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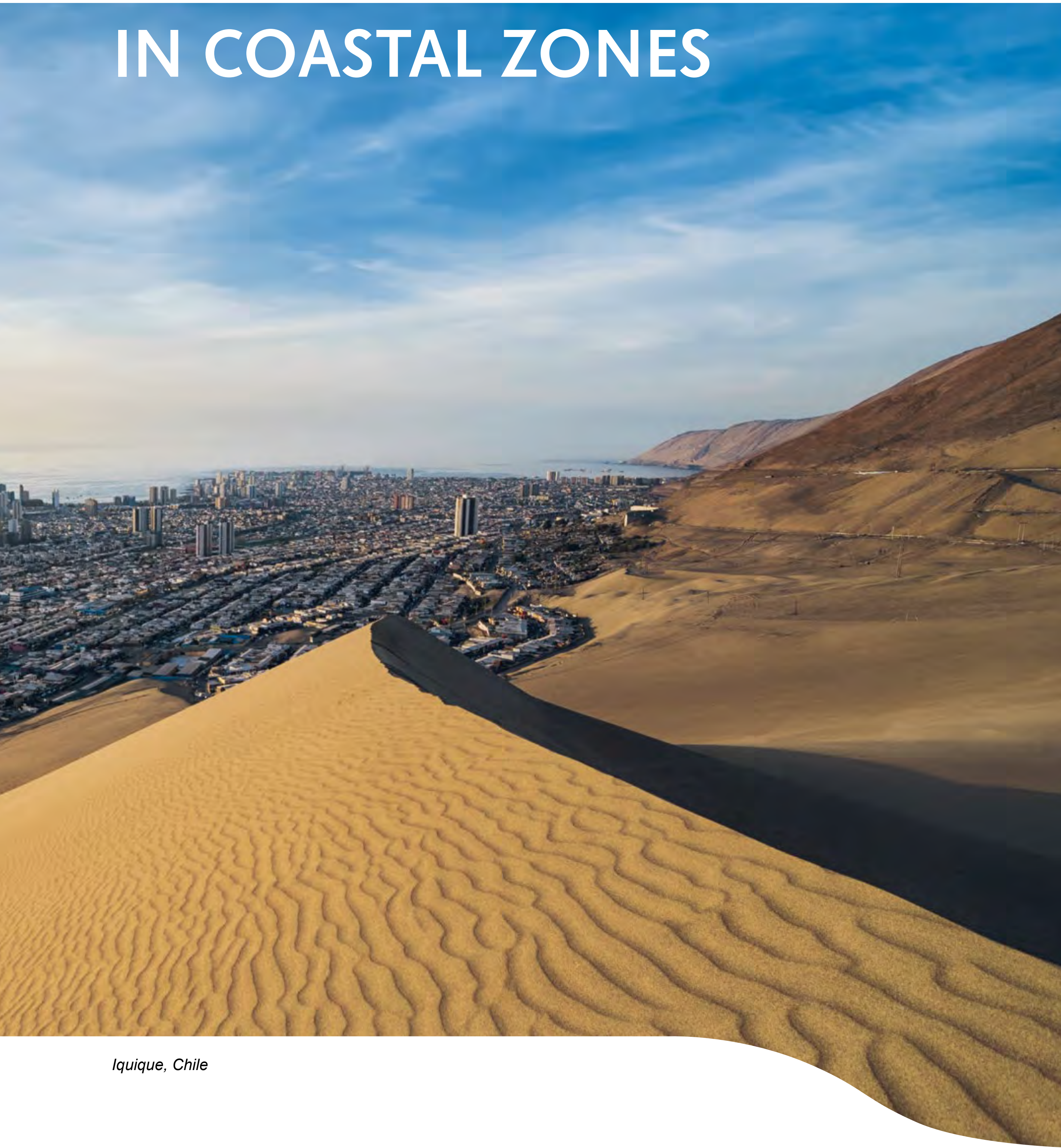
BGR Bundesanstalt für Geowissenschaften und Rohstoffe

