Chapter 7

Groundwater, aquifers and climate change

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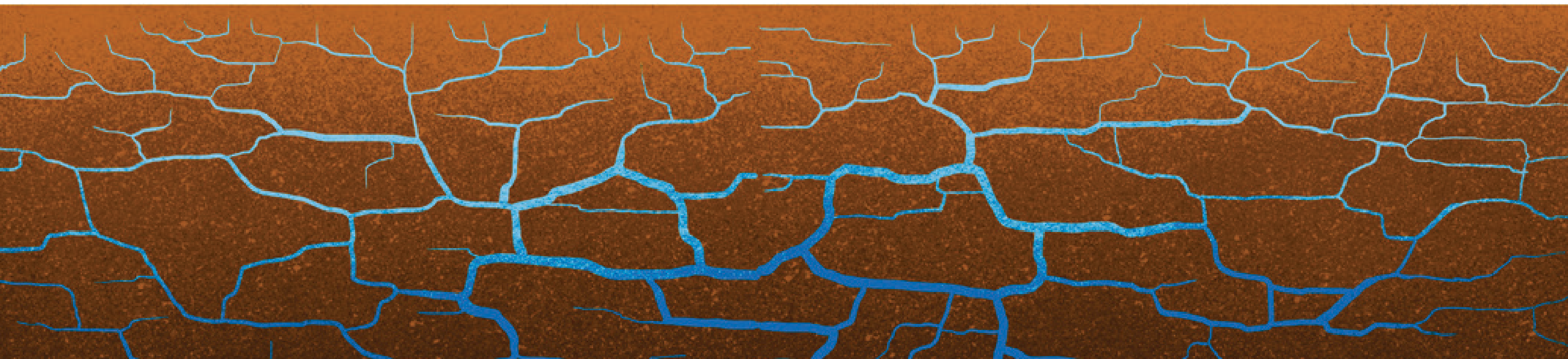

7.1
Introduction

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).

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 km^3/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).

