impact of inadequate or inappropriate sanitation on groundwater varies widely with the pollution vulnerability of different aquifer systems and the types of faecal sludge and solid waste involved. The most serious problems arise in urban areas where main-sewer coverage is low and most domestic faecal waste is discharged into pit latrines. It will usually impact the marginalized the most (women and girls are often disproportionately more at risk of disease due to pathogens and toxins as a result of their exposure to wastewater). In cities in developing countries and larger informal settlements, the majority of the total population are served by in-situ sanitation (septic tanks, various types of latrine and cesspit, and even open defecation), and this will result in significant pollution of shallow aquifers by nitrates, community chemicals and pharmaceuticals. In the most vulnerable aquifers, pollution by pathogenic organisms will also occur. This is well documented for some cities (Box 4.5).

In those locations in the developing world where main-sewer coverage forms the bulk of the sanitation infrastructure, arrangements for wastewater disposal and reuse remain widely inadequate, with significant pollution risks for peri-urban alluvial aquifers. There is a pressing need to avoid agricultural or amenity irrigation with wastewater in the capture areas of public waterwells, unless it is subjected to tertiary treatment.

Where solid waste disposal is by landfill, and especially where these are poorly designed and operated, the groundwater pollution load will locally be more varied and potentially more toxic, if landfills do not have impermeable liners and effluent management. While locally, more serious types of groundwater pollution can occur as a result of the inadequate management of industrial wastewater, pollution arising from the domestic and municipal sector are a far more widespread threat in those contexts where in-situ sanitation and solid-waste landfill predominate.

4.4.3 Groundwater-related energy consumption

The operation of motorized waterwell pumps is a significant energy consumer, and pumping costs also start to escalate in overexploited aquifers with continuously falling water tables. However, the consumption of energy by waterwell pumps is still modest in comparison to the energy requirements associated with complex water treatment plants and long-distance transfer of surface water resources. Thus, provided that groundwater pollution by nitrates, solvents and pesticides can be kept to a minimum, the total energy requirement for the operation and distribution of groundwater sources is much lower than for surface water sources (except where the latter are gravity-fed).

Where electrification is widespread, the most common energy source for groundwater pumping remains electricity, but in Sub-Saharan Africa and some other regions, there is still heavy reliance on diesel-engine pumps or handpumps. Recent years have seen the greatly increased use of solar panels as a source of energy for groundwater pumps, and this is likely to continue in the future.

The cost of energy provision for urban groundwater supply is normally recovered by the water tariffs, commonly with a subsidy for social-minimum volumes recuperated through higher charging for larger volumes (see WWAP, 2019, Chapter 5).

4.5 Role of stakeholders

Several key stakeholders play a role in groundwater abstraction for the water supply of human settlements. These range from the national agencies responsible for groundwater resources and water supply, to the corresponding local municipalities and even individual waterwell owners.

The national agencies have the responsibility for ensuring:

- the basic regulation of groundwater abstraction;
- adequate coordination on groundwater between national actors, basin agencies, local groundwater user organizations, and aid/relief organizations, as appropriate;
- effective mechanisms for groundwater monitoring and regulation enforcement;
- horizontal coordination with other departments on groundwater; and
- support for operational arrangements in transboundary aquifers.

Local municipal agencies will need to:

- ensure that the local water permit system is functioning;
- stress the need for attention to the operation and maintenance of waterwells;
- coordinate solid-waste and wastewater management to protect groundwater;
- consult and support local groups that work on sanitation and waste management;
- communicate the need to prevent groundwater pollution to farmers; and
- encourage education/vocational training institutes (including youth groups) to include water supply and groundwater management in their curricula.

4.6 Concluding remarks

1. Groundwater clearly plays a major role in urban water supply, as well as a critical role in water supplies to rural villages and settlements of displaced people worldwide, but certain factors tend to make this role difficult to quantify precisely. The reasons include the current failure to clearly differentiate types of water supply sources in national and international databases, and the fact that private waterwell abstraction often remains irregular or illegal and falls outside the radar of public databases.
2. There is a pressing need for systematic urban groundwater studies to become a routine element of urban planning at a detailed scale, to mitigate unnecessary conflicts between public and private groundwater use, to ensure sound solutions to the water supply of displaced person settlements, and to avoid unforeseen and costly environmental and social problems related to groundwater supply.

There is a pressing need for systematic urban groundwater studies to become a routine element of urban planning at a detailed scale

3. Water utilities need to put a much more consistent emphasis on protecting their critical waterwell/springhead sources through promoting land use restrictions (on agricultural cropping and housing development) in their groundwater capture zones, in the interest of safeguarding public health and reducing the cost of water supply.
4. Of special concern in relation to the sustainability and cost of groundwater for human water supply are the impacts of groundwater overexploitation for irrigated agriculture and groundwater pollution from agriculture and industry (see Chapters 3 and 5). Of equal importance are the effects of pollution due to inadequate or inappropriate sanitation affecting groundwater sources themselves, as well as the contamination risks caused by poor waterwell design and/or inadequate completion.
5. There is also an urgent requirement to promote full interaction on, and monitoring of, urban groundwater between the main stakeholders: water utilities, environmental agencies and municipal authorities, and local groundwater user organizations. The databases resulting from this joint monitoring activity should be open-access. There is a parallel need to establish stable long-term collaboration frameworks between urban water utilities and local academic research centres to improve the understanding of the groundwater resource.

Chapter 5

Groundwater and industry

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5.1 Context

The industry and energy sectors are usually well aware of what surrounds them at ground level and above. Such things as rivers, lakes and climate variability are perceptible, as are the risks they may present to the viability of companies. Yet the groundwater that lies underneath is often – literally – overlooked. This oversight is surprising as these sectors often rely on self-supply that in many locations has a groundwater component. Groundwater is available to provide a very useful and often underused resource for industry, but it has to be sustainably managed in concert with other stakeholders. It is a key resource for many industries, and contributes in this way to employment and economic growth.

Industries that withdraw groundwater include manufacturing, mining, oil and gas, energy generation, engineering, and construction. Industries with a high groundwater dependency via supply chains include the apparel and food and beverage sectors. Their combined withdrawals can lead to stronger competition/interactions between the different industries, as well as with other sectors, communities and the natural environment, with sometimes unforeseen consequences, such as extreme lowering of groundwater tables, pollution of groundwater and land subsidence (UNEP, 2019).

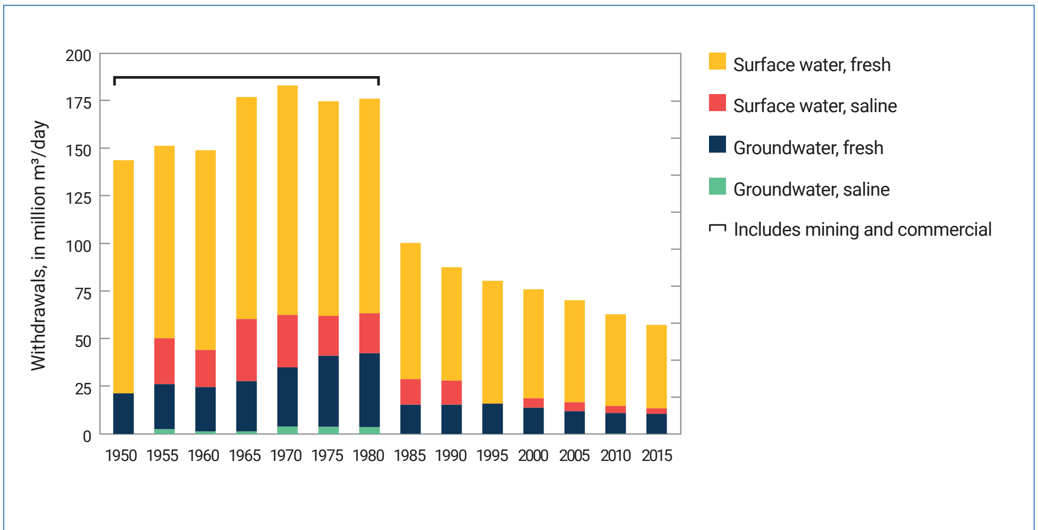
5.2 Groundwater abstraction and use in industry

5.2.1 Quantity

Statistics relating to water abstraction and use in industry are notably scarce. Industry and energy account for 19% of global freshwater withdrawals (Aquastat, n.d.). This number refers to self-supplied water (which includes groundwater). The data also point to big geographic differences, with industrial withdrawal varying from 5% in Africa to 57% in Europe. However, Aquastat data are not parsed out into industrial groundwater withdrawals. Such data can only be found for some higher-income, industrialized countries. The United States Geological Survey (Dieter et al., 2018) shows that for self-supplied industrial use in the USA the total amount of water withdrawn has decreased significantly from 1985 to 2015 (Figure 5.1), while surface water is still the main source. According to another estimate, groundwater contributes 27% of the water withdrawn globally for manufacturing (Döll et al., 2012).[13]

Figure 5.1

Self-supplied industrial water withdrawals in the USA



Source: Adapted from Dieter et al. (2018, fig. 17F, p. 53).

The 15 countries with the largest estimated annual groundwater extractions in 2010 are shown in Table 5.1, clearly evidencing the wide range in groundwater extraction for industry, which varies from country to country from 1 to 48%.

[13] According to 2020 CDP unpublished data, globally across all sectors, 39% companies reported having lowered their groundwater withdrawal compared to the previous year (2019), 30% reported it was about the same, and 24% reported having increased their withdrawals. This includes groundwater withdrawals from non-renewable and renewable sources for their direct operations (CDP, unpublished).

Table 5.1 Fifteen countries with the largest estimated annual groundwater extractions (2010)

Country	Population 2010 (in thousands)	Groundwater extraction			
		Estimated groundwater extraction 2010 (km³/year)	Breakdown by sector		
			Groundwater extraction for irrigation (%)	Groundwater extraction for domestic use (%)	Groundwater extraction for industry (%)
India	1 224 614	251.0	89	9	2
China	1 341 335	112.0	54	20	26
USA	310 384	111.7	71	23	6
Pakistan	173 593	64.8	94	6	0
Iran	73 974	63.4	87	11	2
Bangladesh	148 692	30.2	86	13	1
Mexico	113 423	29.5	72	22	6
Saudi Arabia	27 448	24.2	92	5	3
Indonesia	239 871	14.9	2	93	5
Turkey	72 752	13.2	60	32	8
Russia	142 985	11.6	3	79	18
Syria	20 411	11.3	90	5	5
Japan	126 536	10.9	23	29	48
Thailand	69 122	10.7	14	60	26
Italy	60 551	10.4	67	23	10

Source: Margat and Van der Gun (2013).

More recent data from 2015 (Table 5.2) show many of the same countries and their changes in absolute water withdrawal, with China and Indonesia more than overcoming any savings by other nations.

Table 5.2 The nine countries with the largest annual industrial water withdrawal (km³/year)

Country	2015	Absolute change from 1965
USA	248.4	-55.5
China	133.5	+87.8
Russia	39.6	-7.9
Canada	33.1	-2.9
Germany	32.6	-5.2
Indonesia	24.7	+24.3
France	21.6	-2.9
India	17.0	+1.8
Italy	16.3	+7.3

Source: Ritchie and Roser (2017), based on Aquastat.

The reduced availability of groundwater resources can be a limiting factor for industrial development, because some industries use more groundwater than surface water. In some cases, groundwater is used to preserve surface water resources for the local population – mostly in water-scarce regions – for their everyday food and drinking supplies. Examples include the textile finishing industry in Pakistan and other water-scarce regions. The textile finishing industry in Karachi is confronted with an extreme shortage of process water, and previously available groundwater sources are exhausted. The application of zero liquid discharge (ZLD) techniques is a possible solution to continue the operation of textile finishing processes.

Another example is the challenge facing the development of a new Tesla Factory in Brandenburg (Germany). Due to the region's limited groundwater resources, the regional water utility raised concerns of how the project might affect drinking water supply, which in turn led to a discussion about regional groundwater availability (IGB, 2020). This example indicates that determining proper groundwater allocation is not just a problem confined to developing countries.

5.2.2. Manufacturing

In industry, groundwater is used for many different purposes, including the manufacturing, processing, washing, diluting, cooling and transporting of products

In industry, groundwater is used for many different purposes, including the manufacturing, processing, washing, diluting, cooling and transporting of products. Furthermore, groundwater is used by smelting facilities, petroleum refineries, and by industries producing chemical products, food and paper products (CDC, n.d.). Some industrial operations place great reliance on groundwater, whereas others, such as mining, can also cause groundwater displacement or depletion through dewatering into other ecosystems, such as surface water systems.

In 2020, from 1,375 manufacturing companies worldwide disclosing to the CDP (formerly the Carbon Disclosure Project), more than half (54%) reported groundwater from non-renewable and renewable sources as being relevant for their direct operations. Of those, 46% have lowered their groundwater withdrawals, 32% maintained their withdrawals, and 21% increased their withdrawals from groundwater compared to 2019 (CDP, unpublished).

Process water

Various industrial processes make use of groundwater resources where surface water is limited in quantity but also where quality is important. Groundwater is often less contaminated than surface water and requires less treatment. Industries like textiles and garments, leather, and pulp and paper have a high specific water consumption. For example, the wet processing of 1 kg cotton fabric needs 250–350 litres of water (Kiron, 2014). The tanning industry has a specific water use of 170–550 litres per hide (Schwarz et al., 2017). Water withdrawal in European paper production for pulp, paper and board production was around 3,700 million m³ in 2012 (SpotView, 2018), of which 90% came from surface water, and 8.5% from groundwater sources. These processing operations often use self-supplied groundwater: this is seen not only in developing countries, which sometimes have inadequate monitoring, but also in industrialized countries like the USA.

The textile industry is a large groundwater user. In Bangladesh, for example, this sector supplies itself with groundwater for its different units of the wet processing facility, and therefore is in desperate need for efficient water management (Haque et al., 2021). Almost all dyes, specialty chemicals and finishing chemicals are applied to textile substrates from water baths/wet processes. In addition, most fabric preparation steps, including desizing, scouring, bleaching and mercerizing use aqueous systems and groundwater (Kiron, 2014).

As Table 5.3 shows, wool and felted fabrics processes are the most water-intensive textile operations (with wool processing having a median water use of about 280 l/kg). The figures also show that water consumption in this industry varies widely.

Table 5.3

Water use in textile processing in the USA (in l/kg of production)

Water use in textile processing			
Processing subcategory	**Water use minimum**	**Water use median**	**Water use maximum**
Wool	110	285	660
Woven	5	110	510
Knit	20	80	380
Carpet	8	45	160
Stock/Yarn	3	100	560
Nonwoven	2,5	40	80
Felted fabrics	33	210	930

Source: Adapted from US EPA (1996, table 2-33, p. 65).

An example of a city where groundwater quality and quantity were adversely affected by rapid industrialization, a known problem especially in developing countries, is Tiruppur (India). The city is highly dependent on intensive textile processing activities, but also relies on groundwater as the main source for drinking water. Samples showed that the groundwater is contaminated with salts used in textile processing (Grönwall and Jonsson, 2017a).

Washing and cleaning

Many production processes need a large amount of water for washing and cleaning their products at the end of production, in order to separate residues of processing chemicals. These chemicals remain in the effluent and need treatment to protect the environment and human health. Specific data concerning the quantity of groundwater used for washing and cleaning purposes in the different industries are lacking.

Cooling

The use of groundwater for cooling purposes is very dependent on the location and type of industry and will therefore vary widely from country to country. Primary energy and power production are the biggest single users of industrial water.[14] High-energy processes need large quantities of cooling water. For example, steel and metal smelters use 30 m³ of water per ton of steel, while refineries use 1.5 m³ of water to process 1 m³ of crude oil. In the USA, 15% of the process water used in refineries is sourced from groundwater (US Department of Energy, 2016).

5.2.3 Beverages and bottled water

The beverage, bottled and mineral water sectors are unique in that groundwater is a raw material that becomes the product. According to market research, the industry is expected to grow 8% annually (Facts & Factors, 2020). The sources of mineral water used for human consumption need special attention, as these watersheds and aquifers need to be protected against any type of microbiological and chemical pollution.

[14] The International Energy Agency estimates that industry and energy (primary energy and power production) account for about 10% each of total water withdrawals globally (IEA, 2016a).

Large international food and beverage companies are in increasing competition and in dispute with local communities and municipalities over the amount that can be withdrawn without depleting local groundwater resources and affecting domestic and other supplies. For example, in the city of Guelph (Canada), citizens demonstrated against the renewal of the water withdrawing permit for Nestlé's bottling plant in nearby Aberfoyle, which sources water from the same aquifer that feeds Guelph's supply. The consequence was a moratorium on the permit (CBC, 2016). A response to solve upcoming conflicts regarding common groundwater resources may be the application of the international water stewardship standard (AWS, 2019).

According to CDP's global data, in 2020, 72% of the disclosing beverages companies reported groundwater being relevant to its operations. From those, 26% reported their groundwater withdrawals were about the same as the previous year (2019), 42% were lower, 18% were increased and 8% were in their first year of measurements (CDP, unpublished).

5.2.4 Engineering and construction

Groundwater has a significant impact on engineering and construction

Groundwater has a significant impact on engineering and construction. As with mining (see Section 5.4), it is inconvenient at best and a major issue at worst (too much groundwater in the wrong place at the wrong time) and, for these segments of industry, it is neither an asset nor a hidden resource. Underground construction, such as tunnels, frequently require either temporary or permanent dewatering. Deep excavations and buildings with large underground areas, such as basements and underground parking lots, face the same challenges, frequently exacerbated by the large volumes requiring removal and also by the water pressures that are the result of high local or regional heads. Unlike mining, which mainly occurs in more remote areas often with relatively untouched groundwater, construction is commonly carried out in urban areas, where the groundwater may already be polluted, requiring treatment upon dewatering and before discharge. Indeed, the question where to discharge the sometimes substantial amounts of water can prove challenging in populated areas and involve permitting and regulations. Moreover, both temporary and permanent dewatering can significantly lower groundwater levels, affect groundwater supply, and increase operation and maintenance costs.

In soil mechanics and foundation engineering, groundwater is a vital consideration. According to the principle of effective stress, the presence of groundwater affects the strength of the soil and the loads that can be borne. Moreover, fluctuations in groundwater levels (seasonal and sometimes as a result of dewatering) are particularly significant in affecting the stability of slopes. On a larger scale, aquifer depletion and lowering of groundwater levels can lead to serious land subsidence, as is evidenced in the well-known case of Jakarta, where subsidence rates of 1 to 20–28 cm/year have been observed in a few locations (Abidin et al., 2011). This leads to the need to replace and repair infrastructure and buildings – all engineering and construction tasks. In other locations, karst phenomena produced by the underground erosion of limestone (carbonate) rocks by acidic groundwater leaves caves and voids that can collapse, leading to building failures at ground level and loss of life. Sinkholes in Florida (USA) are a prime example.