GROUNDWATER MANAGEMENT IN COASTAL ZONES



Iquique, Chile

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Abbreviations

ASR	Aquifer Storage and Recovery
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Federal Institute for Geosciences and Natural Resources)
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (German Federal Ministry for Economic Cooperation and Development)
CNY	Chinese Yuan
EC	Electrical Conductivity
FAO	Food and Agriculture Organization of the United Nations
GWP	Global Water Partnership
IGES	Institute for Global Environmental Strategies, Japan
IGRAC	International Groundwater Resources Assessment Centre
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
OECD	Organization for Economic Co-operation and Development
TDS	Total Dissolved Solids
WFD	(European) Water Framework Directive
WHO	World Health Organization
WRD	Water Replenishment District (California, USA)

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1. Introduction

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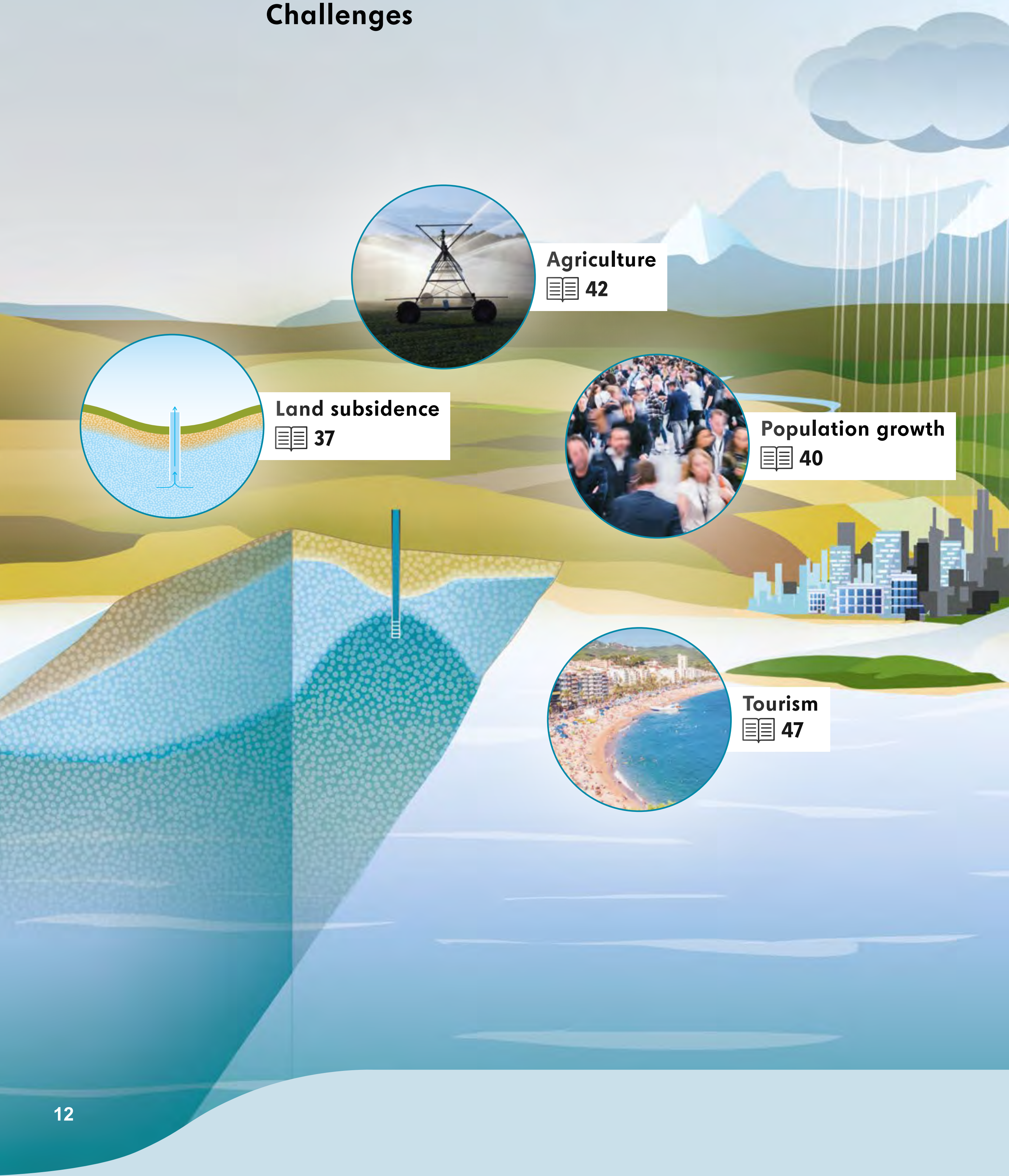
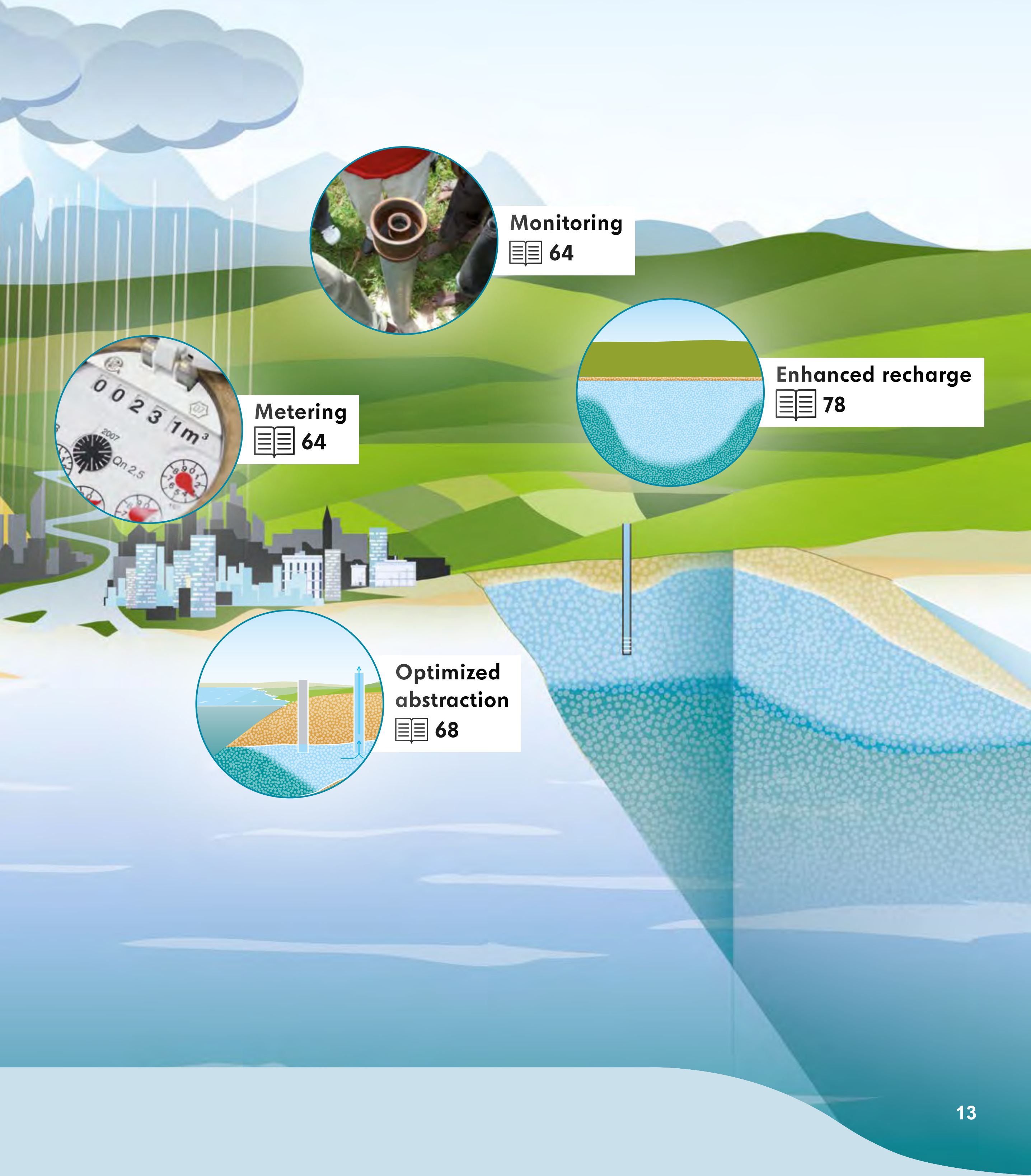
COASTAL GROUNDWATER