> *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*

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

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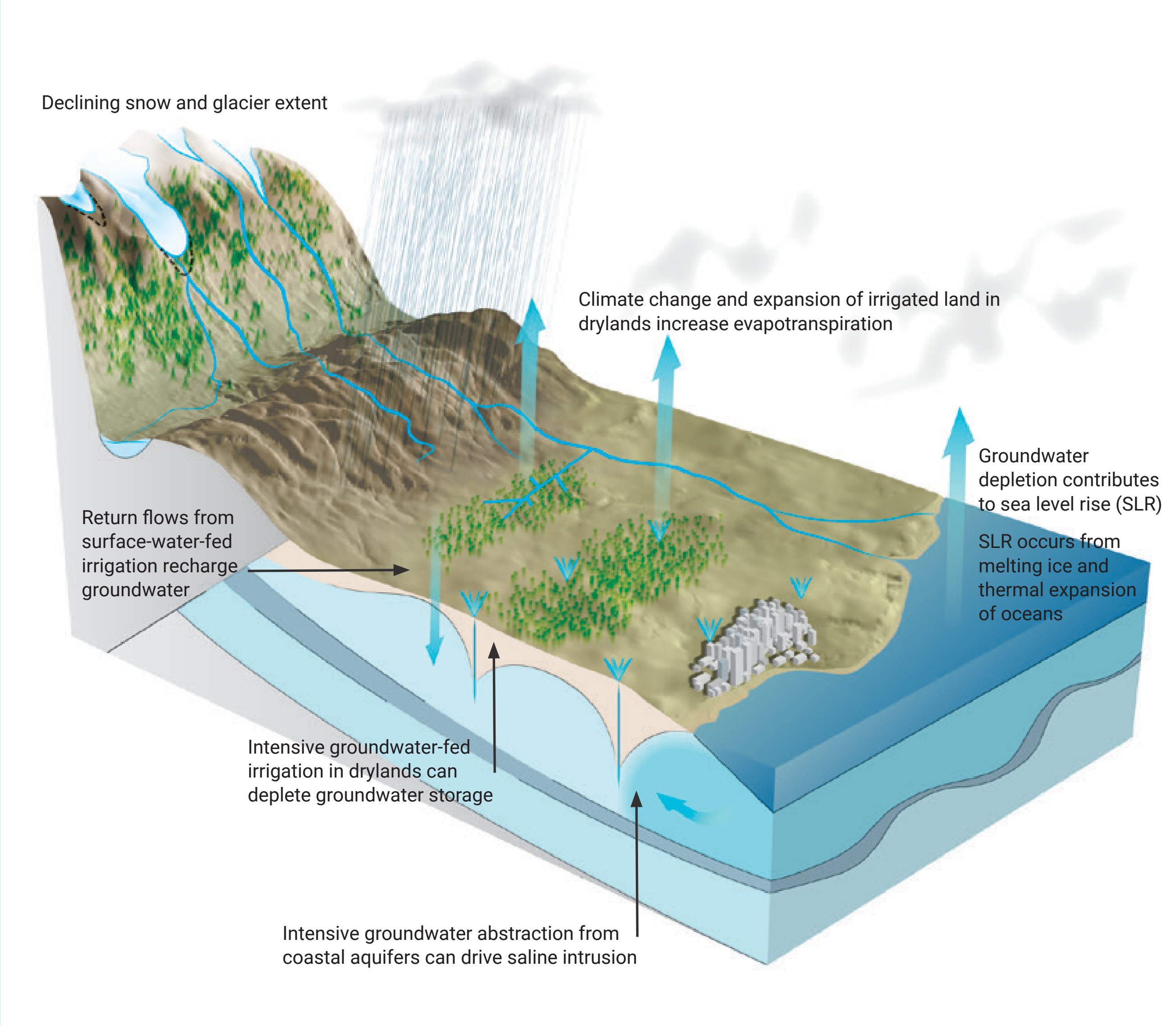
[22] Drylands are areas with a sub-humid, semi-arid, arid, or hyper-arid climate.

