Groundwater Allocation
Managing Growing Pressures on Quantity and Quality

PART I

# Chapter 1

# Overview of groundwater resources and prevailing trends

*This chapter provides an overview of trends documenting increasing pressures on groundwater resources. It examines the range of benefits obtained from groundwater, including the economic value derived from productive uses, the ecological value provided to groundwater-dependent ecosystems, and the option value the resource provides as a buffer against future water shortages. The chapter then reviews the distinctive features of groundwater and their relevance for allocation policy design.*

## Introduction

Groundwater is a valuable natural resource, which provides an important source of water supply for drinking, irrigation and industry in many parts of the world and also contributes to sustaining groundwater-dependent ecosystems. Pressures on the quantity and quality of the resource have increased significantly. Globally, groundwater withdrawals have risen sharply and the resource is becoming increasingly degraded due to pollution and saline intrusion (Margat and van der Gun, 2013). However, groundwater allocation policies have generally not kept pace with these increasing pressures. There are inherent challenges involved in assessing the status of groundwater and investment in monitoring the resource has been inadequate to date (Foster et al., 2013). In many countries, there are persistent problems related to the efficient and equitable use of groundwater (GEF et al., 2015a), reducing the benefits that individuals and society reap from the resource, today and in the future.

Recent work by the OECD[1] and others[2] has contributed to improving policy guidance on water resources allocation, groundwater governance and managing groundwater in agriculture. However, some key gaps remain. In particular, guidance on how the various elements that comprise an allocation regime[3] (policies, laws, regulations and institutional arrangements) can be designed to accommodate the distinctive features of groundwater is lacking. Building on previous work, in particular the 2015 OECD report *Water Resources Allocation: Sharing Risks and Opportunities*, this report aims to fill this gap. Specifically, it focusses on how allocation regimes for groundwater or conjunctively managed surface and groundwater systems can be designed to bring about the desired policy outcomes, in terms of economic efficiency, environmental effectiveness and social equity.[4] Drawing on an assessment of groundwater's distinctive features and nine case studies of groundwater allocation in practice, the report provides guidance for designing policies that balance different types of extractive and non-extractive uses as well as the needs of current and future generations.

## A valuable natural resource under increasing pressure

Groundwater systems make up the predominant reservoir and strategic reserve of freshwater on Earth[5] (Foster and Chilton, 2003). It provides a drinking water source for around half of the global population (Margat and van der Gun, 2013) and accounts for an increasing share for agricultural use making up around 40% of consumptive irrigation water, covering just under 40% of irrigated land globally (OECD, 2015a). More than 60% of abstracted groundwater is consumed by agriculture in arid and semi-arid regions, producing 40% of the world's food (Morris et al., 2003). Industrial uses (including mines and energy production) are also important, accounting for over one-fifth of total groundwater abstraction in some countries (Germany, Japan, Brazil, and the Philippines, among others) (Margat and van der Gun, 2013).

Groundwater and surface water systems are closely interlinked in most places on Earth and human activities, such as water abstraction, irrigation and artificial drainage, have intensified these interactions (GEF et al., 2015a). Often, a substantial portion of groundwater flow emerges to join surface water, supporting the base flow of surface water bodies (Margat and van der Gun, 2013). Also, groundwater withdrawals may be used as a substitute for surface water withdrawals, and vice versa. Thus, groundwater and surface water allocation need to be studied and managed conjunctively, not in isolation, where possible.

The intensifying use and competition for water resources is widely documented (WRI, 2016; OECD, 2012; UNESCO, 2012; Vörösmarty et al., 2010). The OECD *Environmental Outlook to 2050* highlights that water resources are already over-used or over-allocated in many places, with global demand expected to increase by 55% between 2000 and mid-century (OECD, 2012).

Generally, there is significant scientific uncertainty about the state (quality and quantity) of groundwater due in no small part to that fact that it is largely an "invisible" resource stored underground (discussed further below). Data on groundwater use are scarce and remain incomplete (Margat and van der Gun, 2013; Shah et al, 2007), yet some general trends are clear. Globally, groundwater withdrawals[6] have risen almost tenfold in the past 50 years (Shah et al., 2007). Between 1960 and 2000, the rate of groundwater depletion more than doubled (Wada et al., 2010). This boom in groundwater abstraction, driven by population growth and the associated increasing demands for water, food and income, has no precedent in history (Margat and van der Gun, 2013). Advances in drilling and pumping technology have lowered the cost of groundwater abstraction and contributed to greater exploitation of the resource. The rise in intensive use of groundwater by millions of small scale farmers is so striking that it has been dubbed a "silent revolution" (Llamas and Martínez-Santos, 2005).