5.3 Industry, groundwater quality and pollution

5.3.1 Industrial threats to groundwater

The discharge and infiltration into the ground of untreated or only partly treated industrial effluents, by injection wells for example, can pollute groundwater and consequently affect other down-gradient uses for irrigation, drinking water and various industries. Negative impacts from soil contamination and leaching from non-engineered and old industrial dumpsites and legacy mines can lead to significant risks for environment and human health. This can occur even when industrial fallout of particulates in air emissions land on the ground and are subsequently transported to the groundwater by rainfall infiltration.

Industrial contaminants found in groundwater cover a broad range of physical, inorganic chemical, organic chemical, bacteriological and radioactive parameters. Some common groundwater contaminants, associated pollution sources and their effects are shown in Table 5.4.

Table 5.4
Common industrial groundwater contaminants by source

Pollution source	Type of contamination
Gasoline filling stations and garages	Benzene, other aromatic hydrocarbons, phenols, some halogenated hydrocarbons
Solid waste disposal	Ammonium, salinity, some halogenated hydrocarbon, heavy metals
Metal industries	Trichloroethylene, tetrachloroethylene, other halogenated hydrocarbons, heavy metals, phenols, cyanide
Painting and enamel works	Alkylbenzene, tetrachloroethylene, other halogenated hydrocarbons, metals, some aromatic hydrocarbons
Timber industry	Pentachlorophenol, some aromatic hydrocarbons
Dry cleaning	Trichloroethylene, tetrachloroethylene
Pesticide manufacturing	Various halogenated hydrocarbons, phenols, arsenic
Sewage sludge disposal	Nitrates, various halogenated hydrocarbons, lead, zinc
Leather tanneries	Chromium, various halogenated hydrocarbons, phenols
Oil and gas exploration/extraction	Salinity (sodium chloride), aromatic hydrocarbons
Metalliferous and coal mining	Acidity, various heavy metals, iron, sulphates

Source: Adapted from AGW-Net/BGR/IWMI/CapNet/ANBO/IGRAC (2015, table 8.1, p. 9).

Hydrocarbons are one of the most common groundwater contaminants. They either float or sink in groundwater depending on their density. Chlorinated hydrocarbons, such as those used as solvents or for dry cleaning, can be carcinogenic. Only a small amount can be enough to contaminate large volumes of groundwater beyond safe guidelines. Heavy metals, such as hexavalent chromium from the plating industry, are also dangerous. Others, such as arsenic, can occur naturally in groundwater and limit its suitability for industrial use.

The industrial and mining sectors have a strong potential for increasing water use efficiency, stimulating water recycling and reuse, and limiting water pollution

5.3.2 Addressing industrial groundwater pollution

The industrial and mining sectors have a strong potential for increasing water use efficiency, stimulating water recycling and reuse, and limiting water pollution. To reduce or avoid negative impacts of industrial groundwater use, the techniques and methods of Resource Efficient and Cleaner Production (RECP) and the employment of Eco-Industrial Parks (EIPs) will be needed to reach the Sustainable Development Goal (SDG) Target 12.4 on sustainable production and consumption. Resource-efficient value chains, using the circular economy approach, will minimize the consumption of raw materials, as well as water and energy.

The international framework for Eco-Industrial Parks (UNIDO/World Bank Group/GIZ, 2021) states that an EIP should prioritize sustainable water management, use, efficiency and treatment. EIPs use water responsibly, taking into account local water scarcity issues, and sensitive water reservoirs. An EIP should also plan to increase water efficiency for its resident firms and for the park as a whole. Due to the lack of available surface water, many EIPs in water-scarce regions have to draw the needed water resources from groundwater. Wastewater must be treated, and water circularity promoted. Water recycling should have priority over ZLD systems.

Pollutant Release and Transfer Registries (PRTRs) are useful instruments as they report emissions from industrial facilities into water as well as air and land (OECD, n.d.). Public disclosure, through organizations such as the CDP and the Global Reporting Initiative (GRI), has also proven to be an effective mechanism for tracking and driving corporate action to reduce and avoid negative impacts of industrial groundwater use.

Zero Liquid Discharge (ZLD)

The prime objective of ZLD is to prevent wastewater discharge and its negative impacts. ZLD aims to treat effluent to recover it as clean water and reuse it in the industrial process, turning water consumption to near-zero levels. As such, it is a form of process water recycling to control water pollution.

ZLD is achieved in stages – first by making the effluent fit for treatment, either through conventional physicochemical treatment, reverse osmosis and/or biological treatment. Thereafter, a series of post-treatment steps removes hardness, silt, turbidity and organics to a level where fouling of membranes does not occur.

Mining has a different and more direct relationship with groundwater than most other industry sectors

The Indian government has imposed ZLD on its textile and garment manufacturing industry by legislation, starting in 2006 in Tamil Nadu. Many factories were shut down by the state's high court, due to their inability to meet compliance requirements (Kiran and Rao, 2019). The ZLD policy has been expanded to nine states in the Ganges River basin and applied to five industrial sectors: textile, pulp and paper, distilleries, tanneries, and sugar. "*Recent research and development on ZLD replace it by the concept of 'minimal' liquid discharge (MLD) that enables up to 95% liquid discharge recovery. This takes into account that attaining the final 3–5% of liquid elimination to achieve ZLD can nearly double the treatment cost*" (Grönwall and Jonsson, 2017b, p. 27).

Groundwater remediation

Groundwater remediation techniques treat polluted groundwater by removing the pollutants to acceptable levels or converting them into harmless products.

Biological, chemical and physical treatment technologies are employed and often a combination of technologies is utilized. Biological treatment techniques include bio-augmentation, bioventing, biosparging, bioslurping and phytoremediation. Some chemical treatment techniques include ozone and oxygen gas injection, chemical precipitation, membrane separation, ion exchange, carbon absorption, aqueous chemical oxidation, and surfactant enhanced recovery – others may be implemented using nanomaterials. Common physical treatment techniques include pump and treat, air sparging, dual phase extraction, and membrane techniques like reverse osmosis.

5.4 Mining and groundwater

Mining has a different and more direct relationship with groundwater than most other industry sectors. In semi-arid regions, it may entirely depend on it. Mining's interaction with freshwater is often through groundwater and the relationship can be conflicting. On the one hand, the water is a useful asset and resource in mineral extraction and processing. Yet, on the other hand, it is often a hidden liability. On the asset side of the equation, water is required in extracting, separating and processing ore, dust suppression, slurry transport, and washing. On the liability side, groundwater is a nuisance or inconvenience, as both underground and open-pit mines in many cases require frequent or continuous dewatering in order to operate, and there is the risk of contaminating a local aquifer, which may be a source of drinking water. The disposal of the water also presents challenges for treatment if it is contaminated by the mining activities. The extent of dewatering and treatment may add significantly to operational costs.

For example, mining in Poland requires dewatering 1 km^3 of water per year (Kowalczyk et al., 2010). Based on an average household of three using 230 m^3/year,[15] this is the equivalent of the consumption of more than 4.3 million households or about 13 million people. Water use though the mining cycle is shown in Figure 5.2.

Figure 5.2 Water use during a mining project life cycle

Exploration		
Wide range of water use during drilling	Risk of contamination from drilling additives and sumps; stormwater management	Affected community's perception of uncontrolled water extraction
Planning and construction		
Runoff, spills, sediment, settling ponds	Possible chemical contamination, monitoring needed	Develop process to account for water use and related costs/risks
Operations		
Demand during mineral processing, dust suppression, and evaporation losses	Manage wastewater discharge, seepage, groundwater from mine pit dewatering, and runoff	Account for water in all operation cycles incorporating data from all prior phases
Closure and postclosure		
Long-term contamination risk, potential need for water during postclosure land use	Rigorous monitoring needed	Water plan and program legacy

Source: IFC (2014, fig. 1, p. 5).

The liability that comes with mining operations using groundwater and accompanying dewatering can be onerous in terms of moving and treating the groundwater and the associated costs. These issues and impacts are summarized in Table 5.5. There are also related issues – safety of workers and local residents, and impacts to drinking water and the environment. The fact that in 2020 only two mining companies reported leaching of pollutants to groundwater bodies as being a risk highlights that more attention may be needed in this respect (CDP, unpublished).

Contamination of groundwater arises commonly from oxidation and dissolution of pyrite from sulphide ore (acid mine drainage (AMD) is a long-standing issue in the mining industry), or from saline groundwater drainage and leachates. According to the results of national surveys conducted in the 1990s and 2000s, about 9,000 km^2 of groundwater bodies were at risk of metal pollution in the United Kingdom (UK) (IAH, 2018). Tailing storage facilities, common at many mines, can also lead to groundwater pollution (Box 5.1).

Mining can use the same technologies available to other industrial sectors to manage water, decrease its use and improve efficiency. In some cases, poorer-quality water can be used. For example, saline water can be better for some separation processes (Prosser et al., 2011). Groundwater management can be incorporated into regulations covering

[15] City of Toronto average water consumption. www.toronto.ca/311/knowledgebase/kb/docs/articles/revenue-services/customer-service/call-centre/call-centre/city-of-toronto-average-water-consumption.html.

Table 5.5

Groundwater impacts from active and legacy mining

Nature of process/activities	Groundwater impacts and concerns
Groundwater supply for mining processes	Interference with pre-existing water well users, or permanent aquifer depletion, especially in case of non-renewable or weakly recharged aquifers in arid regions.
Groundwater pressure relief for slope stability	Usually in low-permeability formations and mainly a geotechnical issue with only limited groundwater system impact.
Dewatering for mine access drifts and faces	In large and/or deep mines/quarries, this can result in large cones of influence with impacts on water well users and groundwater-dependent ecosystems.
Sudden groundwater in-rush to mine galleries	Potential loss of life, damage to capital equipment and mining continuity with effects also on hydraulically linked springs and ecosystems.
Mine closure with water-table rebound	Can result in new groundwater discharge zones and mobilization of poor-quality groundwater into regional flow systems.
In-situ leaching of target minerals	Risk of strongly acidic or alkaline leachate carrying extracted mineral(s) polluting groundwater.
Accidental/incidental groundwater pollution from mining operations	Mine water drainage and tailings – dam seepage activating pollution sources and potentially impacting groundwater quality (especially in coal/lignite and heavy metal mining).

Source: IAH (2018, p. 2).

a 'cradle-to-grave' approach as part of licensing (IAH, 2018). Moreover, the mining industry, through its various activities, may have ample in-house data on the location and extent of aquifers and their properties. Such data, if made publicly available, would add to the body of knowledge and be very useful to hydrogeologists, governments and water supply utilities.

Box 5.1 Benefits of groundwater quality monitoring: The case of the AngloGold Ashanti in Cerro Vanguardia S.A. (Argentina)

Cerro Vanguardia S.A. (CVSA) is the biggest gold and silver mine in size and production in the Patagonia region of Argentina. The operation includes a tailings storage facility (TSF), where the processed mine residue is continually deposited in a slurry form containing water and tailings/residue. The slurry separates in the TSF, and the water, which has traces of residual cyanide, is continually reclaimed for reuse in the gold recovery process. The TSF is surrounded by a network of monitoring wells to verify if the tailings from the process are affecting the groundwater. The monitoring programme assesses the presence of heavy metals and cyanides.

In 2003, routine water monitoring identified an isolated peak in cyanide levels in one borehole in the TSF. Investigations identified a quartz vein in the bedrock that was acting as a conduit, allowing cyanide to enter the groundwater. A major earthworks operation was started to expose the vein under the tailings dam and cover it with a thick high-density polyethylene (HDPE) liner to prevent the downwards seepage of water. This HDPE liner was two layers thick, with a series of electronic sensors installed between the layers to detect seeps through the liners. Ongoing monitoring of groundwater undertaken since the HDPE was installed indicates that the liner is successfully preventing further ingress of cyanide into groundwater.

Source: Adapted from ICMM (2012, pp. 28–29).

5.5 Energy, power production and groundwater

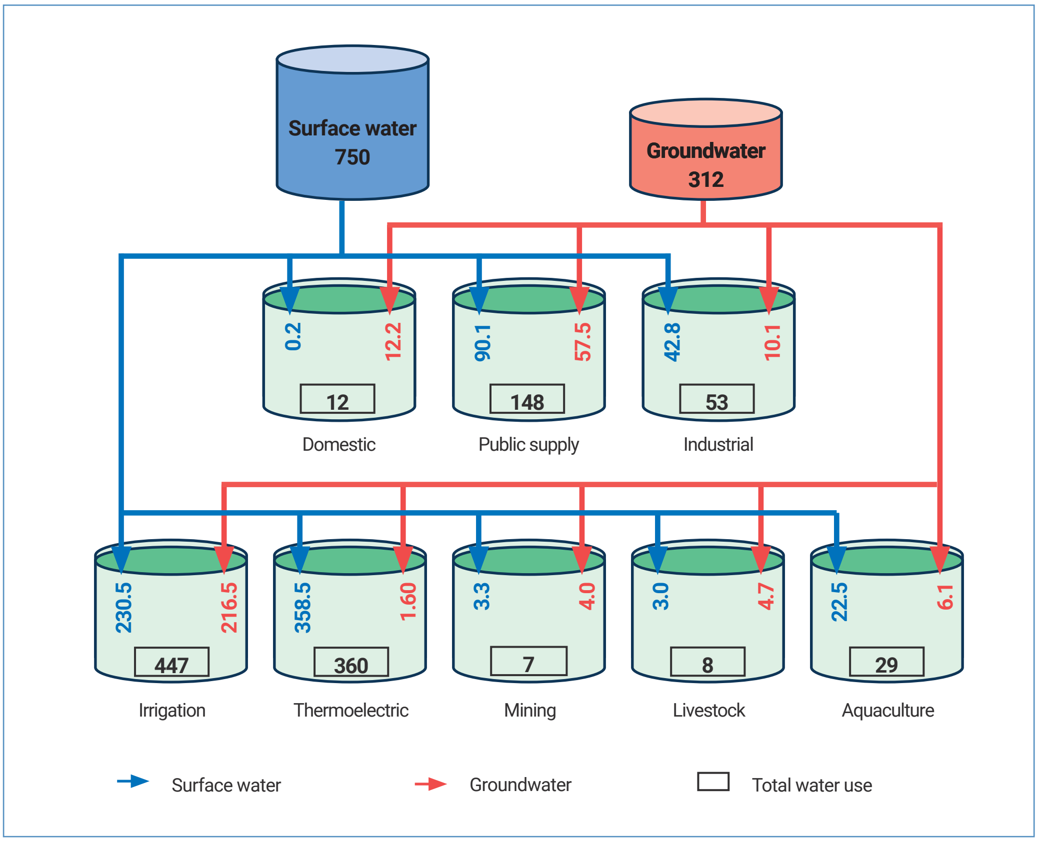
Much has been written about the water–energy nexus, but there is little information about the groundwater component, either in the production of energy or in the use of energy to withdraw, move and treat groundwater. As with industry, data for groundwater use in the energy sector are not commonly disaggregated from overall freshwater use or self-supplied use. Since the data availability may be skewed towards higher-income countries, the data cannot be easily extrapolated to other countries, especially where aquifers may not be present or easily accessible.

5.5.1 Groundwater use in energy

Some national-level data are collected in higher-income countries. Figure 5.3 shows a breakdown of water use in the USA for 2015 (USGS, n.d.). This figure indicates that groundwater comprises about 29% of the freshwater used and that only 0.5% of this 29% is used for thermo-electric power generation,[16] whereas industry uses 3.2% with the majority – 70% – used for irrigation.

Figure 5.3

Source and use of freshwater in the USA, 2015



Note: Data are in million m³/day.

Source: Adapted from USGS (n.d.).

Canada conducts a biennial industrial water survey, which provides a great deal of detail about water use, including groundwater use for energy (Statistics Canada, n.d.). Table 5.6 shows the data for 2017 for the thermo-electric sector. It can be seen that, as with the USA, groundwater comprises only a minuscule percentage of the overall water use. The CDP's unpublished analysis of global data for 2020 found that, of the 37 power generation companies that disclosed water information, 57% depended on groundwater (CDP, unpublished).

[16] *"Withdrawals for thermoelectric power were 133 Bgal/d [500 Mm³/d] in 2015 and represented the lowest levels since before 1970. Surface-water withdrawals accounted for more than 99 percent of total thermoelectric-power withdrawals, and 72 percent of those surface-water withdrawals were from freshwater sources. … Thermoelectric-power withdrawals accounted for 41 percent of total withdrawals for all uses, and freshwater withdrawals for thermoelectric power accounted for 34 percent of the total freshwater withdrawals for all uses."* (Dieter et al., 2018, p. 1)

Table 5.6

Water intake in thermal-electric power generation in Canada (2017), by source

Thermal-electric power generation	Million m^3
Freshwater source, publicly supplied, municipal	26.8
Freshwater source, self-supplied, surface water bodies	20 505.3
Freshwater source, self-supplied, groundwater	0.4
Freshwater source, self-supplied, other	32.9
Saline water source, self-supplied, groundwater	0.0
Saline water source, self-supplied, tidewater	2 700.9
Saline water source, self-supplied, other	1.1

Source: Statistics Canada (n.d.).

Data for groundwater use in primary energy production, such as oil and gas, are not readily available. However, in 2014, primary energy production used 12% of the overall water withdrawals for energy (IEA, 2016a). The CDP's unpublished analysis of the 2020 data indicates that, of the 52 oil and gas companies disclosing water information, 85% depended on groundwater (CDP, unpublished).

Biofuels are very water-intensive, and if their growing relies on irrigation, groundwater is often a significant component. However, their relative water footprint per unit of energy appears to be significantly lower than that of other sources of primary energy. For example, whereas crude oil uses 1.06 m^3/GJ, biomass in Brazil uses on average 61 m^3/GJ (Gerbens-Leenes et al., 2008).

5.5.2 Energy for groundwater use

Much attention is paid to the water side of the water–energy nexus. However, the contribution and use of energy in the water sector has received less visibility, and though the International Energy Agency (IEA) has addressed this more fully (IEA, 2016a), the segregation of specific groundwater information is nonetheless quite limited.

Fracking for natural gas, particularly in shallow aquifers, can present significant risks to groundwater contamination

In their report, the IEA estimated for 2014 the energy required to treat, process and move water at approximately 120 Mtoe[17] (or about 1% of the world's total consumption of 9,425 Mtoe in 2014 (IEA, 2016b)), about the same as the total energy demand of Australia. Electricity comprises about 60% of this total (about 820 TW_h or 4% of the global total electricity consumption),[18] about the total electricity consumption of Russia. Around 40% of the electricity to treat, process and move water is used to withdraw groundwater and surface water.[19] If these estimates are integrated with the estimate that globally groundwater accounts for about a third of water withdrawals, then groundwater abstraction is consuming approximately 108 TW_h per year, representing about 0.5% of global electricity consumption. This may not look like a large number, but seen through a local lens the situation can be very different. An example of an extreme case is India where 60% of the electricity used in the water sector is for groundwater abstraction. This number can be better understood if one considers that India accounts for nearly 26% of groundwater abstracted globally (Margat and Van der Gun, 2013). Pumping groundwater with electricity is about seven times more energy-intensive than surface water abstraction (in kWh/m^3) (Figure 5.4). Electricity demand for pumping groundwater is expected to grow with increased groundwater abstraction, storage depletion and associated water level declines, combined with a shift away from diesel-fuelled pumping. However, there is a contrast in energy intensity for treatment, as groundwater is usually less contaminated than surface water and needs less treatment. It is also worth noting that desalination is up to one order of magnitude more energy-intensive than groundwater abstraction (Figure 5.4).