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

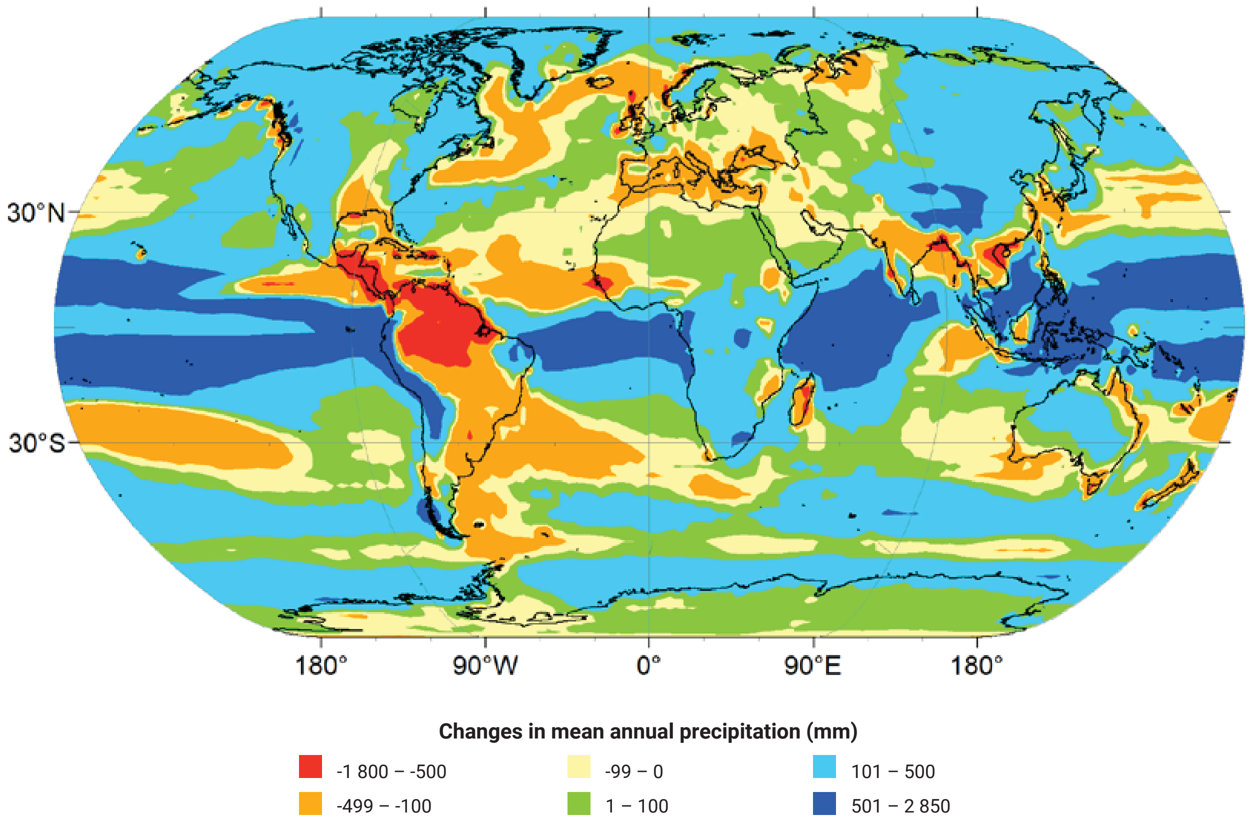


Source: Authors, adapted and revised from Taylor et al. (2013a).

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 km³ 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).

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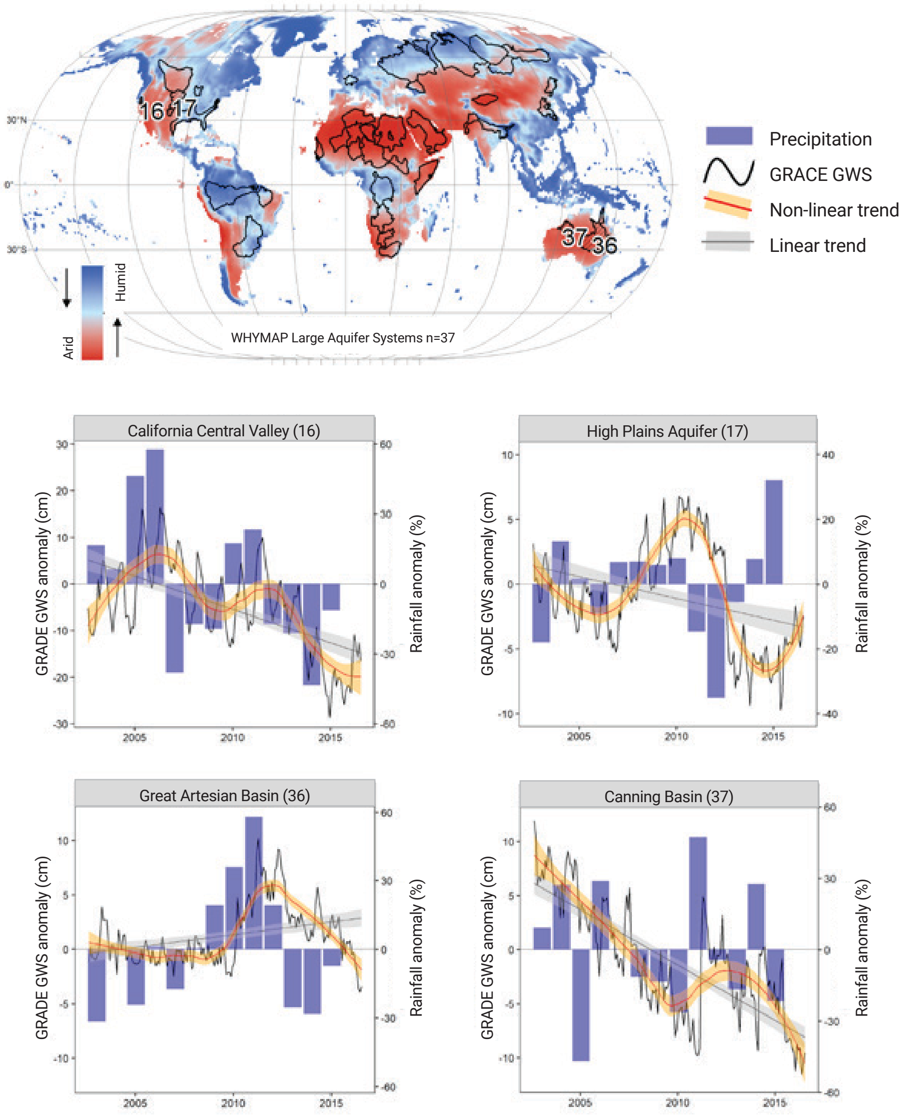
One observed and widespread impact of climate change influencing groundwater replenishment is the intensification of precipitation