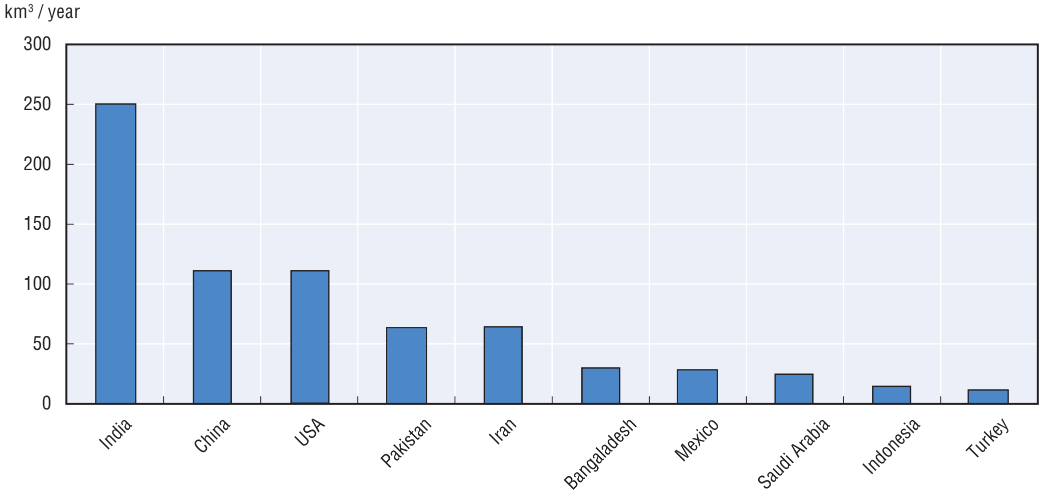
During the second half of the 20th century, groundwater abstraction has followed a pattern similar to total water withdrawals. The most pronounced increases have been observed in countries where current groundwater withdrawals are the highest (Margat and van der Gun, 2013). Intensive groundwater withdrawal is particularly prevalent in countries such as Israel, Mexico, Spain, Turkey, the southwest of the United States (U.S.), Bangladesh, northern parts of The People's Republic of China (hereafter "China"), northern India, Indonesia, Iran, Pakistan and Saudi Arabia (Margat and van der Gun, 2013; Shah et al., 2007). Notably there is a correlation between high aridity, groundwater dependence and abstraction intensity. Figure 1.1. illustrates the top ten groundwater abstracting countries (in terms of volume of water abstracted).

The total global withdrawal of groundwater was estimated at 8% of the mean global groundwater renewal in 2010, but this is highly variable among countries and may reach up to 50% in some cases (GEF, et al., 2015a). Groundwater abstraction is projected to stablise or slightly decrease in industrialised countries, while abstraction is projected to continue to increase in countries where economic and demographic growth is substantial and where irrigation is a significant user, such as countries in Asia (Margat and van der Gun, 2013).

Groundwater is also becoming increasingly degraded due to pollution and saline intrusion (GEF, et al., 2015a; Margat and van der Gun, 2013). This degradation can be caused by the introduction of contaminants, such as those in fertilisers or pesticides, or by changes in the groundwater regime (often triggered by increasing withdrawals), which may increase saline intrusion or the concentration of existing contaminants, such as arsenic (Margat and van der Gun, 2013). Both current pollution as well as legacy pollution are problematic. Land use changes, such as extending impermeable surfaces in urban areas, can reduce groundwater recharge and contribute to pollution. Agricultural intensification can increase

Figure 1.1. **Top ten groundwater abstracting countries**

Abstraction as of 2010



*Source:* Based on data from Margat and van der Gun, 2013.

diffuse pollution and leaching of contaminants, such as nitrates, into groundwater (GEF et al., 2015a; Margat and van der Gun, 2013). At the same time, excessive recharge due to leaking public water supply networks, for example, can cause salinisation, alkalinisation and waterlogging (Margat and van der Gun, 2013). In the energy sector, the recent shale gas boom has increased pressure on the resource in some regions and provoked public concern over potential groundwater contamination risks (e.g. the leakage of fracturing fluids, hydrocarbons or saline water) (IEA, 2012).[7] Degraded groundwater quality reduces its suitability for drinking (and other uses that require high quality water), increases the cost of treatment and can exacerbate water scarcity where degraded groundwater quality limits use.

Climate change is projected to reduce renewable surface water and groundwater resources in some regions, further intensifying competition for water (IPCC, 2014). Climate change is driving an intensification of the water cycle (Huntington, 2006), changing precipitation patterns, increasing evapotranspiration, impacting groundwater recharge and water quality, as well as increasing the frequency and intensity of extreme events (Bates et al., 2008; IPCC, 2014). In addition, sea level rise due to climate change contributes to saline intrusion in coastal aquifers (IPCC, 2014; Clifton et al, 2010). Higher water demand due to increasing temperatures and greater variability in precipitation (inter-annual and seasonal changes) is expected to particularly affect areas where mean groundwater recharge is expected to decrease (Margat and van der Gun, 2013).[8] Climate change is also expected to greatly expand groundwater's role in meeting water demand in some regions (Margat and van der Gun, 2013; OECD, 2015a).

Unsustainable groundwater use creates negative environmental externalities, including saline intrusion, land subsidence and reduction in spring flows and base flow, which puts stress on groundwater-dependent ecosystems such as wetlands (Box 1.1). This undermines the values (economic, environmental, social and cultural[9]) supported by groundwater resources and can result in irreversible damage (Margat and van der Gun, 2013; GEF et al., 2015a). Many cities are affected by land subsidence due to groundwater depletion, such as Tokyo, Shanghai, Calcutta, Venice, Mexico City and San Francisco (GEF et al., 2015a).

### Box 1.1. **Groundwater-dependent ecosystems**

Ecosystems that rely on a supply of groundwater to function are considered to be groundwater-dependent ecosystems. They include rivers, lakes, riparian habitats, wetlands, springs, subterrean aquifers as well as estuarine and nearshore marine ecosystems. These ecosystems provide important ecosystems services, including food production, water purification, recreation, as well as habitats for migratory birds or rare plant and invertebrate species. Groundwater supports these ecosystem services through the provision of water (some ecosystems are fully dependent on groundwater), nutrients, buoyancy (as in the case of peatland bogs) and stability of water temperature. The reliance of ecosystems on groundwater may be continuous or periodic (seasonal or only during a limited period every few years).