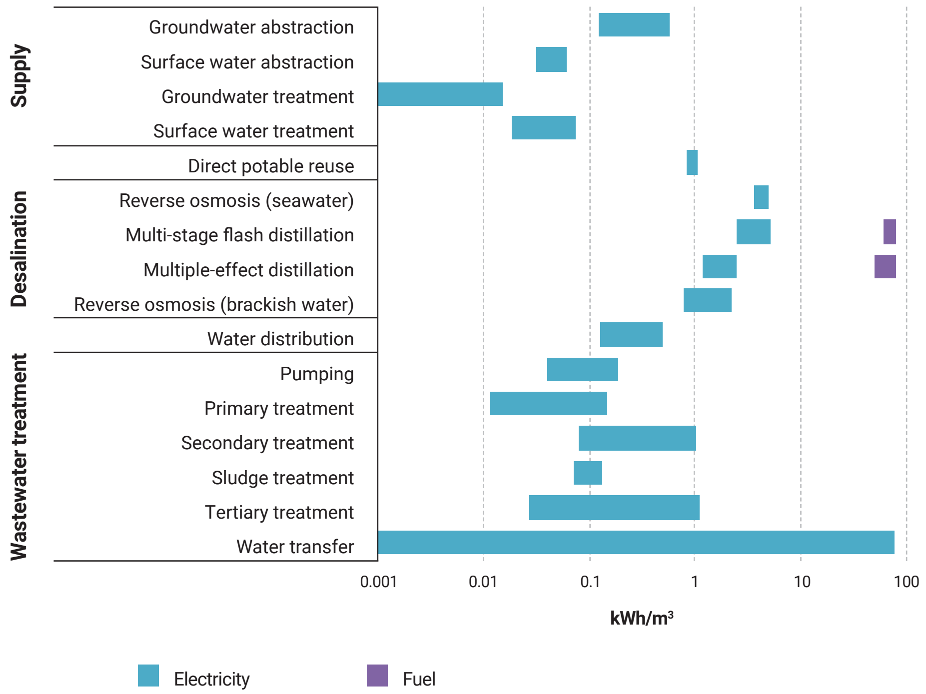
17 Mtoe = Million tonnes of oil equivalent; 1 toe = 11.63 MWh

18 The balance is thermal energy, mainly diesel pumps for agricultural groundwater pumping, and natural gas for desalination plants in the Middle East and North Africa.

19 Wastewater treatment uses about 25% (but about 42% in developed countries) and distribution uses about 20%.

Figure 5.4

Energy used for various processes in the water sector



Source: IEA (2016a, fig. 8, p. 28).

5.5.3 Energy and groundwater contamination

Even though the energy sector appears to use little groundwater, it can have profound effects on groundwater quality. Coal used in the generation of thermal electricity is well known for its deleterious environmental effects such as CO_2 and mercury emissions and air quality impacts. However, it has significant impacts on groundwater as well, as a result of leaching through coal ash waste dumps. This has been investigated in the USA (Box 5.2) and the effects may last for many years. Given the large number of coal-fired power plants worldwide, it might be fair to conclude that the impacts to groundwater globally could be extensive.

Fracking for natural gas, particularly in shallow aquifers, can also present significant risks to groundwater contamination. Pollution sources include wastewater from formation water, flow-back water, and drilling and fracturing liquids (IEA, 2016a). Regulations and best practice (including recycling and reuse) can reduce the amount of water required and the risks. Alternatives to water, or the use of foam to reduce water use, all have downsides as well.

Box 5.2 Coal ash dumps – the legacy of groundwater pollution

Coal contains many toxic chemicals, including arsenic, radium and other carcinogens, several metals that can impair children's developing brains, and multiple chemicals toxic to aquatic life. Coal burning to produce electricity concentrates these toxic chemicals in the waste coal ash. For much of the 20th century, this waste was dumped in waste ponds and unlined landfills, which allowed infiltration to and contamination of groundwater.

In 2015, the US Environmental Protection Agency (US EPA) finalized a federal regulation for the disposal of coal ash: the Coal Ash Rule that established requirements for groundwater monitoring. The 2018 data from 4,600 groundwater monitoring wells included over 550 coal ash ponds and landfills, representing over 75% of the coal plants in the USA. The data showed that groundwater beneath almost all coal plants (91%) is contaminated, sometimes to significant levels. Arsenic and lithium are commonly found and the majority of plants have unsafe levels of at least four toxic chemicals that can seep from coal ash. Moreover, the issue is compounded by older closed coal ash dumps that are not covered by the regulation.

Source: Adapted from EIP (2019).

5.6 Industry and groundwater accountability

Industry is paying increasing attention to the risks and consequent challenges to its freshwater supply. To the extent that groundwater is part of freshwater supply, industry needs to be increasingly aware of this resource, or lack of it, as it can have a significant influence on business viability, return on investment, and profits. This is particularly significant in arid regions where industry makes more use of groundwater. The most recent report by the CDP indicates with regard to water risks that the costs of inaction (US$301 billion) versus action (US$55 billion) are five times greater (CDP, 2021). This is the case for most sectors with the exception of power generation and infrastructure, as large investments are being made to transition energy portfolios. In addition, business opportunities to invest in water security are estimated at US$711 billion.

In 2018, there had been a 7% decrease in the number of companies withdrawing from non-renewable groundwater, but at the same time, there was a significant increase in companies reporting withdrawals from all sources, including renewable groundwater (CDP, 2018). The CDP report for 2020 states that "*almost two-thirds of responding companies are now reducing or at least maintaining their water withdrawals*", but only 4.4% report improvements regarding water pollution (CDP, 2021, p. 4). The CDP's unpublished analysis of the 2020 data suggests that the number of companies maintaining or reducing their renewable and non-renewable groundwater withdrawals has jumped to 25% (721/2934) (CDP, unpublished).

Industry is paying increasing attention to the risks and consequent challenges to its freshwater supply

For action on a plant site basis with regard to groundwater risks, within the fence line there are many technologies and management practices available to increase water efficiency and reduce use. Water audits and water footprints identify weak areas of water use, and measures centring on zero discharge, reusing and recycling water can be introduced to fill the gaps. Such measures may also be encouraged with companies on the supply chain. If groundwater is part of the water budget, then it will become part of these efficiency measures and may tie into RECP initiatives. These efforts may be scaled up into EIPs where industries cooperate in a symbiotic way on a variety of necessary inputs and outputs such as energy, waste and water. The next step is towards a circular economy, which may function on a local to regional scale with aspirations to national levels and where groundwater sustainability will be an integral part.

Economic instruments have taken on a broader perspective in recent years as financial institutions in corporate lending are paying attention to the level of water risk, which naturally includes groundwater. The CDP warns of dangers to "*reputations, revenue and financial stability*" from water risks (CDP, 2018, p. 11). Financial institutions are looking for companies "*to decouple production and consumption from the depletion of water resources*" (p. 11). The CDP reports for 2020 that 2,934 companies out of 5,537 (over one half) disclosed water data when asked by their investors or business customers (CDP, 2021).

However, in order to access and use groundwater resources sustainably, cooperation, sharing and partnerships with the many other stakeholders in groundwater is necessary for overall management of the resource, in other words stewardship (Box 5.3). This approach values water in many ways, from economic accounting and monetary value, through environmental worth, to sociocultural values, such as recreational, cultural and spiritual values (United Nations, 2021). Some of the main company and corporate value drivers are shown in Figure 5.5. Several organizations are actively promoting corporate water stewardship and publishing guidelines. These include the Alliance for Water Stewardship (AWS) and the CEO Water Mandate.

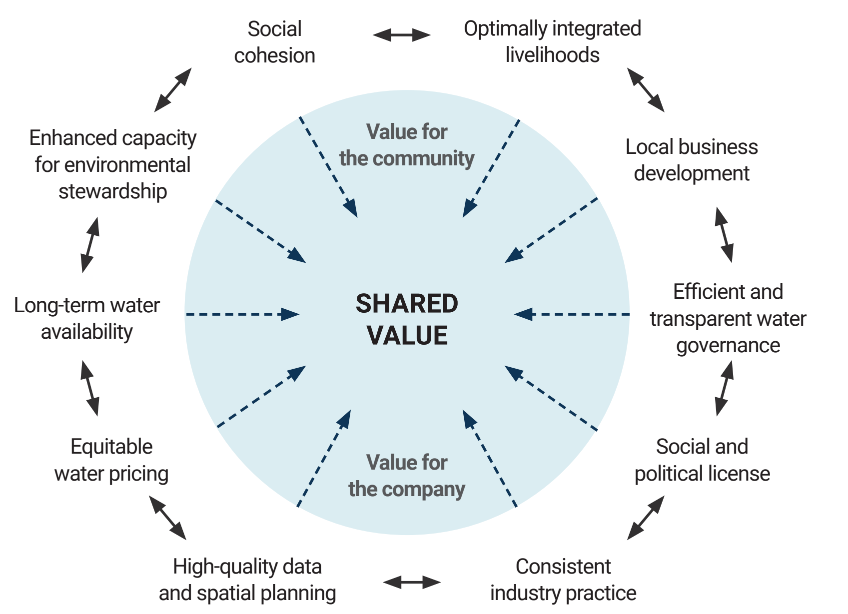
Box 5.3 Partnership between PT Multi Bintang and UNIDO

In East Java, the Indonesian Heineken Operating Company, PT Multi Bintang, in cooperation with The United Nations Industrial Development Organization (UNIDO) has catalysed a public–private partnership to overcome water scarcity. Building up on pilot investments by PT Multi Bintang and the establishment of the Aliansi Air as a multi stakeholder platform, the Global Environment Facility (GEF) endorsed an upscaling project in March 2021. With a GEF-approved budget of US$1.8 million, absorption wells, agro-forestry schemes and riparian bamboo forests will be established by the Ministry of Environment and Forestry (MOEF) and UNIDO. This will enhance water retention in the catchment area, improve water percolation and increase groundwater replenishment. The project will result in the retention and replenishment of aquifers by some 1 million m^3/year. These measures were identified by stakeholders from government, civil society, academia and the private sector in a participatory and inclusive bottom-up stakeholder engagement workshop as a prerequisite to guarantee the sustainable supply of water to people and businesses. As the project evolves, opportunities for further upscaling to the other 14 priority catchment areas targeted by the government of Indonesia will be identified. This will be done in close cooperation with the MOEF, the Indonesian Division of the Water Stewardship Alliance, and the just recently established Water Resilience Coalition, which has brought together the key Indonesian private sector entities with an interest to engage and cooperate in water stewardship.

Source: UNIDO (unpublished).

Figure 5.5

Corporate and community value drivers for water management stewardship



Source: IFC (2014, fig. 2, p. 9).

There is also a different dimension to defining the geography of stewardship. Unlike surface water where river basins form natural territories of stewardship, the boundaries of aquifers are less well-defined and often difficult to define. Those involved in stewarding a groundwater resource may cover a much wider area and many more stakeholders.

5.7 Moving forward

Industry and energy generally use less water than other major water use sectors, such as agriculture and municipalities, and correspondingly much less groundwater. However, they can have a very significant impact on groundwater quality through discharges, spills and leaching of waste. This is not to propose that industry and energy should move away from groundwater use, indeed in some ways their use of groundwater could relieve the stress on surface water resources releasing them for the benefit of other users. The private industry and energy sectors do have the flexibility to move quickly, and the means available for contributing effectively to the sustainable use of groundwater with respect to quantity and quality that other, more public, sectors sometimes lack.

Industry and energy have more control, through their ownership and organizational structures, over how much groundwater they use. As a result, they can act more nimbly and quickly than governments. Water reuse and recycling, zero-discharge initiatives, RECP projects, and EIPs all have a focus of using less water. These activities in turn form part of the shift to greener industry, Environmental, Social Governance (ESG), and industry and energy water stewardship. They can dovetail into Industry 4.0[20] improvements (see United Nations, 2021, Chapter 6, p. 93) and larger societal and government plans and activities such as integrated water resources management (IWRM), and move towards circular economies. Even the financial sector is now exerting its considerable influence over sustainable investing and this will have a knock-on effect, favouring clients, including those in industry and energy who need financing and use groundwater sustainably, and encouraging others to do so.

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[20] Industry 4.0 is the digital transformation of manufacturing/production and related industries and value creation processes.

Chapter 6

Groundwater and ecosystems

WWAP

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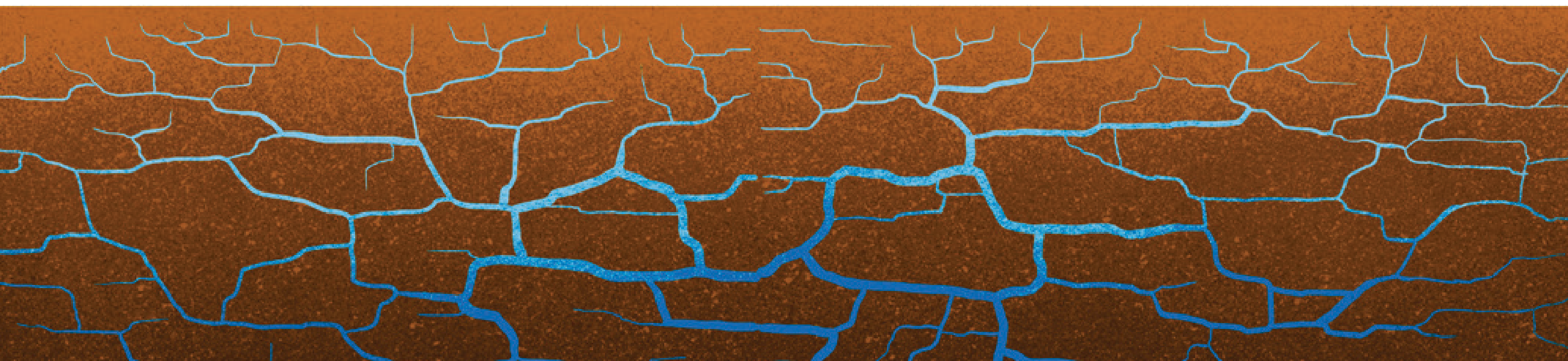


6.1 Introduction to groundwater-dependent ecosystems

Groundwater-dependent ecosystems (GDEs) consist of plants, animals and fungi that rely on the flow, temperature or chemical characteristics of groundwater for all or some of their water needs (Murray et al., 2003; Foster et al., 2006; Kløve et al., 2011) (Figure 6.1). GDEs are extremely diverse and can be divided into three classes based on the expression of groundwater within the ecosystem (Eamus et al., 2015; Figure 6.2). These include:

- aquatic GDEs, which depend on the interaction of groundwater and surface water, such as springs, wetlands and estuaries, as well as groundwater discharge and baseflow in rivers, streams, wetlands and coastal zones;
- terrestrial GDEs, which depend on ecologically accessible groundwater; and
- subterranean GDEs, which depend on aquifers and karst systems, including the hyporheic zones of rivers and floodplains.

While constituting different classes, GDEs may be closely linked and dependent on the same groundwater, which may be the case of riparian vegetation next to a river, and of the river ecosystem itself. GDEs contain endemic species reliant on the living conditions created by groundwater. GDEs can also be the foci of human settlements, centres of religious and cultural practice, and even the source of conflict (Kreamer et al., 2015; United Nations, 2021).

Figure 6.1

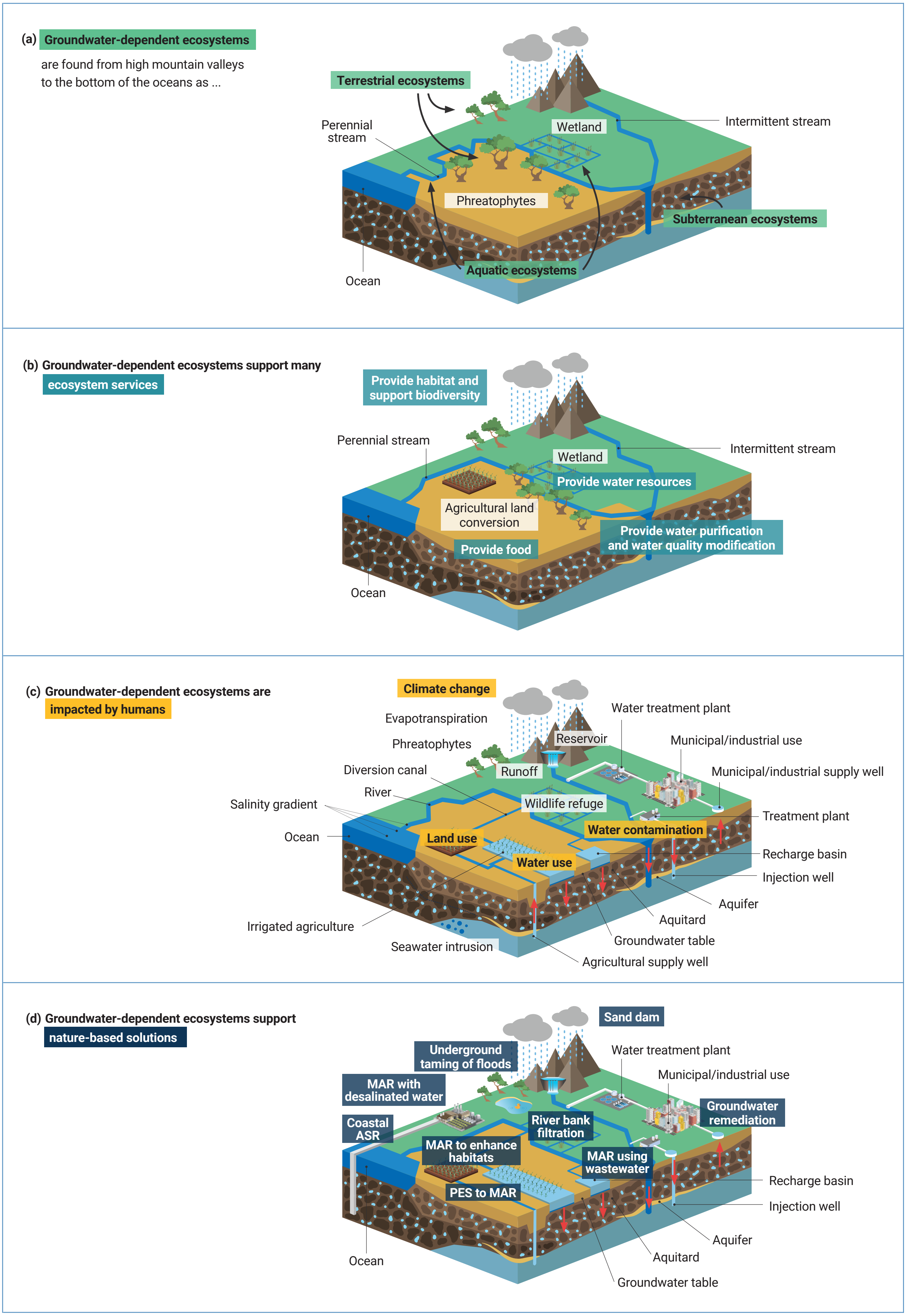
Example of a groundwater-dependent ecosystem: An aerial view of floodplains and islands in the Okavango Delta (Botswana)

Photo: Vadim Petrakov/ Shutterstock.