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

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[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).

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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).

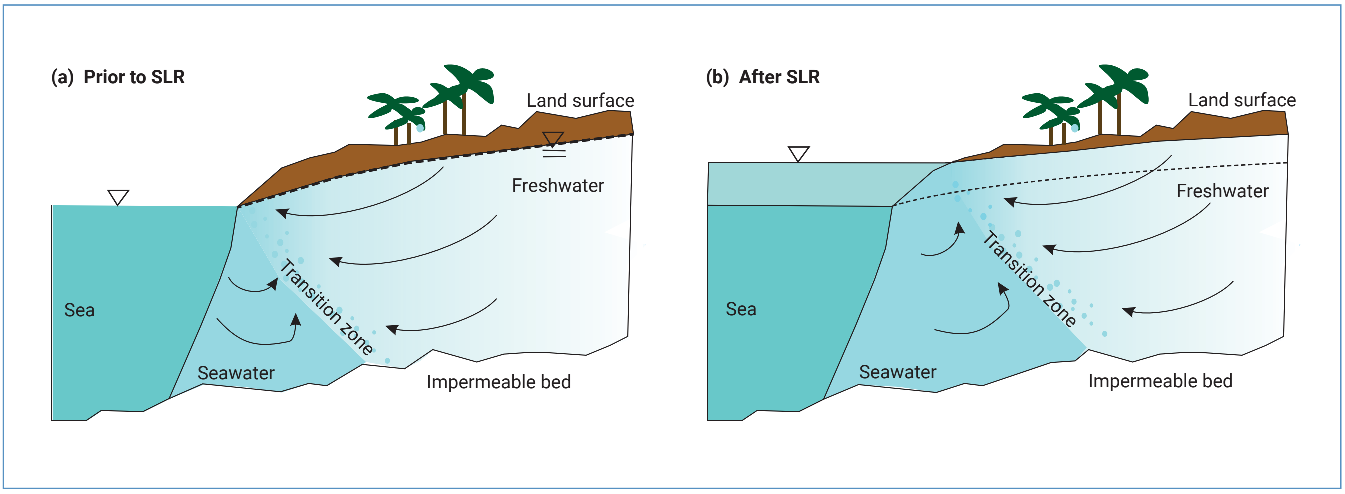
Sea level rise and salinization of coastal aquifers

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

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.

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

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;

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[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).