While the contribution of groundwater to these ecosystems is recognised as vital, there are numerous, complex interactions, which are still poorly understood. Further, there is scant evidence about how groundwater depletion, pollution and land use change affects groundwater-dependent ecosystems. To adequately protect these ecosystems, more study is needed on their status, how they function and the impacts of land and water use, pollution and climate change.

*Source:* Kløve et al. (2011a); Kløve et al. (2011b).

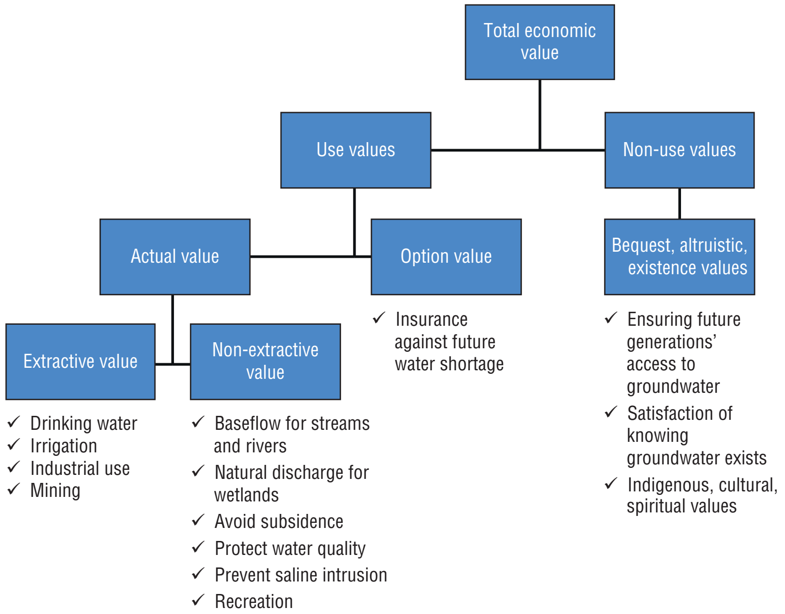
Groundwater depletion also increases the cost of use, as pumping is required from ever-increasing depths, which may put small scale users at a disadvantage in terms of access to the resource (OECD, 2015a). The increasing cost of use may or may not be directly borne by groundwater users, depending on whether the cost of electricity or fuel to operate pumps is subsidised.[10] This depletion can result in water shortage directly affecting users and can have indirect impacts on economic activities, such as lost earnings and foregone profits (OECD, 2013). Groundwater depletion could become the greatest threat to urban water supplies in several regions in the coming decades (OECD, 2012), resulting in potential high replacement costs to secure alternative sources of water.

## The benefits of groundwater: Estimating value

Groundwater resources serve multiple purposes and provide value to individuals, ecosystems, farms, firms, and society (including indigenous communities) in various ways. The benefits obtained from groundwater take many forms – from the economic value derived from productive uses for drinking water, industry and irrigation to the ecological value provided by supporting groundwater-dependent ecosystems to the option value of storing groundwater to use as a buffer against future water shortages. How much groundwater is left in aquifers and how much is abstracted for various uses; who is able to use these resources, how, when and where are questions that directly affect the benefits that individuals and society obtain from groundwater today and in the future. These questions are determined by allocation regimes, whether formal or informal.

The valuation of groundwater in alternative direct uses and also *in situ* non-extractive uses can provide important information to policy makers seeking to design allocation regimes that maximise the benefits of groundwater. Estimating the value of groundwater is a technically complex challenge.[11] However, the total economic value (TEV) approach provides a useful conceptual framework that can be used to identify the various ways in which groundwater generates benefits. The concept consists of several distinct types of values: 1) use values, 2) option values, and 3) non-use, or "passive" values. The use value reflects the direct use of the resource, such as groundwater abstracted for drinking water as well as non-extractive (indirect use) value, which derives from the ecosystem services the resource provides. These ecosystem services include base flow for streams and rivers, which supports recreational uses (fishing, boating) and hydropower production, among others. Figure 1.2 illustrates the various components of TEV and how they relate to groundwater.

Figure 1.2. **Total Economic Value of groundwater**



*Source:* Author, adapted from Qureshi et al. (2012); Johns and Ozdemiroglu (2007).

Groundwater allocation policies need to account for different types of extractive and non-extractive values as well as balance the needs of current and future generations. Allocating groundwater for non-extractive uses that leave groundwater *in situ* as well as option values and bequest values often require trade-offs with current extractive uses (Qureshi et al., 2012). The benefits from direct groundwater use vary considerably by type of use. For example, drinking water is a high value use, from an economic and social perspective. The value added per unit of water use by industry is typically higher than use for irrigation[12] (GEF et al., 2015a). Non-extractive values can be considerable, such as when groundwater supports vital ecosystem services or protects water quality. A range of valuation methods can be used to estimate these values, including revealed preference methods (such as actual or simulated markets, travel cost, hedonic property values, avoidance expenditures) and stated preference methods (such as contingent valuation or choice experiments)[13] (Tientenberg and Lewis, 2016). Overall, the economic value of groundwater varies greatly over time and space, depending on the quality, reliability and degree of substitutability of the resource and how it generates benefits. Box 1.2 provides an illustration of the economic value of consumptive groundwater use in Australia.