Groundwater dependence can be continuous, seasonal or occasional, and becomes apparent when a species loses access to groundwater long enough to display a negative response, such as reduced growth or reproduction, or increased mortality. Some species are completely dependent upon groundwater, such as those that rely on springs or constant baseflow inflow to rivers, lakes or coastal zones. But groundwater dependence can be more difficult to discern for other species because a combination of water sources (e.g. groundwater, surface water, precipitation, irrigation return flow, stormwater runoff) provides certain living conditions in different seasons or different life stages.

GDEs have been mapped for some jurisdictions, such as California (USA, Box 6.1) and Australia (Doody et al., 2017). Mapping is an important component in the emerging interdisciplinary field of ecohydrogeology, which aims to fill existing knowledge gaps between hydrology, hydrogeology and ecology (Cantonati et al., 2020) using a diversity of methods (Eamus et al., 2015; Ramsar Convention Secretariat, 2013; Kalbus et al., 2006, Murray et al., 2003).

Figure 6.2 Interactions between groundwater, ecosystems, human activity and nature-based solutions

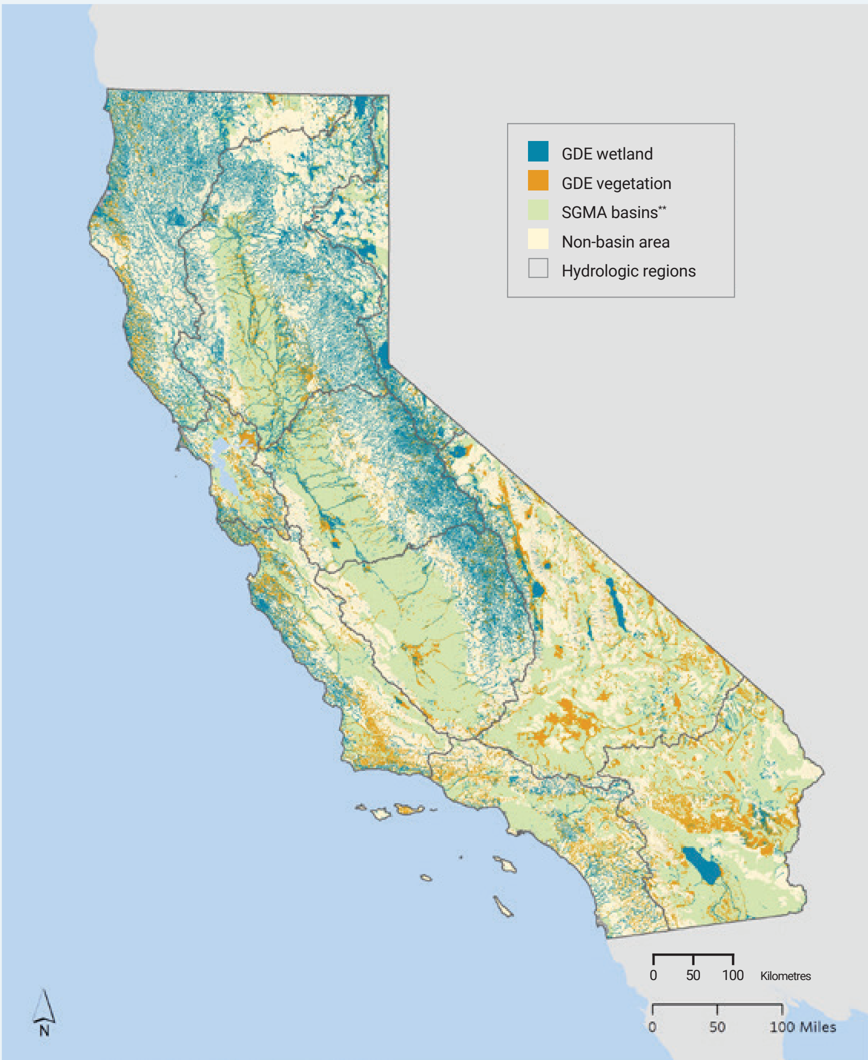


Sources: (a), (b) and (c) based on Maven's Notebook (2015); (d) based on Villholth and Ross (n.d.).

Box 6.1 Mapping groundwater-dependent ecosystems in California (USA)

Mapping groundwater-dependent ecosystems (GDEs) is the first step to managing them. To date, GDE mapping has been predominantly a localized process requiring time-consuming expert review and field studies to verify ecosystem dependence on groundwater. In California, GDEs were first mapped using an inference-based approach that relied on hydrological features in the landscape (springs, wetlands and rivers supported by baseflow; Howard and Merrifield, 2010). This map resulted in specific requirements to identify and consider impacts to GDEs under California's Sustainable Groundwater Management Act (SGMA). To support local agencies in identifying GDEs in their basins, the map was refined using vegetation mapping from aerial photography (Klausmeyer et al., 2018) and the spatial dataset provided online.* GDE mapping at broader landscape scales is increasingly possible through remote sensing and spatial analyses using geographical information systems (Eamus et al., 2015). The Nature Conservancy is leading a global GDE mapping effort, using Google Earth Engine to process massive global remote sensing and land use and climate datasets, which will be released in 2022.

Mapping groundwater-dependent ecosystems in California



Source: Produced by the authors on the basis of the NCCAG database (Klausmeyer et al., n.d.)

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* gis.water.ca.gov/app/NCDatasetViewer/.

** SGMA basins refer to high-priority basins under the Sustainable Groundwater Management Act (SGMA) of California.

6.2 Ubiquity of groundwater-dependent ecosystems

Aquatic groundwater-dependent ecosystems can be found across a variety of landscapes, ranging from high mountain valleys to the bottom of the ocean and even in deserts. Possibly the most obvious groundwater-dependent ecosystems are springs: highly diverse, endemic and abundant ecosystems found in over 2.5 million locations, including caves, oases, fountains, geysers and seepages (Cantonati et al., 2020). Though small, spring habitats are exceptionally biodiverse. A study in northern Arizona (USA) detected 20% of the flora of an entire forest in springs that represented <0.001% of the landscape (Kreamer et al., 2015). Desert oases are large springs, yet they have received little attention in the groundwater-dependent ecosystem literature despite their global prominence (774 oases are documented in the Sahara and Arabian Oases Atlas and the Ramsar List of Wetlands of International Importance includes 225 freshwater springs and oases, reported together).

The ecology of many wetlands, lakes, rivers and other surface water bodies is dependent on the complex interactions between groundwater and surface water, which can change with time over seasons or years, as well as by location across a wetland, lake or river (Swanson et al., 2021; Kreamer and Springer, 2008). Wetlands are referred to here in accordance with their definition under Article 1.1 of the Ramsar Convention as "*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres*" (Ramsar Convention Secretariat, 2013).

Aquatic groundwater-dependent ecosystems can be found across a variety of landscapes, ranging from high mountain valleys to the bottom of the ocean and even in deserts

Groundwater discharge supports baseflows of streams and rivers, a crucial water source that determines a stream or river's risk to fall dry during periods of drought (Boulton and Hancock, 2006; Larned et al., 2010). Baseflow can contribute nearly 100% of streamflow in some humid regions (Beck et al., 2013) (Figure 6.3). In contrast, baseflow can be an insignificant contributor to streamflow in many arid regions. In these environments, ephemeral stream networks can be important sources of groundwater recharge (Cuthbert et al., 2016). Perched aquifers can serve as important supporters of surface water ecosystems, as groundwater levels tend to drop mostly due to evaporation, and not due to downward seepage. Important examples of this are pools in ephemeral streams that may retain some biodiversity during no-flow periods due to survival in these isolated water bodies (Bonada et al., 2020).

Groundwater discharging to marine environments is a ubiquitous phenomenon along coastlines (Luijendijk et al., 2020). It creates unique ecosystems where saltwater and freshwater mix (Lecher and Mackey, 2018) and can be a substantial nutrient source for coastal and estuarine waters. This can lead to eutrophication and hypoxia, especially where upstream catchments are heavily developed through intensive farming and urbanization (Santos et al., 2021; Hosono et al., 2012). The high salinities of coastal terrestrial *sabkha*[21] environments are mostly sustained by groundwater, which provides solutes that remain after the water has evaporated and create these special biomes (Yechieli and Wood, 2002). In high-salinity water like the Dead Sea, groundwater inflow sustains local ecosystems that otherwise would not be able to tolerate the salinity (Ionescu et al., 2012). In many desert inland areas, valuable wetlands with delicate ecologies are also commonly present at the margins of salt flats (Marazuela et al., 2019).

Terrestrial ecosystems depend on groundwater in managed and natural landscapes in all anthropogenic biomes (Ellis and Ramankutty, 2008) around the world where groundwater is accessible to plants (Fan et al., 2017; Figure 6.2a). The impact of different forest canopies on infiltration and recharge is debated (Ellison et al., 2017). Even the effect of forestry on groundwater recharge and low season flows is variable, with different impacts in different regions and climates as well as at different stages in the forestry cycle (Reynolds and Thompson, 1988).

[21] A coastal, supratidal mudflat or sandflat in which evaporite-saline minerals accumulate as the result of a semiarid to arid climate.

Vegetation impacts have not yet been thoroughly researched or integrated in the management of groundwater recharge. In the Sahel, groundwater levels have increased over decades primarily as a result of changes in vegetation from deep-rooted natural vegetation to shallow, less water-consuming crops (Favreau et al., 2009). Water holes in arid environments are often purely groundwater-fed, and thus groundwater is crucial to sustaining the complex food webs of arid landscapes, such as savannahs. Wildlife-dug waterholes can be life-supporting, and demonstrate the intricate link between groundwater, ecosystem support and biodiversity (Lundgren et al., 2021). In cropland and rangeland biomes, groundwater supports the ecology of both managed and natural landscapes, even if these landscapes are typically viewed from an agricultural rather than ecological perspective. Finally, riparian zones, wetlands and other surface water bodies often depend on groundwater and can provide crucial ecosystem services. For example, in more humid areas, riparian forests and wetlands can purify nitrogen-rich runoff and drainage from agricultural and livestock farming activities (Bahn and An, 2020), reducing the nutrient loading in GDEs. Conversely, in more arid areas, seasonal flooding may enhance groundwater recharge in floodplains, while sedimentation may provide significant nutrient and soil-improving amendments (Talbot et al., 2018).

Interactions between groundwater and ecosystems are of increasing importance in the major freshwater ecosystems of the world

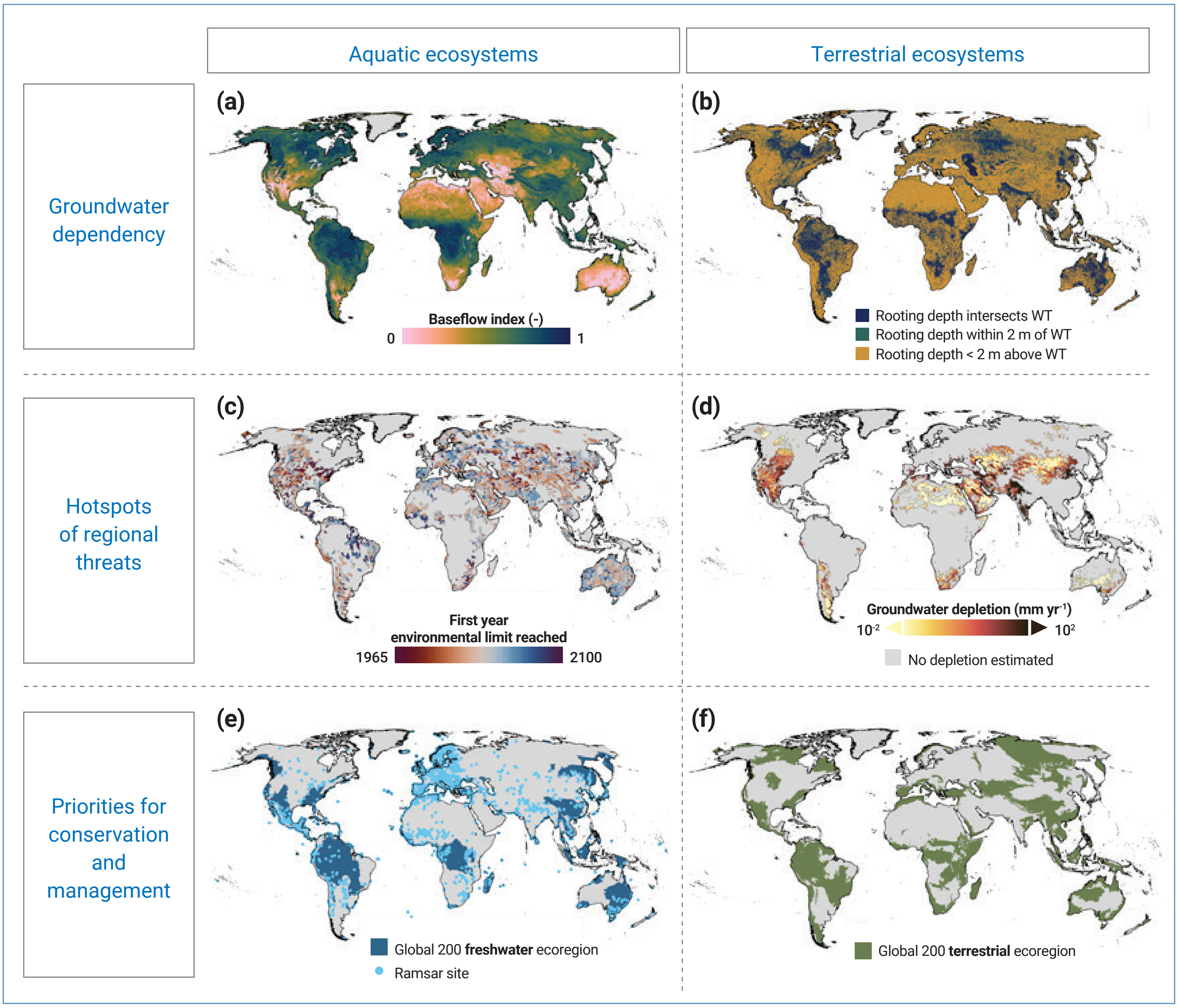
Subterranean ecosystems are ubiquitous but generally poorly understood. Organisms and microorganisms are found in varying composition and abundance in all aquifers (Humphreys, 2006, Danielopol et al., 2003). These subterranean ecosystems often help purify water and impact aquifer storage, sometimes increasing storage through bioturbation and feeding on biofilms and other times decreasing storage through clogging pore space. In many places, land use strongly influences the abundance, composition and community structure of groundwater invertebrates; Tione et al. (2016) describe an example located in Argentina. As subterranean ecosystems are sensitive to changes in groundwater quality, monitoring abundance and other bio-indicators within these ecosystems can provide alternative and useful approaches to tracking changes in groundwater quality (Griebler and Avramov, 2015).

Interactions between groundwater and ecosystems are of increasing importance in the major freshwater ecosystems of the world, such as those found on the list of priority freshwater ecoregions for global conservation (Olsson et al., 2002; Figure 6.3e), including certain eastern Australian rivers, the Indus River, the Congo River, the Amazon River, the Colorado River; and other notable wetland complexes such as the Okavango Delta in Southern Africa, the Sudd Swamps in South Sudan, the Inner Niger delta in the Sahel and the Pantanal in South America. These regions not only provide habitat for globally significant levels of biodiversity but are also crucial to larger Earth system processes, including nutrient cycling, carbon sequestration and atmospheric water and energy processes (Erwin, 2009). That many of these regions routinely experience drought (eastern Australia), suffer from ongoing groundwater depletion (Indus River, Colorado River), or will experience increasingly variable or anomalous groundwater storage due to climate change (Okavango Delta; Hughes et al., 2011) is indicative of the breadth and severity of implications arising from threats to groundwater-dependent ecosystems worldwide (Section 6.3).

6.3 Groundwater ecosystem services and threats

Ecosystem services are defined as the numerous and wide-ranging benefits to humans afforded by the natural environment (IPBES, 2019). GDEs support critical ecosystem services (Figures 6.2 and 6.4). Each type of GDE supports a number of ecosystem services (Figure 6.2) across the categories of supporting, provisioning, regulating and cultural services (see Section 1.5). Aquatic and terrestrial GDEs provide habitat, support biodiversity, buffer floods and droughts, and provide food, as well as offering cultural, recreational, spiritual and aesthetic services. Throughout human history, springs have inspired art and music, have been both the object and a strategic tool in conflict and war, and have provided focal points for religious ceremony and belief (Kreamer et al., 2015). Many Indigenous cultures believe that springs, wetlands and their associated ecosystems have a broader, intrinsic value beyond the

Figure 6.3 Global patterns in groundwater dependency, hotspots of regional threats, and priorities for conservation and management for aquatic and terrestrial ecosystems

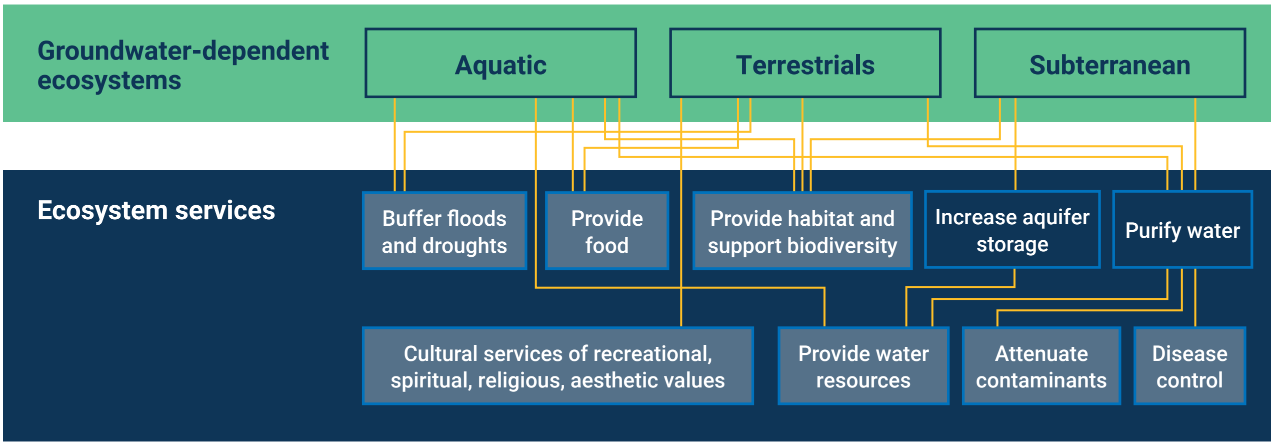


Note: (a) baseflow index, representing the relative contribution to streamflow from groundwater and other delayed sources; (b) relationship between steady-state water table (WT) depth and maximum rooting depth; (c) estimated year in which environmental flow limit is reached (Section 6.4); (d) groundwater depletion rates; (e) Ramsar Sites, identifying wetlands of international importance and Global 200 freshwater ecoregions; and (f) Global 200 terrestrial ecoregions. The Global 200 ecoregions are a prioritized set of 238 ecoregions (53 terrestrial, 142 freshwater, and 43 marine – not included here) developed to protect regions of exceptional biodiversity and representative ecosystems.