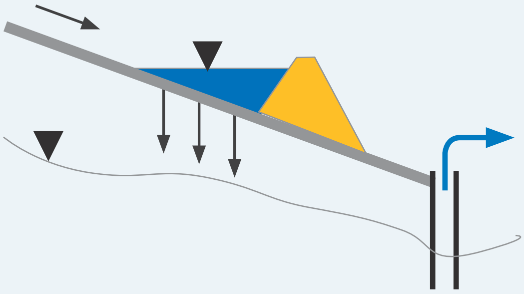
7.5.1 Geothermal energy for low-carbon electricity generation

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

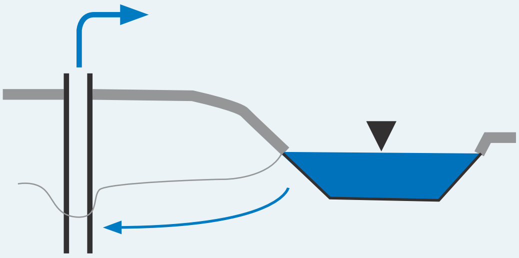
(a) Streambed channel modification

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).



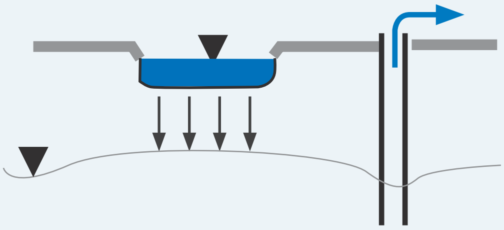
(b) Bank filtration

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.



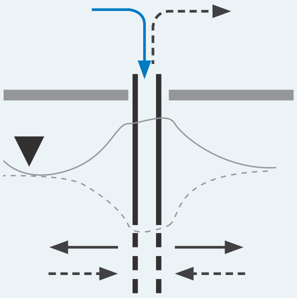
(c) Water spreading

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, 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).

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

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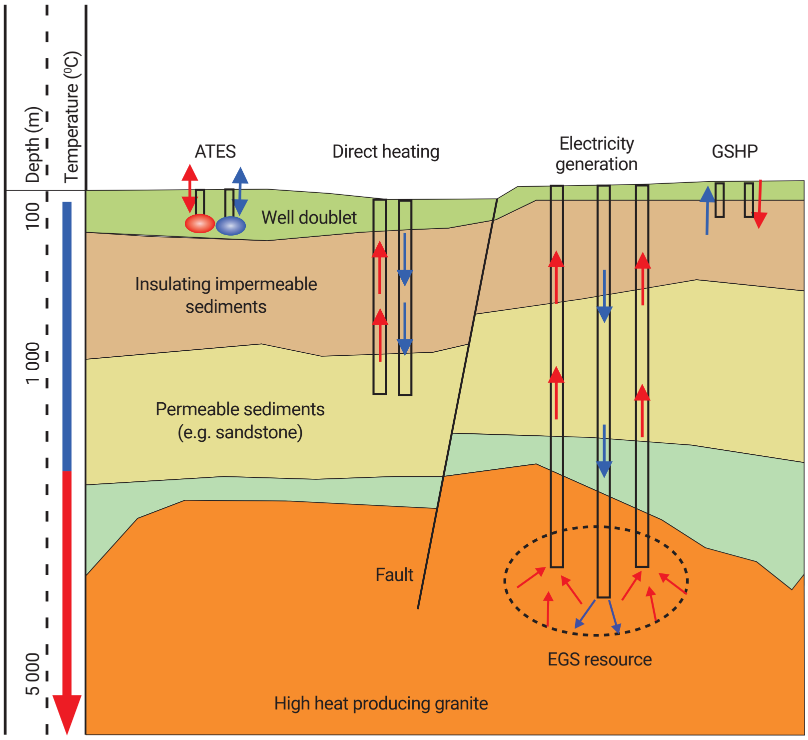
[25] Note that GW (gigawatt) is a unit of power (rate of energy delivery), while TW_h (terawatt-hour) is a unit of total energy delivered. The subscripts e and t refer to electrical and thermal energy, respectively.

[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).

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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).