Groundwater resources can also be considered as natural capital, generating income flows through direct uses and sustaining ecosystem services through indirect uses. From this perspective, the level of the "stock" of groundwater is vital to the generation of such

### Box 1.2. **Consumptive groundwater use in Australia: A valuable contribution to the economy**

A recent study aggregates disparate estimates of the value of consumptive groundwater use in Australia. Overall, an estimated 3 500 giga litres (GL) of groundwater provides a direct use value of between AUD 1.8 to 7.2 billion per year, with a midpoint estimate of AUD 4.1 billion. As for groundwater's contribution to Australia's GDP, the estimated range spans from AUD 3 to 11 billion per year, with a midpoint estimate of AUD 6.8 billion. This is in addition to AUD 419 million of use value annually to households. These estimates are only a partial view of the total economic value of groundwater, as non-extractive uses and options values have not been quantified.

The table below summarises the breakdown by groundwater use by sector.

Table 1.1. **Estimated value of consumptive groundwater use in Australia**

| Sector | Groundwater volumes (ML) | Direct value-add (AUD millions) | Direct value add (AUD/ ML) range and central estimate | Contribution to GDP (AUD millions) |
|---|---|---|---|---|
| Agriculture – irrigation | 2 050 634 | $410 | $30-500<br>$200 | $820 |
| Agriculture – drinking water for livestock | – | $393 | | $818 |
| Mining | 410 615 | $1 129 | $500-5 000<br>$2 750 | $1 637 |
| Urban water supply | 303 230 | $606 | $1 000-3 000<br>$2 000 | $1 146 |
| Households | 167 638 | $419 | $1 400-6 400<br>$2 500 | n/a |
| Manufacturing and other industries | 588 726 | $1 177 | $1 000-3 000<br>$2 000 | $2 355 |
| **Total** | **3 520 843** | **$4 136** | | **$6 777** |

*Note:* Figures provided are broad estimates using data from a range of sources between the years 2006 and 2012.
*Source:* Adapted from Deloitte Access Economics, 2013.

flows both today and in the future (GEF et al., 2015a). Box 1.3 provides an illustration of the estimated value of groundwater in the Kansas High Plains Aquifer in the U.S. using a natural capital approach.

### Box 1.3. **Groundwater as natural capital: The Kansas High Plains Aquifer**

Fenichel et al. (2016) developed a framework to assess natural capital asset prices consistent with economic capital theory and applied it to the Kansas High Plains Aquifer. This aquifer supports significant food production in the U.S., but is rapidly depleting. The analysis shows that between 1996 and 2005, the profits attributable to the Kansas portion of the aquifer dropped from USD 2.3 billion to USD 1.2 billion. This amounted to a loss of approximately USD 110 million per year (2005 USD, 3% discount rate) of capital value due to groundwater withdrawal and changes in aquifer management.

By way of illustration, the study highlights that this yearly decline in wealth is twice as large as the state's investment in school infrastructure (an investment in physical capital, which enables the development of human capital) over the period.

*Source:* Fenichel et al., 2016.

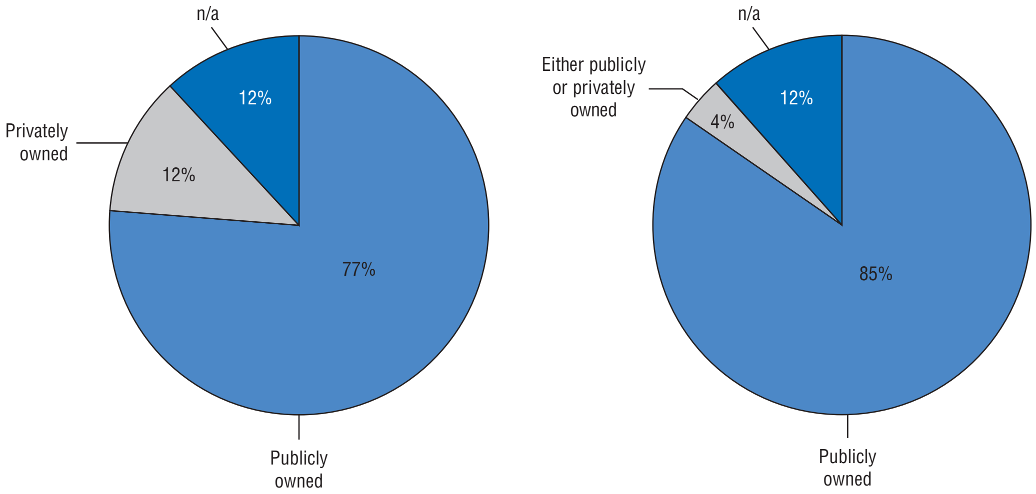
## A need for robust groundwater allocation regimes

Without effective policies to control abstraction, there is little or no incentive for users to limit groundwater pumping and conserve the resource, resulting in an inefficient allocation of the resource. Further, perverse incentives, such as subsidies for electricity to pump groundwater, can exacerbate pressure on the resource.

A 2014 OECD survey of water resources allocation practices in OECD and select non-OECD countries[14] confirmed that in most countries, water allocation arrangements are strongly conditioned by historical preferences and usage patterns, locking in water use to uses that may no longer be as valuable today as they were years ago (OECD, 2015b). Moreover, certain water uses may no longer be viable in the future, considering the potential magnitude of some climate change scenarios.

Weak allocation policies may be a particular problem for groundwater. Historically, water legislation has focused on surface water resources, while groundwater legislation has lagged behind remaining fragmented, incoherent or simply ignored in many countries (Mechlem, 2012). More prevelant private ownership of groundwater (as compared to surface water) can limit the authority of governments to control abstraction (Figure 1.3) (OECD, 2015b). The rule of capture, whereby farmers have the right to access and use any groundwater under their land, is still dominant in some places (GEF et al., 2015a; OECD, 2015a).