Sources: Authors, based on data from: (a) Beck et al. (2013); (b) Fan et al. (2013, 2017); (c) De Graaf et al. (2019); (d) Wada et al. (2010); (e) Ramsar Sites Information Service (n.d.) and Olson and Dinerstein (2002); and (f) Olson and Dinerstein (2002).

services they provide to people (United Nations, 2021). Subterranean ecosystems also provide important ecosystem services, such as storing and providing water resources, attenuating contaminants, and controlling disease (Griebler and Avramov, 2015). These services are sometimes called groundwater-related ecosystem services (Manzano and Lambán, 2011). GDEs and ecosystem services, which are linked with vegetation and soils in the unsaturated zones, play critical roles in protecting aquifers from contamination by ensuring physical separation, enabling biophysical processes like filtration, biodegradation and sorption of contaminants, and by facilitating and protecting natural recharge (CGIAR WLE, 2015).

Figure 6.4 Connecting groundwater-dependent ecosystem types with the ecosystem services they provide



Source: Author.

GDEs and services are generally under-represented in the United Nations Sustainable Development Goals (SDGs). The importance of groundwater is poorly recognized and captured at the SDG target level, which is compounded by the lack of globally useful, up-to-date and SDG-relevant groundwater data and the lack of clarity on the essential linkages between aquifers and the SDGs (Guppy et al., 2018). The role of groundwater in aquatic ecosystems is linked with Target 6.4 (Water use and scarcity) and Target 6.6 (Water-related ecosystems). Target 6.4, the only SDG target that currently operationalizes groundwater and ecosystem services, incorporates environmental flows into 'water stress' Indicator 6.4.2. It has a methodology and online tool for calculating sustainable groundwater abstraction linked to guidelines on environmental flow assessment (FAO, 2019). Target 6.6 monitors changes through time in water-related ecosystems such as vegetated wetlands, rivers, lakes, reservoirs and groundwater (Dickens et al., 2017). But to date, the focus of data collection has been on the spatial extent of open water with no focus on groundwater, nor on the differentiation or mapping of GDEs – an important missing link in the SDG methodology.

Water quality, temperature and contamination all impact GDEs and the services they provide

Groundwater-dependent ecosystems and the related ecosystem services are threatened by groundwater depletion, climate change and land use changes (Figures 6.2, 6.3 and 6.5). Groundwater depletion, the persistent decline in water levels, impacts both aquatic and terrestrial ecosystems (Figure 6.5). Hotspots of groundwater depletion (Figure 6.3d) are found around the world, often in regions with intensive groundwater withdrawals for irrigation. Streamflow depletion, the lowering of streamflow due to groundwater pumping, is a significant concern for aquatic ecosystems (Gleeson and Richter, 2017). The ecological impacts of streamflow depletion (Figure 6.3c) occur where streamflows are below environmental flows (defined in Section 6.4), which is predicted to occur in roughly 40 to 80% of all basins with active groundwater pumping by mid-century (De Graaf et al., 2019).

There is a significant drying of springs, wetlands and oases around the world. Climate change impacts on GDEs (Kløve et al., 2014) are important to consider, especially since groundwater often acts as a buffer during drought, either naturally through feeding streams in dry periods, or indirectly through increased human use during such periods. Undermining these functions can be detrimental to human and ecological systems. Finally, land use changes impact GDEs. For example, the loss of dry forests has led to regional salinization in Australia (Clarke et al., 2002) and the Chaco region of Argentina and Paraguay (Giménez et al., 2016; Marchesini et al., 2013).

Water quality, temperature and contamination all impact GDEs and the services they provide (Figure 6.5). Groundwater quantity (volume, level, flux and their variations in time) is this Chapter's primary consideration, but groundwater quality (natural and as affected by human impacts) and temperature are also essential. Each ecosystem is conditioned by specific water quality requirements, and what is appropriate in certain ecosystems may be detrimental in others. For example, salinity in coastal wetlands or in salt flats is necessary for these ecosystems. However, in other environments, such as terrestrial ecosystems, an increase in salinity due to artificially raised water tables as a result of land use change (e.g. deforestation in Australia) or excessive irrigation (e.g. Lower Indus Valley, Pakistan) can lead to habitat degradation, decreased agricultural outputs, soil erosion, altered biogeochemical cycling and decreased carbon storage (Foster and Chilton, 2003). Geogenic contamination (i.e. with naturally occurring chemical contaminants) affects the health of millions of people worldwide, and may also impact GDEs – a problem that requires more attention (Bretzler and Johnson, 2015). GDEs can be impacted by known and emerging organic contaminants (pesticides, pharmaceuticals, recreational drugs, surfactants and personal care products), and by nutrient pollution from domestic and urban wastewater and agriculture. Organic contaminants and their degradation products can cause health problems, including developmental and reproductive effects in humans, wildlife and ecosystems (Campbell et al., 2006). Previous studies of ecosystem impacts of contamination have focused on surface water. Less is known about ecosystems impacted by groundwater contamination.

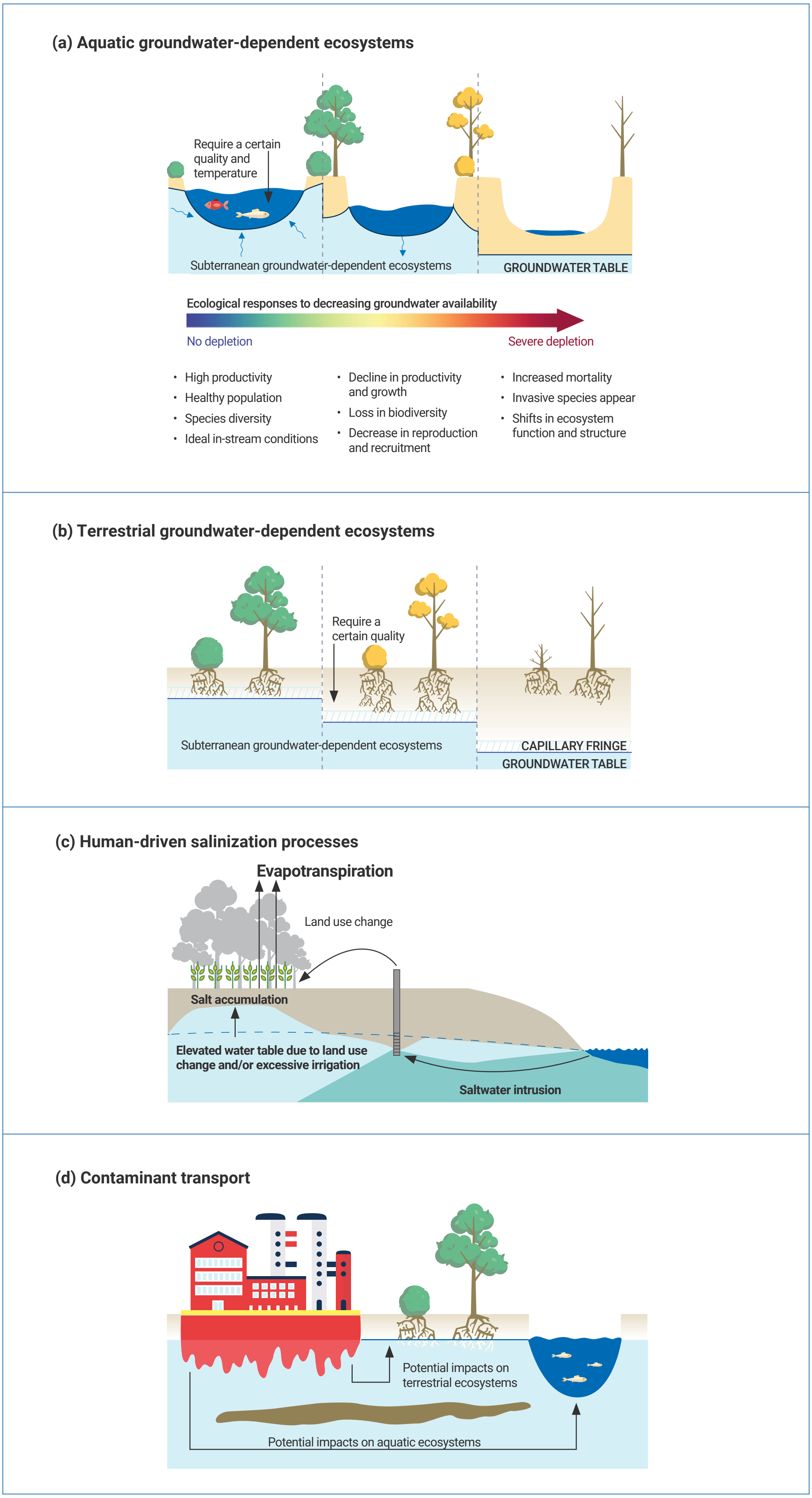
6.4 Conjunctive water and land management, nature-based solutions, and ecosystem protection

The shared well-being of groundwater, ecosystems and humans may be enhanced by groundwater management, conjunctive water and land management, nature-based solutions (WWAP/UN-Water, 2018), and improved ecosystem protection. Groundwater management, as described in Chapter 11, often focuses on groundwater or aquifers themselves. While important, this is often insufficient to ensure that groundwater and ecosystems together continue to provide critical ecosystem services. Conversely, groundwater knowledge or management is often insufficiently incorporated into ecosystem protection and management. Even though groundwater discharge and baseflow are the basis for the good state of many aquatic ecosystems, groundwater dependency of these systems is often not considered in mapping freshwater habitats or biodiversity (McManamay et al., 2017). For example, the World Wildlife Foundation's Global 200 list of ecoregions (terrestrial, freshwater, and marine subclasses) does not directly or explicitly consider groundwater or map GDEs (Box 6.1) when highlighting key areas of protection for aquatic and terrestrial ecosystems (Olson and Dinerstein, 2002). Explicitly considering groundwater in conjunctive water and land management, nature-based solutions, and ecosystem protection is a practical entry point to achieving groundwater and ecosystem sustainability.

Groundwater is part of both the water cycle and complex aquatic, terrestrial and subterranean ecosystems. It is thus essential to integrate groundwater management with ecosystem and watershed planning and protection, as is currently done at different scales: subnational (e.g. California), national (South Africa or Australia), or supranational (e.g. European Union) (Rohde et al., 2017). Land use planning that better incorporates groundwater generally has two elements: (i) resource quantity maintenance and quality protection, based on the vulnerability of a groundwater system or an aquifer to depletion, subsidence, degradation or pollution; and (ii) source protection around individual groundwater withdrawal sites, such as boreholes or springs, with a focus on protection from pollution (Smith et al., 2016).

Groundwater nature-based solutions (sometimes also called groundwater-based natural infrastructure) intentionally use and manage groundwater and subsurface systems and processes in order to increase water storage, flood retention, water quality, and environmental functions or services for the overall benefit of water security, human resilience and environmental sustainability (Villholth and Ross, n.d.). The best-known groundwater nature-based solution is managed aquifer recharge (see Box 7.1 and Section 11.5), which is increasingly implemented

Figure 6.5 Ecological impacts of decreasing groundwater quality and quantity



Note: (a) and (b) ecological responses to decreasing groundwater availability: (a) aquatic and (b) terrestrial groundwater-dependent ecosystems; (c) and (d) water quality and contamination impacts on groundwater-dependent ecosystems: (c) soil and groundwater salinization processes due to land use change, coastal pumping and irrigation, and (d) local and regional impacts of contamination events due to regional groundwater flow systems.

Sources: (a) and (b) based on Rohde et al. (2017, fig. 2, p. 297); (c) based on Foster and Chilton (2003, fig. 8, p. 1965); and (d) authors.

(Dillon et al., 2019). Other solutions exist along a spectrum of grey (more engineered) to green (more natural) infrastructure, including conservation agriculture, water infiltration basins, runoff harvesting, riverbank filtration and in-situ bioremediation of groundwater. Many cities have installed green infrastructure to improve water quality and quantity (so-called sponge cities; Harris, 2015), but there is a lack of knowledge and understanding of the quality and potential impacts of water infiltrated into urban aquifers (Box 6.3).

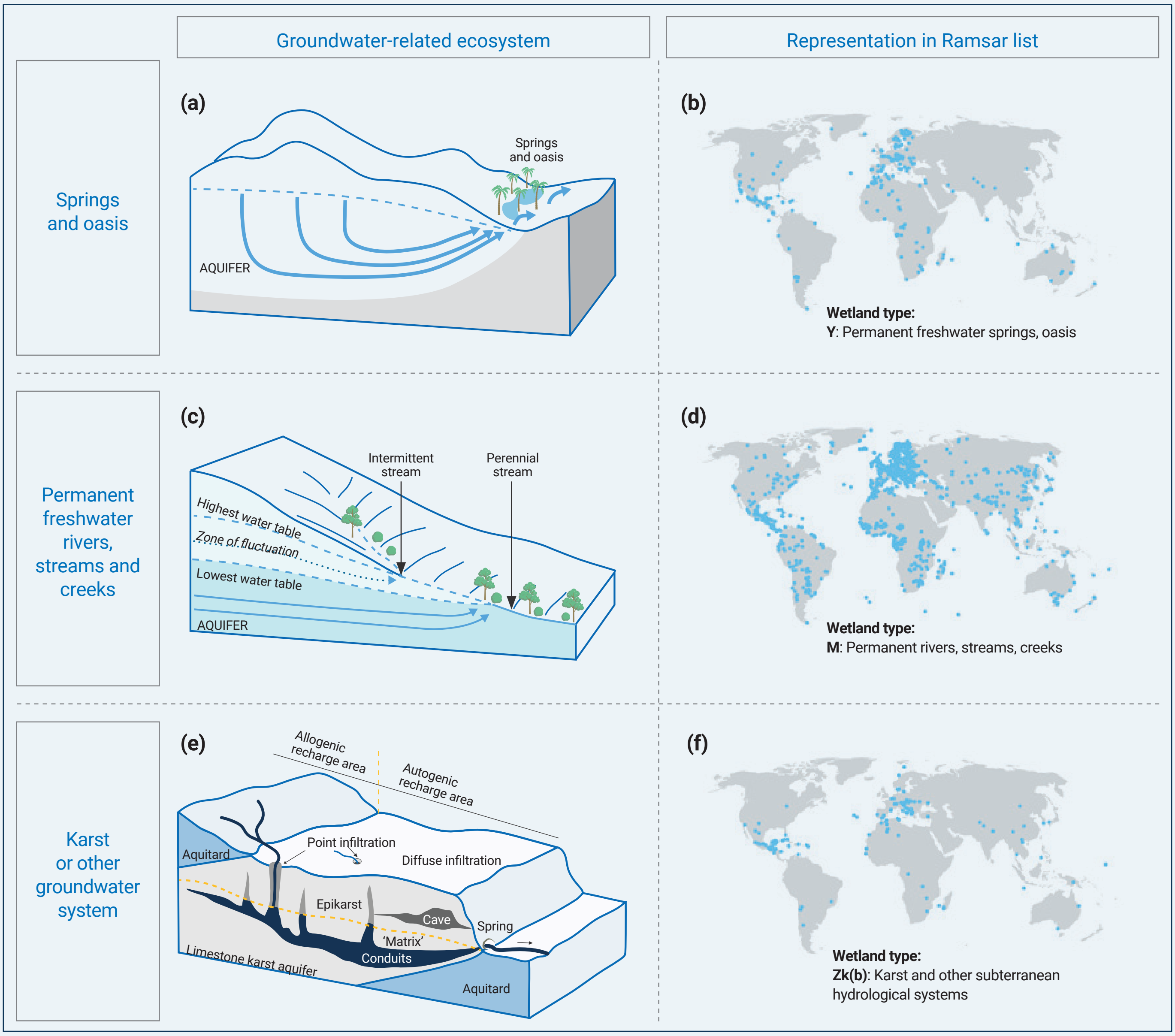
Finally, GDEs are usually not directly or formally protected. Protection of GDEs, especially terrestrial and subterranean, are largely ignored (Kreamer et al., 2015). An important exception to this is the Ramsar Convention (Box 6.2), which developed a seven-step groundwater management framework to maintain the ecological character of wetlands of international importance (Ramsar Convention Secretariat, 2010). Many of these are transboundary and require international cooperation for their protection and sustainable development, with explicit focus on shared groundwater and aquifers (cf. Chapter 12). Another widely used tool to protect aquatic ecosystems is the monitoring of environmental flows, which are the quantity, timing and quality of freshwater flows and levels necessary to sustain aquatic ecosystems that, in turn, support the cultures, economies, sustainable livelihoods and well-being of humans (Arthington et al., 2018). For example, the European Union Water Framework Directive establishes groundwater quantity and quality thresholds for GDEs (European Parliament/Council, 2000). In this case, minimum environmental flows should not be considered as 'ecological demands', but as 'restrictions to various uses' (both from the GDE or from nearby groundwater) in order to prevent environmental flows from competing with other human water demands. There are many environmental flow methods, but very few explicitly consider or quantify the groundwater contribution to environmental flows (FAO, 2019; Gleeson and Richter, 2017). Finally, there is a need to better understand the water quality aspects of environmental flows associated with groundwater.

Box 6.2 Groundwater, wetlands of international importance (Ramsar Sites), and UNESCO-designated sites, such as World Heritage sites, Biosphere Reserves and Geoparks

Groundwater is under-represented in global conservation networks, such as the Ramsar List of Wetlands of International Importance (Ramsar Convention Secretariat, 2013) and UNESCO-designated sites (World Heritage sites, Biosphere Reserves and Geoparks). The Ramsar List recognizes wetlands (Ramsar Sites) that are significant for 'humanity as a whole' based on site rarity, biological diversity and ecological community criteria. The Ramsar List (Figure) identifies groundwater processes or surface expressions such as 'permanent freshwater springs; oases' and 'karst and other subterranean hydrological systems', as well as groundwater-dependent environments like 'freshwater rivers/streams/creeks'. Ramsar Convention Parties are individually responsible for designating Sites and for the wise use and management of transboundary wetlands. However, there is no systematic assessment of groundwater's supporting role across the global network of Ramsar Sites nor of the Sites' roles in supporting groundwater resources.

The UNESCO-designated sites provide space for sustainable development experimentation and exemplification. Alongside Ramsar Sites, UNESCO-designated sites are critical to achieving targets across the Sustainable Development Goals (SDGs). Global wetlands, punctuated by Ramsar Sites, contribute to 75 SDG indicators (Ramsar Convention Secretariat, 2018). Currently, there are more than 130 Ramsar Sites that overlap wholly or partially with more than 100 UNESCO-designated sites. An iconic example is the Okavango Delta World Heritage site (Okavango Delta System Ramsar Site) in Botswana, a large flood-pulsed inland wetland forming a mosaic of water paths, floodplains and islands (Figure 6.1). Groundwater under islands acts as a sink for dissolved minerals due to the 'water pumping' by trees and vegetation on the islands that remove water through evapotranspiration, hence preventing salinization of this virtually enclosed, evaporation-dominated hydrological system. This process enables surface water in the delta to remain fresh, providing a source of water for wildlife and local people in the middle of the dry Kalahari Desert (UNESCO, n.d.). Despite their importance in maintaining the resilience of several ecosystems, there remains no comprehensive study of groundwater dependencies or relationships across UNESCO-designated sites. The Ramsar Convention and UNESCO-designated sites can be mutually supportive and complementary to ensure that ecosystem processes as well as cultural values are fully embedded in the protection and management of the designated sites.