Figure 1.3. **Public and private ownership of ground and surface water resources**



*Note:* It is important to note that "ownership" here refers to ownership of the resource itself, not the entitlement or right to use the resource. Does not include Switzerland. "n/a" refers to cases where water resources are not subject to legal ownership (either public or private). In these cases, water resources may be designated as *res nullis*, or "ownerless property" in legal terms.

*Source:* OECD (2015b), *Water Resources Allocation: Sharing Risks and Opportunities*, OECD Studies on Water, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264229631-en*. See country profiles at *www.oecd.org/env/resources/water-resources-allocation.htm*.

The rapid growth of unregulated groundwater use has spurred many countries to try to redefine groundwater ownership and use rights as within the public domain and to support this with a legally enforceable regulatory regime (GEF et al, 2015a). Even where groundwater is formally declared by law as a public good and users only have usufructuary rights (or "use" rights), the perception that the resource is still private property can linger on (Mechlem, 2012).

## Distinctive features of groundwater and implications for policy design

Given the close interlinkages between groundwater and surface water in most parts of the world, ground and surface water allocation need to be managed conjunctively wherever possible. Still, there are a number of distinctive features of groundwater systems (as compared to surface water), which deserve consideration in the design of allocation regimes. This section provides a brief summary of these features.

### *Uncertainty about state and use of the resource*

There is greater scientific uncertainty about the state (quality and quantity) of groundwater resources as compared to surface water, due in no small part to that fact that it is an "invisible" resource stored underground. Although flows are generally easier to measure than stocks, recharge measurements are very difficult (OECD, 2015a). Data on groundwater use are scarce and remain incomplete (Margat and van der Gun, 2013; Shah et al., 2007). Shallow aquifers have been inventoried globally, but comprehensive mapping and assessment of larger, deeper aquifers has typically only been undertaken in developed countries (GEF et al, 2015a).

Groundwater is often available to multiple users without visible control or monitoring. Monitoring aquifers is technically demanding and costly, leaving the scientific understanding of many aquifers incomplete and complicating groundwater management (Mechlem, 2012). Relative to surface water, groundwater is much more poorly monitored and well metering requirements are only a recent development in many countries (Wheeler et al., 2016). However, well metering and reporting is on the rise in a growing number of groundwater management areas.[15] In some basins, remote telemetry may be used to monitor groundwater use (Aladjem and Sunding, 2015). For example, NASA's Gravity Recovery and Climate Experiment (GRACE) is the first satellite mission of its kind to map surface and groundwater resources and changes in these resources over time. It does so by monitoring changes in the Earth's gravitational field with an unprecedented temporal and spatial resolution and precision (NASA, 2016).[16]

### *Physical characteristics: Stocks, flows and quality*

The quantity of groundwater resources can be characterised by two key variables: stock (volume stored) and flow (rate of renewal). With the exception of "fossil" groundwater, for most aquifers, the flow is a more relevant variable for characterising groundwater quantities than the stock (Margat and van der Gun, 2013). All aquifers have natural inflows and outflows of water, but the rates and speed of recharge and discharge vary greatly. In general, the storage capacity of aquifers is high relative to inflows (Giordano, 2009). It can take up to decades before groundwater depletion manifests as lower pressure in wells or lower water tables.

Whereas the time between surface water leaving and entering the system may be a matter of weeks, for groundwater, it can take up to thousands of years (Oki and Kanae, 2006). Thus, groundwater can serve as a strategic reserve and buffer against shocks (GEF et al., 2015b) and provide an important contribution to resilient water management. Conjunctive management of a range of water sources (aquifers, rivers, reservoirs, treated wastewater or desalination) gives water managers and users a portfolio of options, which generally provides more secure, flexible and resilient supplies.

Some aquifers are considered "non-renewable" since the time it takes to renew them can extend to hundreds of millennia. Most "pure non-renewable" aquifers (containing "fossil" groundwater) are located in North Africa and the Arabian Peninsula. They are large, deep, confined aquifers that formed long ago and receive an insignificant amount of recharge. The use of these groundwater resources may be likened to irreversible mining[17] (OECD, 2015a).

Groundwater recharge can be increased by inefficient water systems (e.g. leaky irrigation systems). Thus, unless the water allocation regime properly accounts for return flows (the residual of water abstracted, but not consumed), improvements in efficiency of use can result in unintended consequences (such as reduced groundwater recharge) (OECD, 2015b).

The quality of groundwater is generally superior to that of surface water (especially with regards to bacterial contamination), hence its importance as a source of drinking water. However, groundwater is particularly vulnerable to long-term, cumulative pollution, which may only manifest after significant time lags (Margat and van der Gun, 2013).

Compared to surface water, groundwater is relatively insulated from the direct effects of climate variability and climate change. However, as noted above, the impacts of climate change on groundwater systems are expected to be considerable. Higher water demand due to rising temperatures, greater variability in precipitation (inter-annual and seasonal changes) as well as an increasing risk of drought is expected to greatly expand groundwater's role in meeting water demand (OECD, 2015a; Margat and van der Gun, 2013).

### *A need for a long term exploitation strategy considering both stocks and flows*

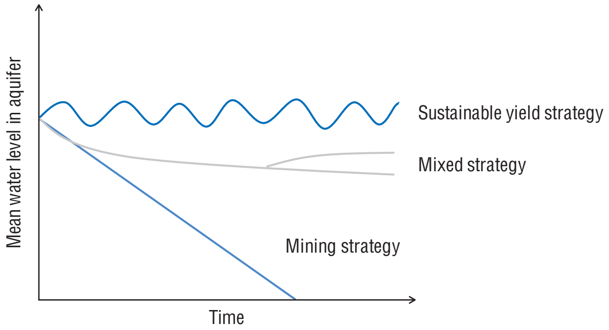
Only a portion of groundwater resources (consisting of total stocks and flows) should be considered as exploitable. To limit negative externalities, groundwater exploitation may be subject to significant constraints in order to maintain ecosystem services, avoid land subsidence or quality degradation. Further, the exploitation of some groundwater bodies or a portion of groundwater may be technically infeasible or economically undesirable, when pumping costs outweigh benefits. Exploitable groundwater resources can be augmented, typically via artificial recharge or through induced recharge (Margat and van der Gun, 2013).

Determining how to allocate groundwater stocks and flows among current and future users is a critical element of an allocation regime. Several long term exploitation strategies can be employed to determine the appropriate level of abstraction over time: 1) a sustainable yield[18] strategy aims to abstract inflows and keep the groundwater flow in a balanced state. This strategy aims to harvest inflows sustainably (limiting abstraction to the portion of recharge or inflow that is not needed to sustain base flows); 2) a mixed strategy, with depletion during a limited period and abstraction at a sustainable rate in the longer term and possibly recharge to help the stock recover; and 3) a mining strategy whereby stocks are progressively depleted (Margat and van der Gun, 2013). Figure 1.4 illustrates these three exploitation strategies.

Any of these strategies may be deliberately chosen, or in many cases, may become a *de facto* strategy in an unregulated situation or one where attempts are made to control pumping and let stocks recover. Box 1.4 provides an illustration of how "sustainable management" is defined in the 2014 Sustainable Groundwater Management Act (SGMA), a major reform in California.

From an economic perspective, optimal groundwater exploitation would maximise the present value of benefits minus costs (Qureshi et al., 2012). An efficient allocation of the resource requires that the marginal benefit (or value) of extracting an additional unit of water at all times and locations equals the full marginal opportunity cost of extracting that unit of water. The latter consists of the actual marginal costs of extracting a unit of water

Figure 1.4. **Groundwater exploitation strategies**



*Source:* Adapted from Margat and van der Gun, 2013 and BGS, 2009.

### Box 1.4. **Defining a "sustainable" groundwater management strategy**

California depends on groundwater for a significant portion of its water supply (40% in an average year, even more in drier years). Until recently, groundwater use was largely unregulated, contributing to substantial depletion. In 2014, the state passed Sustainable Groundwater Management Act (SGMA), which came into effect on 1 January 2015. For the first time in California's history, this major reform empowers local authorities to adopt and enforce groundwater management plans to put resource use on a sustainable footing.

According to SGMA, sustainable groundwater management is defined as "the management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results". These "undesirable" effects include:

- Chronic lowering of groundwater levels, but excluding reductions in groundwater levels during a drought if they are offset by increases in groundwater levels during other periods;
- Significant and unreasonable reductions in groundwater storage;
- Significant and unreasonable seawater intrusion;
- Significant and unreasonable degradation of water quality;
- Significant and unreasonable land subsidence; and
- Surface water depletions that have significant and unreasonable adverse impacts on beneficial uses.

Over-drafted basins are required to achieve groundwater sustainability by 2040 or 2042, depending on the completion of management plans. The State Water Resources Control Board has the authority to intervene if deadlines are not met and establish an interim plan.

*Source:* Water Education Foundation (2015).

in addition to the present value of the increase in future marginal costs resulting from the absence of that unit of water[19] (Qureshi et al., 2012).

Non-renewable groundwater resources represent a special case. In this case, the stock is the focus of the exploitation strategy, rather than the flow. The main constraint on mining non-renewable resources is the rising cost of extraction due to declining water levels. Allocation policies have to balance the benefits of current abstraction and future abstraction and should account for the scarcity rent of exploiting a non-renewable resource.

### *Often a common pool resource, difficult to exclude users from access*

Groundwater often exhibits the characteristics of a common pool resource, in terms of high rivalry and low excludability, although this is not always the case. As Brozovic et al. (2006) demonstrate, the impact of one user on others varies depending on the hydrological conditions of the aquifer. When the amount of water released in an aquifer due to a reduction in pressure (storativity) is low and the speed of lateral flow (transmissivity) is high, groundwater can easily flow across the aquifer. Thus, the effect of a user's pumping is widely transmitted through the aquifer. On the other hand, an aquifer with high storativity and low tranmissivity is closer to a private good than common pool resource (Huang et al., 2012).

The degree of connection with surface water systems can also affect whether groundwater is characterised as a private good or common pool resource (OECD, 2015a), which has important implications for how groundwater should be managed (OECD, 2015b; Huang et al., 2012). Considering the specific collective action problems posed by common pool resources (Ostrom, 1990), this is particularly relevant for allocation policies, including how to appropriately define water entitlements and determining rules regarding water trading (if permitted) (Wheeler et al., 2016).

### *Decentralised access by users on demand*

As aquifers can cover large areas spread out horizontally, users can directly access water on demand under their land and, in the case of shallow aquifers, at relatively low cost (OECD, 2015a). Thus, the access and use of groundwater is usually more decentralised than for surface water, and does not always require co-operation among users, as each operators controls his or her own pumps (OECD, 2015a). Since groundwater is more poorly monitored than surface water and well metering requirements are only a recent development in many countries, groundwater markets may be more difficult to establish than surface water markets (Box 1.5).