Representation of groundwater-dependent ecosystems in the Ramsar List of Wetlands of International Importance



Sources: (a) and (c) based on Foster et al. (2006, fig. 1, p. 2); (b), (d) and (f) authors, based on data from RSIS (n.d.); and (e) based on Goldscheider and Drew (2007, fig. 1.1, p. 3).

Box 6.3 Nature-based solutions to protect groundwater-dependent ecosystems

Nature-based solutions can be an effective part of the management, protection or rehabilitation of groundwater-dependent ecosystems (GDEs) by reducing anthropogenic impacts (land use/climatic changes, groundwater abstraction, nutrient loads due to agricultural practices, point-source and diffuse pollution). Two examples highlight the diversity of nature-based solutions and their impacts on GDEs.

Nature-based solutions were designed and implemented in the catchment area of the Sulejów Reservoir (Poland), an area characterized by cyanobacterial blooms due to heavy pollution of groundwater with nitrates and phosphorus from nonpoint source pollution. A subsurface zone of pine sawdust mixed with soil or limestone led to a reduction in phosphate and nitrates concentrations in the groundwater of 58% and 85%, respectively (Izydorczyk et al., 2013; Frątczak et al., 2019).

Another example of groundwater-based natural infrastructure is from rural coastal Bangladesh. Here, carefully designed local rainwater harvesting and groundwater storage schemes support water security and resilience in areas afflicted by salinity and naturally occurring arsenic in groundwater (Ahmed et al., 2018). These schemes capture seasonal rainfall often lost to surface runoff to the sea through simple wells and filters, making it available throughout the year. Further, due to the density of the saline groundwater, the infiltrated freshwater tends to float on top without mixing. Every scheme serves small communities of up to several hundred people, who are able to maintain the system themselves, after training. These systems have been upscaled to over 100 communities in Bangladesh and hold great potential in flood-prone yet water-scarce areas.

Chapter 7

Groundwater, aquifers and climate change

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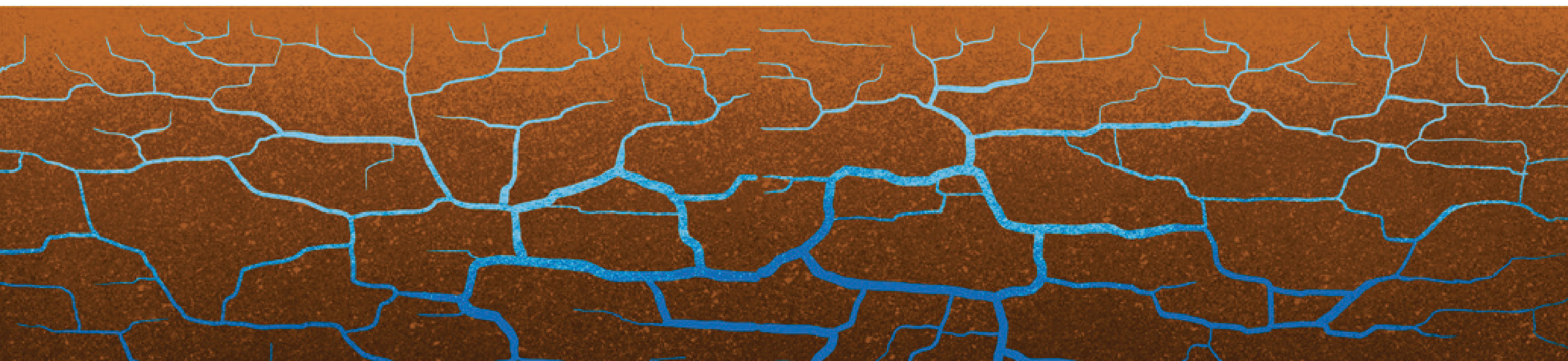


7.1 Introduction

Climate change strongly influences freshwater supply and demand globally. Warming of ~1°C over the last half century globally has directly impacted the supply of freshwater through the amplification of precipitation extremes, more frequent and pronounced floods and droughts, increasing evapotranspiration rates, rising sea levels, and changing precipitation and meltwater regimes. Groundwater, the world's largest distributed store of freshwater, is naturally well placed to play a vital role in enabling societies to adapt to intermittent and sustained water shortages caused by climate change. It is also essential to satisfy the increased demand for water in order to realize many of the United Nations' Sustainable Development Goals (SDGs), including no. 2 (zero hunger), 6 (water for all) and 13 (climate action). Aquifers transmitting and storing groundwater can also contribute to climate change mitigation through the use of geothermal energy to reduce CO_2 emissions, as well as the capture and storage of emitted CO_2. This chapter reviews the latest understanding of the impacts of climate change on groundwater quantity and quality as well as the opportunities, risks and challenges posed by the development of aquifers for climate change adaptation and mitigation.

7.2 Climate change impacts on groundwater resources

Climate change influences groundwater systems directly through changes in the water balance at the Earth's surface, and indirectly through changes in groundwater withdrawals as societies respond to shifts in freshwater availability (Figure 7.1 – Taylor et al., 2013a; Lall et al., 2020). The impacts of climate change on terrestrial water balances can be further modified by human activity such as land use and land cover (LULC) change (Favreau et al., 2009; Amanambu et al., 2020). Global warming also triggers the release of freshwater from long-term storage in continental icesheets and thermal expansion of the oceans, both of which contribute substantially to sea level rise (SLR).

Groundwater, the world's largest distributed store of freshwater, is naturally well placed to play a vital role in enabling societies to adapt to intermittent and sustained water shortages caused by climate change

7.2.1 Direct impacts of climate change on groundwater

Climate change directly impacts the natural replenishment of groundwater. This replenishment can occur across a landscape by precipitation directly (i.e. diffuse recharge) and via leakage from surface waters, including ephemeral streams, wetlands or lakes (i.e. focused recharge). The latter process is more prevalent in drylands[22] (Scanlon et al., 2006; Cuthbert et al., 2019a). Globally, mean modelled estimates of contemporary (1960s to 2010s) diffuse recharge range from 110 to 140 mm/year (Mohan et al., 2018; Müller Schmied et al., 2021), equivalent to 15 to 19 km³/year, and comprise ~40% of the world's renewable freshwater resources (Müller Schmied et al., 2021). Substantial uncertainty persists, however, in global projections of the impacts of climate change on groundwater recharge. This uncertainty stems primarily from limitations in the representation of climate change by Global Circulations Models (GCMs) and groundwater recharge by Global Hydrological Models (GHMs) (Reinecke et al., 2021).

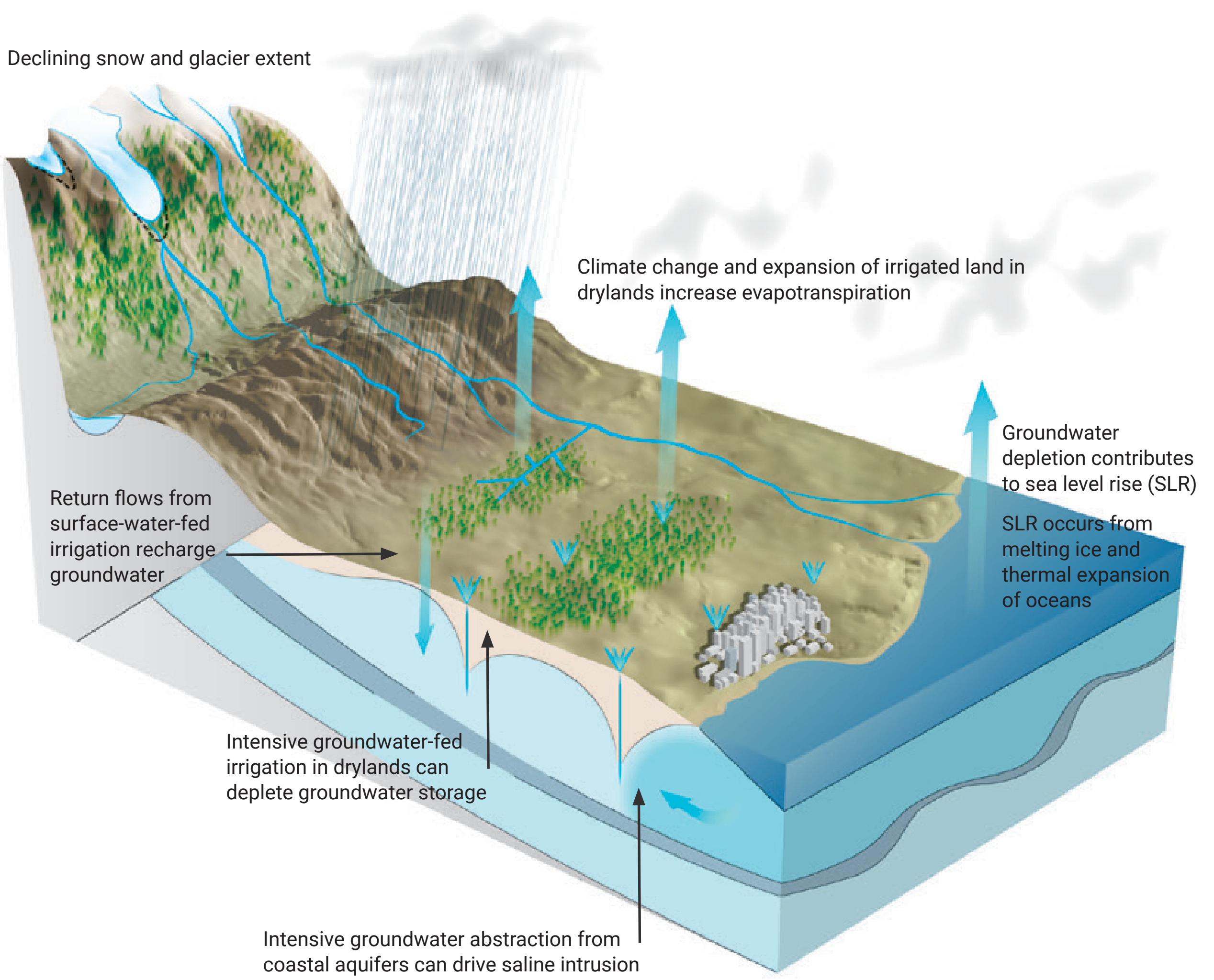
Changes in precipitation and evapotranspiration

Climate and land cover largely determine rates of precipitation (*P*) and evapotranspiration (*ET*), whereas the underlying soil and geology dictate whether a water surplus (*P* - *ET*) can be transmitted to an underlying aquifer. The amplification of *ET* rates in a warming world constrains the generation of water surpluses; globally *ET* is estimated to have increased by ~10% between 2003 and 2019 (Pascolini-Campbell et al., 2021).

Spatial variability in diffuse recharge is controlled primarily by distributions in precipitation. As the planet warms, however, considerable uncertainty persists in where, when, and how much rain or snow will fall. A key conclusion of the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014a, p. 1085), the idea that hydrological responses to climate change can be described as "*wet gets wetter, dry gets drier*", has

[22] Drylands are areas with a sub-humid, semi-arid, arid, or hyper-arid climate.

Figure 7.1 Key interactions between groundwater and climate change showing how direct and indirect impacts of climate change affect groundwater systems

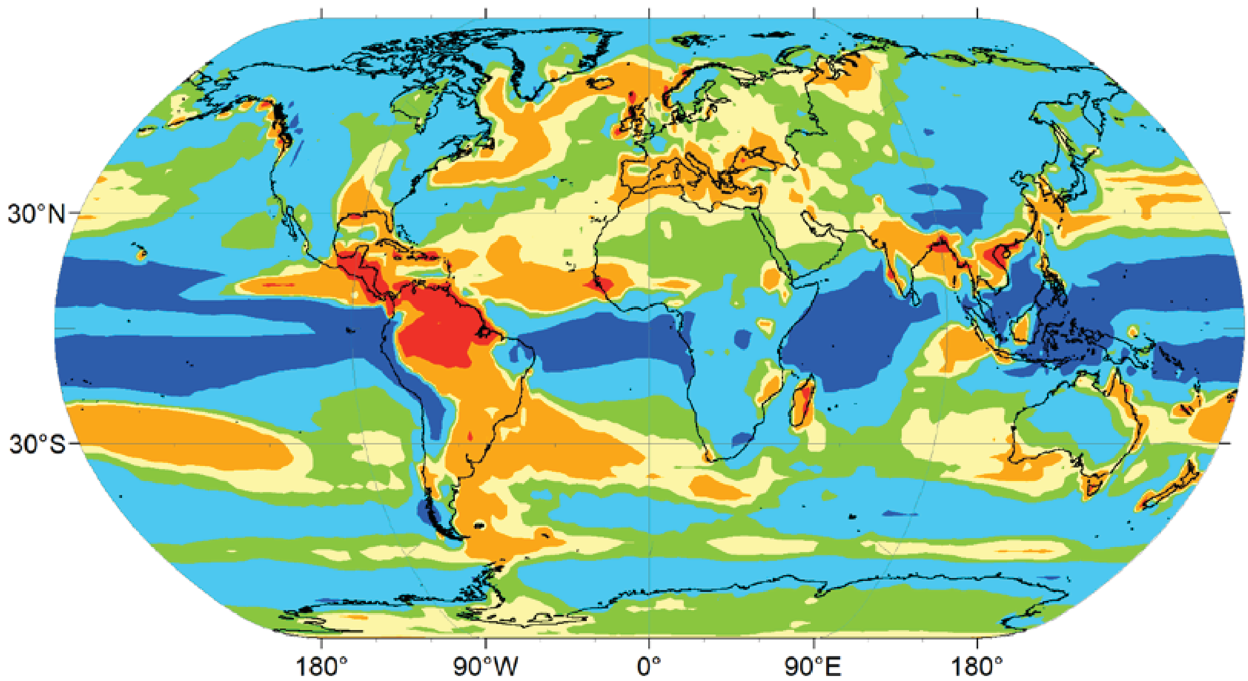


Source: Authors, adapted and revised from Taylor et al. (2013a).

since been shown to be too simplistic (Byrne and O'Gorman, 2015). Substantial reductions in precipitation, for example, are projected in wet equatorial regions of the Americas and Asia, with the largest projected increases in precipitation occurring over oceans in the tropics, and not over land (Figure 7.2).

Over time, climate extremes (i.e. droughts and floods), which strongly influence groundwater recharge, often correlate to modes of climate variability such as the El Niño Southern Oscillation (ENSO, e.g. Taylor et al., 2013b; Kolusu et al., 2019) and Atlantic Multi-decadal Oscillation (Green et al., 2011). No consensus exists, however, in how large-scale controls on climate variability like ENSO are projected to respond to global warming (McPhaden et al., 2020). During the multi-annual Millennium Drought in Australia (1995–2010), groundwater storage in the Murray-Darling basin declined substantially and continuously by ~100 ± 35 km^3 from 2000 to 2007 in response to a sharp reduction in recharge and an absence of extreme rainfall events (Leblanc et al., 2009). Wetter conditions do not, however, consistently produce more groundwater recharge: incidences of greater (x 2.5) winter precipitation in the southwestern USA during ENSO years, for example, can give rise to enhanced ET from desert blooms that largely or entirely consume the water surplus (Scanlon et al., 2005).

Figure 7.2 Projected changes in mean annual precipitation globally under climate change



Note: Areas in red (dark blue) and brown (light blue) indicate where substantial reductions (increases) in precipitation are projected this century.

Changes are defined as the difference between projected (2071–2100) CMIP5 (Coupled-Modelled Inter-Comparison Project Phase 5) ensemble mean annual precipitation and observed (1979–2019) mean annual GPCP v2.3 (Global Precipitation Climatology Project) precipitation.

Source: Authors, based on CMIP5 data from Taylor et al. (2012a) and GPCP data from Adler et al. (2003).

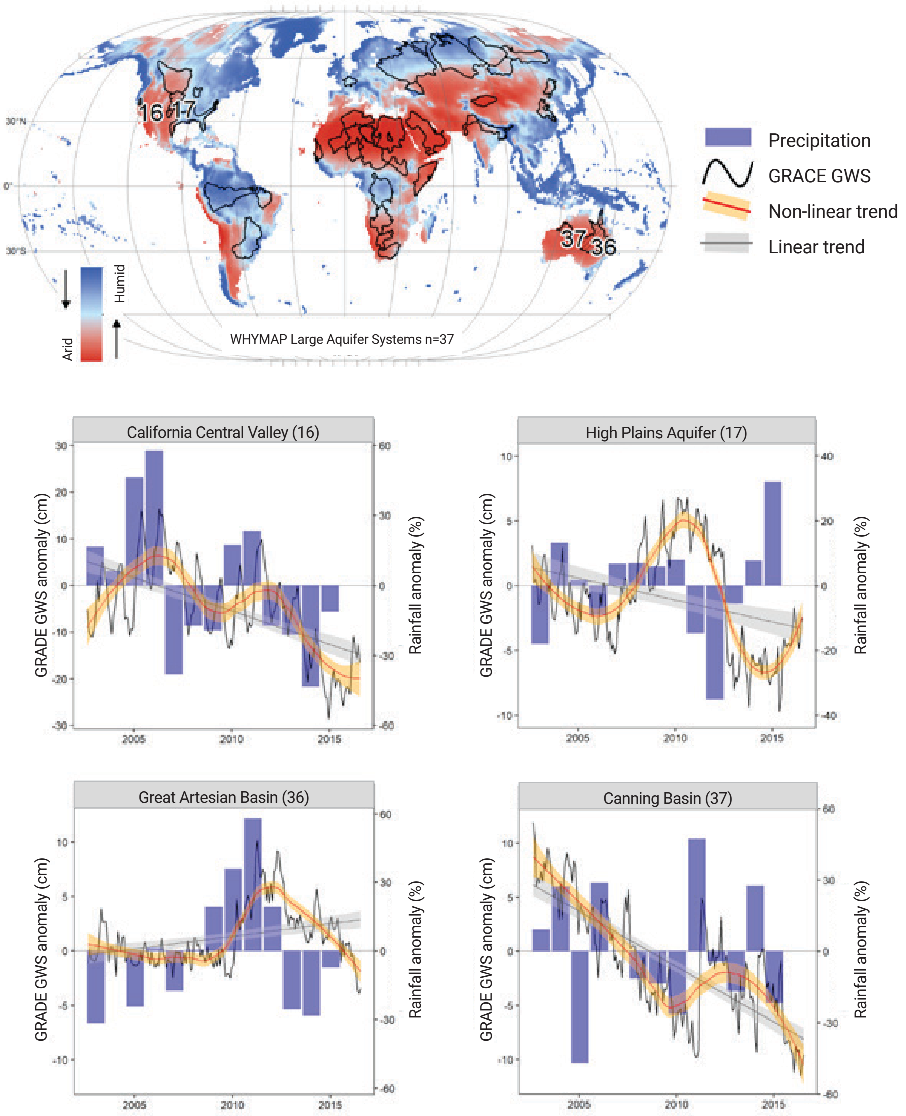
One observed and widespread impact of climate change influencing groundwater replenishment is the intensification of precipitation

One observed and widespread impact of climate change influencing groundwater replenishment is the intensification of precipitation. As warmer air holds more moisture, greater *ET* is required to reach condensation (dew) points in a warming world. This transition results in fewer light precipitation events and more frequent heavy precipitation (Myhre et al., 2019). This 'intensification' of precipitation is strongest in the tropics (Allan et al., 2010), where the majority of the world's population is projected to live by 2050 (Gerland et al., 2014). The consequences of this changing distribution in global precipitation include more variable and reduced soil moisture, more frequent and intense floods, as well as longer and more frequent droughts.