The cost of accessing groundwater is usually borne by the user. It consists mainly of a fixed cost for a well and a variable cost for pumping, which depends on the state of the resource and the cost of energy (Garrido et al., 2006). In the case of surface water, the fixed cost, related to infrastructure to store and transport the water, is often borne by public agencies. For both surface and groundwater resources, the variable costs include abstraction charges if they are in place, which usually do not reflect actual costs (OECD, 2015a). Energy consumption for groundwater pumping is on the rise and appears to be a significant share of total energy consumption in countries where groundwater is intensively exploited (such as India, China and the U.S.), although lack of adequate data prohibits reliable estimates (Margat and van der Gun, 2013). Subsidies for energy to pump groundwater (such as in India or Mexico) provide a perverse incentive to over-exploit the resource. In addition, groundwater pumping can generate multiple external costs, including falling water levels, wetland degradation and land subsidence (Margat and van der Gun, 2013).

### *Acute governance challenges due to fragmented legislation, decentralised use and lack of data*

Groundwater governance faces many of the same challenges as surface water governance, but at times to a greater degree. For example, challenges for both surface water and groundwater governance arise from the mismatch between administrative boundaries and the

### Box 1.5. **Groundwater markets: Challenges and opportunities**

Groundwater markets are less common than surface water markets, but have emerged in a number of countries, including Australia, China, India, the US, Oman, Pakistan. In principle, markets can improve the efficiency of allocation by shifting water use to higher value uses. The functioning of groundwater markets differs depending on the context. In China, Oman or India, groundwater is usually sold and transported to be used on another property. With informal groundwater markets, such as in India or Pakistan, farmers who can afford large wells and pumps sell water to smaller farmers who cannot afford such infrastructure in exchange for labour or cash (Olmstead, 2010). In Australia and the US, trading usually involves selling water entitlements to another user within the same aquifer. However, in the US some major transfers involve purchasing water from farms and pumping it to distant cities (for example in Arizona, California or Texas) (Wheeler et al., 2016). In addition, groundwater banking schemes can be used to transfer water among users and shift use over time. Groundwater banking consists of storing surface water in aquifers during abundant periods for use during drier periods. This is a relatively cost-effective means to increase water supply during droughts and offset loss of seasonal storage historically provided by snowpack-fed systems (Wheeler et al., 2016).

Groundwater markets face distinct challenges, including accounting for the characteristics of the aquifer, uncertainties about the resource and aquifer boundaries, changes in water quality and local drawdown impacts (Wheeler et al., 2016). Groundwater trading can change the location of pumping and thus, the distribution and magnitude of pumping externalities (Aladjem and Sunding, 2015). To address this issue, zoning schemes (such as in the Murray Darling Basin in Australia) may be used or trading ratios (such as in Nebraska, US), which adjust for the different impacts of a change in pumping location (Aladjem and Sunding, 2015).

Establishing formal groundwater markets entails adequately defining water entitlements, establishing and enforcing a regulatory framework and accounting for resource costs and externalities (GEF et al, 2015a). Accurate monitoring and measurements of groundwater use is a prerequisite for the establishment of a well-functioning market. A growing number of groundwater management areas require well metering and reporting (Aladjem and Sunding, 2015).

*Source:* Wheeler et al., 2016; Aladjem and Sunding, 2015; GEF et al., 2015a; Olmstead, 2010.

relevant scale for water governance, typically river basins. In addition, aquifer boundaries generally do not correspond to river basins, which compounds these governance challenges.

In most parts of the world, groundwater governance is generally poor or absent (GEF et al., 2015a). Historically, groundwater legislation has lagged behind legislation for surface water. While legislation on groundwater is found in nearly all countries, it is often fragmented, incoherent or outdated (GEF et al 2015a; Mechlem, 2012). Groundwater legislation is usually comprised of rules on ownership, abstraction and use based on entitlements, protection from pollution, and assignment of roles and responsibilities to competent authorities. Laws and enforcement responsibilities related to quality are often distinct from other aspects of groundwater management (GEF et al., 2015a). Land law has important implications for access to groundwater and its protection (Mechlem, 2012), whereas for surface water land law relates mainly to riparian rights.

Both the effective management of surface water and groundwater may be undermined by a lack of coherence among sectoral policies. In the case of groundwater, subsidies for energy used to pump groundwater can be particularly problematic. Both surface water and groundwater are typically managed in a decentralised way, but since access to groundwater tends to be more decentralised than access to surface water, it does not always require co-operation among users. This lack of co-ordination among groundwater users can cause significant issues in circumstances where use of the resource widely affects availability for other users.

The lack of data and knowledge of groundwater resources and limited monitoring systems contributes to weak governance. The issue or unregulated wells is prevalent in some regions, such as Southern Europe (OECD, 2010). In European Mediterranean countries, as many as half of the wells may be unregistered or illegal (EASAC, 2010). Further, as an "invisible" resource the lack of awareness of the state of groundwater resources hinders stakeholder engagement. In general, the state of groundwater governance varies widely and is closely linked to the stage of development of the resource and the level of development of the country (GEF et al. 2015a).

## Conclusion

Groundwater is under increasing pressure due to intensive abstraction and degraded quality, which reduces the value of the resource and the ecosystem services it provides as well as increases pumping and treatment costs and other negative effects, such as land subsidence. Groundwater is a valuable resource, providing benefits through direct productive uses, such as drinking water or irrigation, and indirect uses, such as flows for ecosystems. The resource also provides an option value, in that it can provide a buffer against future shortages and other values, such as ensuring availability for use by future generations.