The transition towards fewer but heavier rainfalls is expected to enhance groundwater recharge in many environments. Heavy rainfall has been shown to contribute disproportionately to groundwater recharge in locations across the tropics (Jasechko and Taylor, 2015; Cuthbert et al., 2019a; MacDonald et al., 2021), including drylands, where extreme (heavy) rainfall creates ephemeral surface water bodies that generate focused recharge (Favreau et al., 2009; Taylor et al., 2013b; Seddon et al., 2021). The disproportionately greater contribution of heavy rainfalls to groundwater recharge has similarly been noted in drylands outside of the tropics in Australia (Crosbie et al., 2012) and the southwestern USA (Small, 2005). Episodic increases in groundwater storage from recharge, estimated from GRACE[23] satellite data in drylands around the world, are associated with extreme (> 90th percentile) annual precipitation (Figure 7.3). In contrast, in temperate regions characterized by shallow water tables that can rise quickly to the ground surface during heavy rains, potential increases in recharge are limited (Rathay et al., 2018) and groundwater flooding can occur (Macdonald et al., 2012).

Figure 7.3

Changes in monthly groundwater storage and annual precipitation in four large aquifer systems in drylands areas of the USA and Australia



Note: Years of extreme (90th percentile) precipitation include 2006 (Central Valley), 2015 (High Plains Aquifer), 2011 (Great Artesian Basin) and 2011 (Canning Basin). Monthly time series of changes in groundwater storage derived from GRACE satellite data with changes in annual precipitation, Climatic Research Unit (CRU) v. 4.01; Harris et al., 2014) and fitted non-linear and linear trends. Shaded envelops around the trends indicate a 95% confidence interval of the fitted trends; locations of the four large aquifer systems (defined by WHYMAP, 2008) are shown on the world map on the top left, with the aridity index as blue-red shading.

Source: Authors, based on Shamsudduha and Taylor (2020).

Changes in ice and snow

Across continental northern latitudes, as well as in mountainous and polar regions, global warming alters meltwater flow regimes from ice and snow, impacting groundwater recharge. In temperate regions, warming results in less snow accumulation and earlier snowmelt, as well as more winter precipitation falling as rain and an increased frequency of rain-on-snow events (Harpold and Kohler, 2017). The aggregate impact of these effects is a reduced seasonal duration and magnitude of recharge, which lowers water storage in catchments and amplifies

[23] Gravity Recovery and Climate Experiment: https://grace.jpl.nasa.gov/mission/grace-fo/.

the severity of extreme summer low flows (Dierauer et al., 2018). Aquifers in mountain valleys exhibit shifts in the timing and magnitude of: (1) peak groundwater levels due to an earlier spring melt, and (2) low groundwater levels associated with longer and lower baseflow periods (Figure 7.1) (Allen et al., 2010). Summer low flows in streams may be exacerbated by declining groundwater levels, so that streamflow becomes inadequate to meet domestic and agricultural water requirements (see section 7.2.2) and to maintain ecological functions such as in-stream habitats for fish and other aquatic species. These hydrological changes are compounded by the higher temperature of summer low flows (Dierauer et al., 2018).

The impacts of receding alpine glaciers on groundwater systems are not well understood. As glaciers recede due to climate change, meltwater production initially increases to a maximum, known as 'peak water', before dropping off as the glaciers continue to retreat; approximately half of the world's glacierized drainage basins are considered to have passed peak water (Huss and Hock, 2018). In the tropical Andes of Peru, glacier meltwater flows steadily decrease after peak water but during the dry season groundwater continues to discharge to streams, maintaining baseflow during the water-stressed dry season (Somers et al., 2019). Similarly, recent analyses highlight increases in focused recharge due to increased meltwater contributions to streamflow in glacierized drylands (Liljedahl et al., 2017). Over the longer term under climate change, a reduction in recharge occurs due to increasing *ET*, which may reduce meltwater contributions that generate focused recharge from summer low flows (Taylor et al., 2013a).

The impact of sea level rise alone on seawater intrusion is often small relative to that of groundwater abstraction

The seasonal freezing of soils that affects ~50% of exposed land in the Northern Hemisphere (Zhang et al., 2003) is an important control on snowmelt infiltration and strongly influences the amount and timing of winter and spring runoff in cold regions (Hayashi, 2013). From 1901 to 2002, the extent of seasonally frozen ground in the northern hemisphere decreased by 7% due to rising air temperatures (Lemke et al., 2007). Climate change also modifies the distribution and extent of permafrost, altering soil moisture, streamflow seasonality, and the partitioning of water stored above and below ground (Walvoord and Kurylyk, 2016). Enhanced thawing of permafrost under climate change decreases the distribution and thickness of permafrost, creating new lateral groundwater pathways that increase the connectivity of aquifers and surface waters (Lamontagne-Hallé et al., 2018). This transition explains the observed paradox in the Arctic of both wetting (i.e. increased baseflow to downslope rivers) and drying (i.e. shrinking of upslope wetlands and lakes).

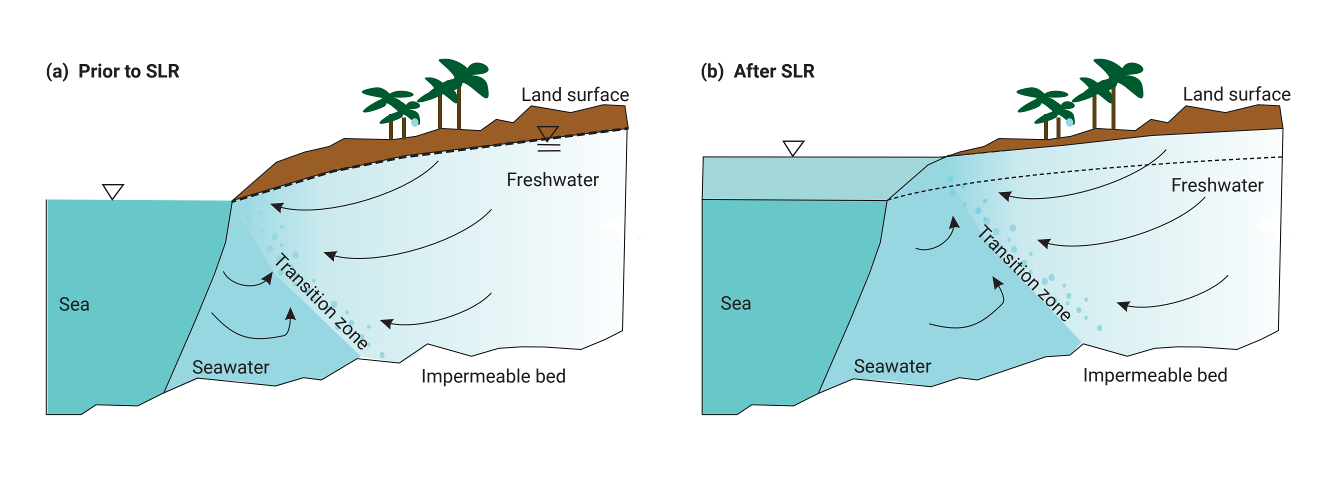
Sea level rise and salinization of coastal aquifers

Coastal aquifers form the interface between oceanic and terrestrial hydrological systems and provide a critical source of freshwater for people in coastal regions. Global SLR of ~3 mm/year since 1990, relative to ~1 mm/year from 1902 to 1990 (Dangendorf et al., 2017), has induced seawater intrusion into coastal aquifers around the world (Michael et al., 2013). Seawater intrusion depends on a variety of factors beyond SLR, including coastal geology and topography, as well as replenishment and abstraction of fresh groundwater (Stigter et al., 2014). The threat posed by SLR to groundwater is highest for low-lying deltas (e.g. the Ganges-Brahmaputra and Mekong deltas) and islands with limited rates of groundwater discharge, that include Small Island Developing States (SIDS) (Holding et al., 2016).

Seawater intrusion is the consequence of an inland shifting of the freshwater–saltwater interface in the subsurface (Figure 7.4). The impacts of SLR are exacerbated by seawater inundations during storm surges, cyclones (Holding and Allen, 2015; Ketabchi et al., 2016; Shamsudduha et al., 2020) and tsunamis (Villholth, 2013b), causing vertical and lateral intrusion into the aquifer. Atolls (i.e. coral reef islands) are extreme examples of such vulnerable environments (Werner et al., 2017), where fresh groundwater lenses are highly dynamic and heterogeneous due to the combined effects of a complex geology, episodic ocean events, strong climatic variability and human interventions (e.g. LULC change, groundwater pumping).

The impact of SLR alone on seawater intrusion is often small relative to that of groundwater abstraction (Ferguson and Gleeson, 2012). As a result, seawater intrusion is often observed most prominently in heavily exploited coastal aquifers with high population densities (e.g. Jakarta; Gaza, State of Palestine). Intensive groundwater pumping can accelerate seawater intrusion through land subsidence as has been observed in Australia, Bangladesh, China, Indonesia, Saudi Arabia and the USA (Polemio and Walraevens, 2019; Nicholls et al., 2021), where subsidence rates can exceed projected rates of SLR. Low-lying deltas, in which the subsurface is dominated by clayey sediments prone to compaction from the lowering of groundwater tables, are especially vulnerable to seawater intrusion (Herrera-García et al., 2020).

Figure 7.4 Impact of sea level rise (SLR) on seawater intrusion in a sloping unconfined coastal aquifer system



Source: Authors, adapted from Ketabchi et al. (2016).

Climate change presents direct risks to the quality of groundwater, not only as a result of the amplification of precipitation extremes but also through reductions in recharge

Other direct impacts of climate change on groundwater quality

Climate change presents direct risks to the quality of groundwater, not only as a result of the amplification of precipitation extremes but also through reductions in recharge. Heavy rainfalls (e.g. >10 mm/day) have the potential to amplify recharge and mobilize contaminants such as chloride and nitrate in the vadose zone immediately above aquifers in drylands (e.g. Gurdak et al., 2007) and temperate regions (Graham et al., 2015); further, surface runoff can intercept poorly contained waste and stored chemicals on or near the ground, which then leach into aquifers (WHO, 2018). In areas with inadequate sanitation provision, these events can also serve to flush faecal microbial pathogens and chemicals (e.g. nitrate) through shallow soils to the water table (e.g. Taylor et al., 2009; Sorensen et al., 2015; Houéménou et al., 2020), sometimes aided by preferential flowpaths such as soil macropores (Beven and Germann, 2013). Indeed, recharge from heavy rainfall events in such environments has been associated with outbreaks of diarrhoeal diseases, including cholera (Olago et al., 2007; De Magny et al., 2012). Drought-induced changes to sanitation practices in the town of Ramotswa in semi-arid Botswana led to a switch from water-borne sanitation (flush toilets) to on-site sanitation facilities (e.g. pit latrines), that have amplified the risk of groundwater contamination (McGill et al., 2019).

Reductions in groundwater recharge attributed to climate change in the Mediterranean region (e.g. Stigter et al., 2014) have led to the concentration of solutes such as chloride, nitrate and arsenic in soils and shallow aquifers, due to enhanced evaporation and less dilution (Mas-Pla and Menció, 2019).

The combination of global warming and the heat island effect from urbanization on subsurface temperatures also has implications for groundwater quality, as a result of changes in the solubility and concentration of contaminants such as manganese and dissolved organic carbon (Taniguchi et al., 2007; Riedel, 2019; McDonough et al., 2020). The thawing of permafrost releases greenhouse gases (e.g. methane, carbon dioxide, nitrous oxide) and increases contamination risks from mining operations through increased hydrological connectivity between groundwater and surface waters.

7.2.2 Indirect impacts of climate change

The impacts of climate change on groundwater may be greatest through its indirect effects on irrigation water demand

Increases in groundwater withdrawals arise indirectly from climate change as societies strive to adapt to increased *ET* associated with global warming (Figure 7.1) as well as increased variability and overall declines in soil moisture and surface water availability. Indeed, the impacts of climate change on groundwater may be greatest through its indirect effects on irrigation water demand (Taylor et al., 2013a). Strategies employing groundwater to adapt to more variable (less reliable) precipitation and to meet growing global food demand (Chapter 3) have clear consequences for sustainable groundwater governance and management (Chapters 2 and 10), potentially leading to depletion or contamination of groundwater resources, impacting environmental flows (De Graaf et al., 2019; Jasechko et al., 2021) and jeopardizing groundwater-dependent ecosystems (Chapter 6). Global-scale modelling suggests that between 1991 and 2016, irrigation accounted for ~65% of global freshwater withdrawals and ~88% of consumptive water use (Müller Schmied et al., 2021); groundwater was estimated to comprise 25% of all withdrawals and 37% of total consumptive use. This large-scale redistribution of freshwater from rivers, lakes and groundwater to arable land has led to: (a) groundwater depletion in regions with primarily groundwater-fed irrigation; (b) groundwater accumulation as a result of recharge from return flows from surface water-fed irrigation; and (c) modifications of local climates as a consequence of enhanced evapotranspiration from irrigated land (Figure 7.1). The expansion of irrigated and rainfed agriculture also complicates the relationship between climate change and groundwater, as managed agro-ecosystems do not respond to changes in precipitation in the same manner as natural ecosystems.

Waterlogging in inland areas, amplified by surface-water irrigation and increased recharge arising from the conversion of natural vegetation to shallow-root crops (Favreau et al., 2009) can lead to rising water tables and soil salinization through upward capillary flow that then evaporates. Many irrigated areas of the world are thus facing the twin problems of soil salinization and waterlogging. These problems currently affect over 20% of the total global irrigated area (Singh, 2021).

7.3 Resilience and vulnerability of aquifer systems to climate change

Groundwater is the world's largest distributed store of freshwater, with an estimated volume of ~23 million km³ in the upper 2 km of Earth's continental crust (Gleeson et al., 2016). Although a small fraction of this (less than 6%) is considered 'modern' (i.e. replenished less than 50 years ago), this volume (~1.4 km³) is still equivalent to a body of water with a depth of about 3 m spread over the continents, dwarfing all other unfrozen components of the active hydrologic cycle. The relationship between climate change and groundwater systems differs fundamentally from surface water systems, as distributed groundwater storage derives from recharge contributions over periods ranging from years to decades and even millennia (Ferguson et al., 2020). Such residence times of groundwater explain the comparative resilience of aquifer systems, relative to surface waters, to climate variability and change, as demonstrated by groundwater-based solutions to drought (Section 7.4) and long-term lags observed between groundwater withdrawals, depletion and recharge (Cuthbert et al., 2019b). Developing water supplies that are resilient to climate change will, in many parts of the world, involve the use of groundwater conjunctively with rivers, lakes and surface water reservoirs. There is much to be done in terms of optimizing conjunctive management of these sources, including increasing recognition that the systems often are interlinked; in humid areas, groundwater mostly feeds rivers and other surface water systems whereas in drylands ephemeral river flows often replenish groundwater (Scanlon et al., 2016).

7.3.1 Aquifer systems resilient to climate change

The natural resilience of aquifer systems to climate change varies considerably and is controlled primarily by geology, vegetation, topography and climate, both past and present. Aquifer systems comprising thick, expansive sedimentary rock sequences (e.g. limestone, sandstone), which typically transmit and store large volumes of groundwater, are more resilient to climate variability and change than aquifer systems within hard rock environments (e.g. fractured crystalline rocks), which possess more restricted capacities to transmit and store groundwater (Cuthbert et al., 2019b). Aquifer systems in humid regions receiving regular recharge may be more sensitive to climate disturbances such as drought, but also relatively quick to recover. In contrast, aquifer systems in drylands, where recharge is low and episodic, are less sensitive to short-term (seasonal to inter-annual) climate variability, but vulnerable to long-term climate trends from which they will be slow to recover (Opie et al., 2020). The resilience to climate change of water supplies drawn from exploited aquifer systems is also context-specific (Gleeson et al., 2020b) and depends upon the magnitude of groundwater withdrawals, among other factors. For example, low-intensity abstraction for domestic water supplies from low-storage, weathered crystalline rock aquifers receiving recharge annually across humid equatorial Africa is generally resilient to groundwater depletion. Abstraction of largely 'fossil' groundwater from regional-scale sedimentary aquifer systems (e.g. Nubian sandstone, Kalahari sands) in African drylands (MacDonald et al., 2021) is climate-resilient but ultimately unsustainable and controlled by the prevailing available groundwater storage.

The relationship between climate change and groundwater systems differs fundamentally from surface water systems

7.3.2 Aquifer systems vulnerable to climate change

Aquifer systems that are vulnerable to climate change include: those where impacts (outlined in Section 7.2) are largely independent of human withdrawals (examples 1 to 4); and those where the intensity of human groundwater withdrawals plays a key role in amplifying vulnerability to climate change (examples 5 to 8):

1. *low-relief coastal and deltaic aquifer systems*, such as those found in Asian megadeltas and SIDS[24] that are vulnerable to SLR, storm surges and climate change impacts on recharge;
2. *aquifer systems in continental northern latitudes or alpine and polar regions* where long-term recharge and discharge are impacted by changing meltwater regimes (e.g. Rocky Mountains, Indus basin) and a thawing permafrost (e.g. Canada, Russia) that increases hydrologic connectivity and risks of contamination;
3. *aquifers in rapidly expanding low-income cities* (e.g. Dakar, Lucknow, Lusaka) *and large displaced and informal communities* (e.g. in Bangladesh, Kenya, Lebanon) reliant on on-site sanitation provision (e.g. pit latrines, septic tanks), where the increased frequency of extreme rainfall can amplify leaching of surface and near-surface contaminants;
4. *shallow alluvial aquifers underlying seasonal rivers in drylands*, fed by ephemeral river runoff (Duker et al., 2020), which have a storage capacity that largely depends on the size of the river and thickness of the sand deposits; smaller systems have a limited storage capacity and are highly vulnerable to more variable precipitation, including longer droughts projected under climate change;
5. *intensively pumped aquifer systems for groundwater-fed irrigation in drylands* (e.g. in northwest India; the California Central Valley and central High Plains, USA; the Souss aquifer, Morocco; the North China Plains) where there is high consumptive use of groundwater and reductions in recharge under climate change could threaten the continued viability of irrigated agriculture;
6. *intensively pumped aquifers for dryland cities* (e.g. Lahore; San Antonio) where potential reductions in recharge under climate change could threaten the continued viability of public water supplies, given that other perennial sources of water are either limited or do not exist;

[24] www.unesco.org/new/en/natural-sciences/priority-areas/sids/resources/sids-list/.

7. *intensively pumped coastal aquifers* (e.g. Gaza City; Jakarta; Tripoli), where pumping reduces groundwater levels and substantially enhances saline intrusion beyond that from SLR alone; and
8. *low-storage/low-recharge aquifer systems in drylands* (e.g. Bulawayo; Ouagadougou), where alternative perennial water sources are limited or do not exist, and recharge is episodic so that even small reductions in recharge can lead to groundwater depletion.

7.4 Groundwater-based adaptations to climate change – human responses

Groundwater-based adaptations to climate change exploit distributed groundwater storage and the capacity of aquifer systems to store water surpluses (e.g. seasonal, episodic). They incur substantially lower evaporative losses than conventional infrastructure, such as surface dams. The importance of groundwater as a vital buffer to the impacts of climate change, including not only droughts and increased *ET* but also more variable soil moisture and surface water (Section 7.3), is expected to increase in the coming decades. The 'green revolutions' in Asia have relied on the continued widespread use of shallow groundwater for dry-season irrigation by smallholder farmers and increased regional resilience to seasonal water availability (Schneider and Asch, 2020). In tropical Africa there are growing calls (Cobbing, 2020) to draw from groundwater storage to improve the climate resilience of water and food supplies, in pursuit of the SDGs 2, 6, and 13 among others. Adaptations to climate-driven shortages in water supplies to cities such as Dar es Salaam (Tanzania) in 1997 and Cape Town (South Africa) in 2017 involved not only reductions in freshwater demand but also supply-side strategies that increasingly used groundwater as a climate-resilient source of freshwater that can be used conjunctively with surface water resources (CoCT, 2019). Further, improved community hygiene and sanitation provision can enhance the resilience of groundwater-fed water supplies to climate change in densely populated, low-income communities by reducing risks of faecal contamination (WHO, 2019).

Human responses to climate change employing groundwater-based adaptations include a range of managed aquifer recharge (MAR) strategies to augment freshwater availability (see Section 11.5). Dillon et al. (2019) divide MAR strategies into four broad categories: (a) streambed channel modification, (b) bank filtration, (c) water spreading and (d) recharge wells. Each is described with examples of their application in Box 7.1.

7.5 Groundwater-based climate change mitigation via low-carbon geothermal energy

Geothermal energy is heat stored and transmitted in the subsurface. This section focuses on groundwater as an agent in the storage, movement, and extraction of geothermal energy. The development of geothermal energy plays an important role in reducing CO_2 emissions and enabling transitions to sustainable energy sources. Although high-enthalpy (>150°C) subsurface fluids can be used to produce electricity and heating, lower-enthalpy (40°C to 150°C) groundwater can also be used, primarily for heating. Even shallow low-temperature groundwater (often in the range of 5 to 25°C) can be used to provide low-carbon cooling and heating via ground source heat pumps (GSHPs).

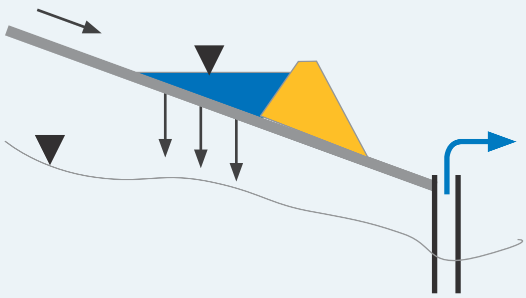
7.5.1 Geothermal energy for low-carbon electricity generation

Geothermal electricity production typically requires deep drilling to access high temperatures, and significant permeability at such depths to allow for the free circulation of fluids. The fluids used may be natural groundwaters within deep sedimentary aquifers (e.g. in Italy and California, USA) or igneous complexes (e.g. in El Salvador, Iceland, Kenya). Alternatively, where rocks have limited permeability, they can be artificially stimulated or hydraulically fractured to allow for the circulation of introduced fluids, forming an Enhanced Geothermal System (EGS, e.g. Soultz-sous-Forêts, France). Generation of electricity conventionally requires production of steam at the surface to drive turbines. Electricity can, however, be generated at lower temperatures (<180°C) in binary cycle systems, with produced hot water used to vaporize organic fluids (e.g. high-pressure butane or pentane) that drive turbines.

Box 7.1 Managed aquifer recharge (MAR) strategies

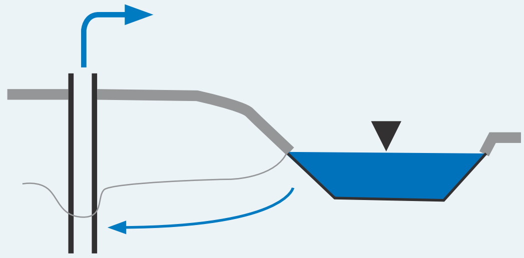
(a) Streambed channel modification

Streambed channel modification describes infrastructure such as small dams, ponds and tanks that detain surface runoff to supply drinking water and irrigation via directed infiltration, replenishing underlying aquifers. Application of this MAR strategy has a long history in hard-rock aquifers of peninsular India (Boisson et al., 2014) and alluvial plains of Rajasthan in northwest India (Dashora et al., 2018). Other examples include huge recharge dams in Oman that are operated in combination with water spreading in a series of connected recharge basins (Dillon et al., 2019).



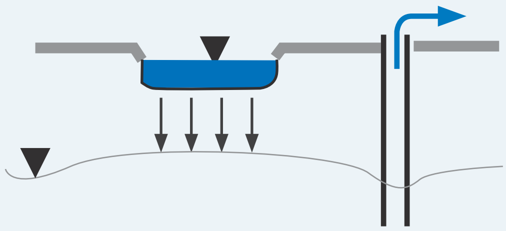
(b) Bank filtration

Bank filtration refers to the process of enhancing infiltration of surface water through groundwater abstraction next to rivers and other surface water bodies so that the hydraulic gradient from surface water to the pumping well is increased. As reported by Dillon et al. (2019), the city of Budapest's water supply is sustained entirely by bank filtrate from the River Danube.



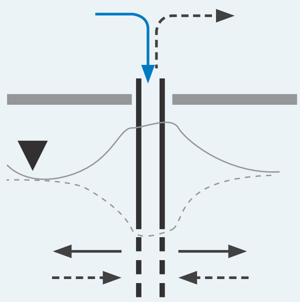
(c) Water spreading

Spreading refers to the use of floodwaters to increase soil moisture for food production on dry cropping land. Water spreading projects employing flood discharges from the River Colorado in Arizona (USA) have shown to increase groundwater storage for dryland cities such as Phoenix and Tucson (Scanlon et al., 2016). In the Netherlands, treated river water from the Rhine is transported by pipeline to coastal dune areas where it is infiltrated as groundwater recharge in basins (Sprenger et al., 2017).



(d) Recharge wells (aquifer storage and recovery, ASR)

Using recharge wells is the practice of injecting water into aquifers via wells and is often referred to as Aquifer Storage and Recovery (ASR) or Aquifer Storage Transfer and Recovery (ASTR). In northern Europe, seasonal (winter) surpluses in surface water collected in reservoirs are often transferred to shallow aquifers via injection wells to sustain anticipated increases in summer water demand (Hiscock et al., 2011). In coastal Bangladesh, the resilience of rural communities to increasing coastal salinity has been improved through the creation of freshwater lenses within shallow partly saline, confined aquifers. This is achieved via the injection of seasonal pond water from flood discharges or rainwater harvested in wells under gravity drainage (Sultana et al., 2015). In Windhoek (Namibia), the resilience of the city's water supply to climate variability and change has been augmented through the transfer via injection wells of treated, seasonal surface waters into the fractured quartzite aquifer system (Murray et al., 2018).



Source: Based on IAH (2005).

By 2020, around 30 countries were generating a total of 95 TWh_e of geothermal electricity per year, with a total installed capacity of 16.0 GW_e. This marks an increase of 3.7 GW_e over 2015 at an estimated cost of US$10.4 billion.[25] The largest producing nations (in order of total installed capacity) are: the USA, Indonesia, the Philippines, Turkey and Kenya, all of which are known for their active geothermal and volcanic provinces (Huttrer, 2021). The relative growth in wind and solar energy has in recent years outstripped that of geothermal electricity, reflecting the lower cost and perceived risk of the former, and their shorter payback periods. However, geothermal power plants are, contrary to wind and solar energy plants, well suited to producing an electrical base load. Installed capacity is projected to grow by ~20% between 2020 and 2025 (Huttrer, 2021).

7.5.2 Groundwater use for low-carbon heating and cooling

One of the main opportunities provided by lower-enthalpy geothermal energy is its contribution to decarbonizing domestic, commercial and industrial heating and cooling

One of the main opportunities provided by lower-enthalpy geothermal energy is its contribution to decarbonizing domestic, commercial and industrial heating and cooling, which accounts for at least 40% of global energy consumption and CO_2 emissions (IEA, 2019b). The installed geothermal capacity for direct (including GSHPs) thermal supply in 2020 was almost 108 GW_t, marking a growth rate of ~9% per annum, with 284 TWh_t per year being supplied (Lund and Tóth, 2020). Leading nations include (in order of installed capacity) China, the USA and Sweden, with Scandinavian nations having a high per capita uptake (mostly due to GSHPs). Of the installed capacity, 78 GW_t (72%) was provided by geothermal heat pumps (Lund and Tóth, 2020).

Shallow groundwater (at a depth ranging from 0 to 200 m) typically has a rather constant temperature that is slightly warmer than the annual average air temperature (Figure 7.5). It thus ranges from ~5°C in northern Scandinavia to over 25°C in Sub-Saharan Africa. The temperature typically increases by 2.5 to 3°C for every 100 m of depth, so that at a depth of 1.5 km, temperatures often approach or exceed 50°C. If a transmissive aquifer is present at such depths, the groundwater can be used for the direct heating of individual buildings, multiple buildings (district heating networks), swimming pools, horticulture (greenhouses) or aquaculture. After heat has been extracted from the groundwater via a heat exchanger, the 'thermally spent' water is often returned to the reservoir via a reinjection well (or wells) in order to maintain reservoir pressure and to avoid potential surface contamination by unwanted natural solutes. Such an arrangement is termed a well doublet (Figure 7.5 – Fridleifsson et al., 2008; Banks, 2012; Kramers et al., 2012).

Large modern buildings (offices, data centres, hospitals, etc.) have a large cooling requirement, even in winter and in temperate climates. Many industrial processes also have cooling requirements, and the need for low-carbon cooling will likely increase as climate change progresses. Cool shallow groundwater (e.g. 10 to 12°C in many parts of the United Kingdom) is well suited for receiving surplus heat and effecting cooling, via a well doublet arrangement. Cool shallow groundwater can also be used for heating via GSHP. A heat pump is an electrically powered refrigerant device that transfers heat from a cold medium (e.g. groundwater at 10°C) to a warm medium (e.g. a central heating system at 45°C).[26] Although wind and solar technologies can generate low-carbon electricity, relatively few technologies exist to provide low-carbon heating. The heat pump is a key technology that utilizes electricity highly efficiently to deliver heating and cooling. It may be able to deliver 3.5 kW of heat to a building for every 1 kW of electrical power consumed, resulting in dramatic cost and CO_2 emission reductions. As of 2020, around 6.5 million geothermal heat pumps are thought to be installed worldwide, representing the fastest growing part of the geothermal sector (Lund and Tóth, 2020).

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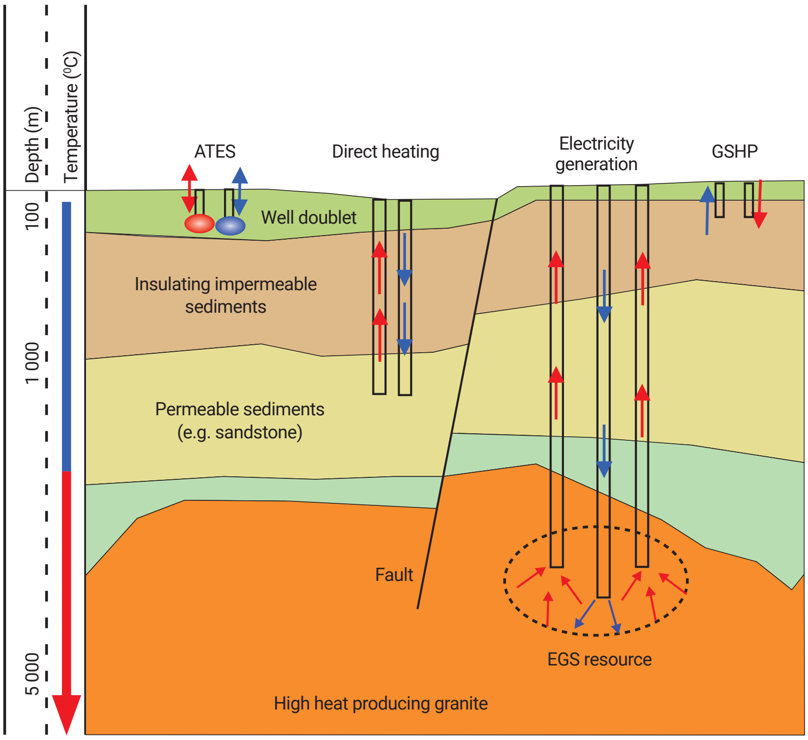
[25] Note that GW (gigawatt) is a unit of power (rate of energy delivery), while TW_h (terawatt-hour) is a unit of total energy delivered. The subscripts e and t refer to electrical and thermal energy, respectively.

[26] Note that heat pumps do not need groundwater: they can also extract heat from unsaturated/low-permeability soils and rock, from surface water, from sewage and from air.

Figure 7.5

Schematic diagram showing different types of geothermal energy systems, including Aquifer Thermal Energy Storage (ATES), Ground Source Heat Pump (GSHP) and Enhanced Geothermal System (EGS)

Source: Authors, adapted from Driscoll and Middlemis (2011).



Use of shallow (low-enthalpy) geothermal technology for heating and cooling is especially attractive in temperate continental climates, where there is a large seasonal air temperature 'swing' and where groundwater temperatures are not only much warmer than winter air temperatures but also much cooler than summer air temperatures. Here, surplus heat from cooling processes, injected to the ground during summer, can be stored in the aquifer and recovered to be used during winter. This is termed Aquifer Thermal Energy Storage (ATES). In pioneering nations, such as the Netherlands and Sweden, the ground/groundwater is increasingly seen as just one component (a seasonal source, sink or thermal 'buffer') in flexible 5th Generation District Heating and Cooling Networks (e.g. Verhoeven et al., 2014, Buffa et al., 2019).

7.5.3 Impacts, risks and incentives

The environmental impacts of well-designed geothermal systems are limited, but adverse impacts can occur if aquifers are poorly managed. Where reinjection of geothermal fluids is not practised, groundwater storage can be depleted and subsidence can be induced, as observed in Shanghai (China) (Banks, 2012). Where 'thermally spent' groundwater is reinjected, risks are lower but local ground movement can still occur, and high densities of heating or cooling schemes can lead to aquifer temperature changes. Net aquifer temperature changes can have environmental impacts and also ultimately make the geothermal resource less suitable for exploitation. For example, the Dutch regulatory framework requires ATES systems to be approximately thermally balanced to avoid such temperature changes (Dutch ATES, 2016). Poorly managed reinjection of groundwater also carries some risk of mixing groundwater resources of good and poor quality, potentially leading to overall deterioration of groundwater quality. For deep geothermal systems, where high reinjection pressures are applied, the risk of miscroseismicity needs to be carefully monitored (Holmgren and Werner, 2021). In addition to environmental impacts, there can be economic and risk-based limitations to the development of geothermal energy. Costs and project risks tend to increase with depth as the cost of drilling increases disproportionately with depth, while the requisite hydrogeological understanding becomes less certain. Once the well has been constructed, an operator has to face the almost ubiquitous challenge of preventing clogging of the reinjection wells, as well as the costs involved in monitoring well performance, temperature and chemistry. As deep drilling to prove new high-enthalpy geothermal resources entails sizeable 'up-front' capital expenditure and considerable economic risk of exploration failure, it is debatable whether production of geothermal energy should be subsidized at a given rate per MWh produced. A more appropriate approach may be a government- or industry-backed insurance scheme to underwrite the risks of developing a new geothermal prospect, as has been done in the Netherlands (RVO, 2015).

7.6 Climate change mitigation through carbon capture and sequestration

Carbon capture and sequestration (CCS) is the process of storing carbon in deep aquifers to curb accumulation of carbon dioxide in the atmosphere. It is undertaken because natural carbon dioxide (CO_2) sinks (i.e. forests, oceans and soils) are considered unable to accommodate the increasing amounts emitted by humans and to mitigate their consequences for climate change. CCS reduces CO_2 emissions from point sources such as industrial processes or power generation through the chemical capture of emitted CO_2. This CO_2 is then compressed and injected into subsurface strata at depths in excess of 800 m where prevailing pressures and temperatures are sufficient to convert CO_2 gas into a liquid. Geological sites that are suitable for the storage of CO_2 include deep aquifers and depleted hydrocarbon reservoirs that are overlain by an aquitard. Buoyant (less dense) CO_2 rises and migrates through the formation but is physically trapped by the cap rock (aquitard). CO_2 from single sources are stored on pilot sites for CCS research (e.g. Ketzin, Germany (Wiese and Nimtz, 2019); Lacq, France (Prinet et al., 2013); In Salah, Algeria (Ringrose, 2018); Aquistore, Canada (Lee et al., 2018a)) and operational facilities (Sleipner and Snøhvit, Norway (Chadwick et al, 2012; Ringrose, 2018); Decatur, USA (Finley, 2014); Gorgon, Australia (Trupp et al., 2021)). Projects are also planned at industrial sites, where many emitters of CO_2 can use the same storage site or sites (Porthos, Netherlands; Northern Lights, Norway; Teesside, UK).

Carbon capture and sequestration is the process of storing carbon in deep aquifers to curb accumulation of carbon dioxide in the atmosphere

Large-scale geological storage of CO_2 (i.e. projects in the order of 1 Mt of CO_2 per year) include the Sleipner and Snøhvit projects in the North Sea and the Quest Project in Canada (Government of Alberta, 2019). At each of these sites, ~1 Mt of CO_2 that would otherwise be released to the atmosphere is captured and permanently stored annually. Extensive saline aquifer formations, both onshore and offshore, have a theoretical capacity to store billions of tonnes of CO_2, although the practical useable capacity will be lower (Bachu et al., 2007; Bradshaw et al., 2007; Bachu, 2015; Goodman et al., 2016; Celia, 2017). As sites are often far from large emission sources and intercontinental transport of CO_2 incurs substantial costs, the economic CCS storage potential is country- and region-specific. In most regions, storage capacities themselves do not pose a constraint to CCS use, but government subsidies are still required to cover the costs. CCS is considered an important tool to reduce emissions from fossil fuels from the industrial sector and, when combined with biomass combustion and direct air capture, to achieve net negative emissions (IPCC, 2014b).