Given the close interlinkages between surface and groundwater in many places, allocation need to be studied and managed conjunctively, not in isolation. However, there are a number of distinctive features of groundwater that require specific attention in allocation policy design. This includes the significant scientific uncertainty about the state (quality and quantity) of groundwater resources and scarce data on use. Since groundwater generally exhibits the characteristics of a common pool resource, excluding users from access can be difficult and costly. Acute governance challenges arise from the lack of data, fragmented legislation and largely decentralised use of the resource. Groundwater resources consist of both stocks and flows, which require a long-term exploitation strategy that considers both variables. The trend towards redefining ownership and use rights previously considered private property as within the public domain is a positive step towards encouraging more sustainable use, however evidence suggests that enforcement of laws and regulations on groundwater remains generally weak.

The following chapter sets out policy guidance for groundwater allocation in the form of a "Health Check", which can be used to assess the current state of allocation practice and identify areas for improvement. Part II of this report examines nine case studies (Denmark; Tucson, Arizona; Kumamoto, Japan; Mexico; the Upper Guadiana Basin, Spain; Texas; France; Gujarat, India and North China) to examine how various groundwater allocation challenges are being addressed in diverse contexts.

### *Notes*

1. For example, the OECD report *Water Resources Allocation: Sharing Risks and Opportunities* (2015) provides a comprehensive analysis of water allocation policies in OECD and key partner countries and developed related policy guidance. The OECD report Drying Wells, Rising Stakes (2015) provides a comprehensive analysis of the economics and policies for groundwater management in agriculture in OECD countries.
2. A major, multi-year initiative on groundwater governance was recently completed by the Global Environment Facility, the United Nation's Food and Agriculture Organisation, UNESCO's International Hydrological Programme, the International Association of Hydrologists and the World Bank. The main project outcome, the Global Framework for Action provides a set of guidelines for groundwater governance at the local and national levels.
3. See the glossary defining key terms appended at the end of this report.
4. A framework detailing these elements at a general level and how they may influence policy objectives is set out in the report Water Resources Allocation: Sharing Risks and Opportunities (OECD, 2015b).
5. Groundwater accounts for around 30% of global freshwater and as much as 98% if water frozen in the polar ice caps and glaciers are excluded
6. Estimates of the proportion of abstracted groundwater that is actually consumed are scarce, with the exception of irrigation, which is on average around 80% (varying depending on overall irrigation efficiency). For domestic and industrial uses, the portion consumed is usually much smaller, but varies considerably (Margat and van der Gun, 2013).
7. The U.S. EPA has studied the link between fracking and drinking water in the U.S. and identified factors that are more likely to result in more frequent or severe impacts on drinking water resources. These include fracking in areas with low water availability (especially areas with limited or declining groundwater); spills of fracking fluids; inadequate wells; discharge of inadequately treated fluids, etc) (U.S. EPA, 2016).
8. This could cause severe problems, especially in small and shallow alluvial aquifers in arid and semi-arid regions (Van der Gun, 2009).
9. Cultural values of groundwater include indigenous values.
10. See case study on Gujarat, India, for an example. Also, in Mexico, Tarifa 9, is a preferential tariff for electricity to pump groundwater for rural users, which has led to overexploitation of many aquifers in water scarce regions (OECD, 2013 MRHMEX).
11. Given the limitations in understanding of all of the benefits of groundwater (environmental and otherwise) and the methodological challenges related to the economic evaluation of these benefits, the TEV approach does not provide an exhaustive view of all of the benefits of groundwater.
12. While the value added of food production may be lower than industry, in some regions, groundwater supports also supports other policy objectives, such as food security.
13. The appropriate method will vary, depending on the situation, the availability of state and the type of value being assessed. These methods present a number of challenges and typically only provide a partial estimation of values. However even a partial estimate can be preferable to ignoring such values entirely.
14. The survey collected information about 37 examples of allocation regimes in 27 OECD countries as well as Brazil, China, Colombia, Costa Rica, Peru and South Africa (OECD, 2015b).
15. For example, well metering is required in certain basins in the U.S. and can also be found in Australia, New Zealand and China (Aladjem and Sunding, 2015).
16. The decade-long study has documented that 21 of the world's 37 largest aquifers are being depleted. This novel approach is helping to fill gaps in the scarce data on freshwater resources, especially groundwater, but many findings are only relevant for very large aquifers.
17. Groundwater mining is geographically concentrated in four countries Saudi Arabia, Algeria, Libya and United Arab Emirates, which account for 86% of the total estimated global groundwater mining (Margat and van der Gun, 2013).
18. Sustainable yield is defined as the flux of groundwater that can be withdrawn from an aquifer without causing undesirable side effects, in particular without causing a permanent state of imbalance in the hydrological budget of an aquifer. It includes economic and environmental criteria and underlies the concept of "overexploitation" (Margat and van der Gun, 2013).

19. The increase in future marginal cost consists of: (1) the future increase in marginal costs of all extractors and (2) the marginal reduction of future non-extractive benefits that depend on water stock or flows from that water stock (Qureshi, 2012).

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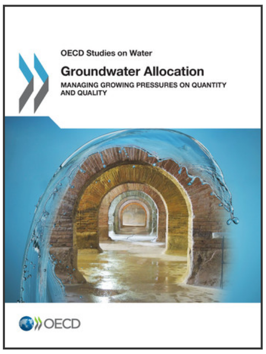

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