Challenges



Solutions


Monitoring
📖 64
Metering
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Enhanced recharge
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Optimized abstraction
📖 68
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Foreword

A large part of the human population lives in coastal zones, often concentrated in major urban centers. Ongoing population and economic growth place an increasing demand on already-stressed water resources, and put coastal aquifers at risk of seawater intrusion. Intensive groundwater abstraction has caused groundwater salinization in coastal regions all over the world. Rising sea levels and increased incidence of storm surges due to climate change as well as land subsidence are likely to exacerbate the issue over the coming decades.

In the context of a rising demand and decreasing resources, water use efficiency and source diversification are key ingredients for a secure water supply. Groundwater plays a crucial role in this, but the available amounts and renewal rates vary from one coastal region to the other. Therefore, sustainable water resource management is only possible when the groundwater system is fully understood, which requires a well-designed monitoring network. While data are the first prerequisite for management, good governance is another equally important precondition. Without a clear understanding of groundwater's role in a region's economic development, cross-sectoral coordination and legislative enforcement, no management policy can be effective.

This handbook gives an overview of risks and hazards to coastal groundwater and discusses the principles of good groundwater management and governance. It also provides a selection of examples of proven strategies to safeguard fresh groundwater resources through abstraction management, demand-reduction, enhanced freshwater recharge and engineering measures to prevent seawater intrusion. As each coastal zone is unique in its combination of hydrogeological and socio-economics conditions, a different set of measures is needed for every region. I hope this handbook will assist and inspire you in identifying and implementing the best solution for the coastal area you work in.

Ralph Watzel

Prof. Dr. Ralph Watzel,
President of the
Federal Institute for
Geosciences and
Natural Resources
(BGR)

Coast of Sri Lanka

1. Introduction

Coastal zones are at the interface between land and sea and are influenced by both marine and terrestrial processes that are highly dynamic and continually change in time. Typical landscape components include, amongst others, river deltas, wetlands, beaches, dunes, reefs, mangrove forests, and lagoons (Post and Lundin 1996). Coastal zones offer a variety of natural resources such as fisheries and fertile agricultural land, as well as access routes for commerce. Their natural beauty also makes them popular tourist destinations. The population in coastal zones continues to rise, and natural ecosystems are under ever greater pressure.

1.1 About this handbook

The management of groundwater resources in coastal areas is a difficult task. The hydrological processes are complex, and the lack of observational data makes it difficult to fully understand the resource and manage it sustainably. But even with an adequate understanding of the groundwater system, governance aspects can render the sustainable use of freshwater resources difficult.

The objective of this handbook is to provide basic information about coastal groundwater systems and their management. It is not meant as an exhaustive reference. Instead, because every region is unique in its combination of physiographic and socio-economic conditions, this document aims to bring together a range of solution ideas. Following this introductory chapter, chapter 2 gives an overview of the most important hydrological processes in coastal zones. Chapter 3 contains a selection of case studies of fresh groundwater resource deterioration caused by human activities. Chapter 4 deals with management practices and outlines good governance aspects. Chapter 5 provides examples of solutions to salinization problems that have proven successful in diverse geographical regions around the world. Finally, chapter 6 summarizes the main findings from the foregoing chapters.

1.2 Coastal zone dynamics

Coastal zones have always formed focal points for human settlement and economic activity. Globally, some 37% of the world’s population lives within 100 km of the coast and the population density in these areas is twice the global average. Two-thirds of the world’s cities are located on shorelines. Coastal zones all over the world show an extraordinary population growth (Figure 1.1), especially in urban centers. China is considered the hotspot of this development with a projected population of about 200 million inhabitants in low-elevation coastal zones in 2030, but the coastal areas of India, Bangladesh, Indonesia and Vietnam also experience strong population growth. While the population in Africa is numerically lower than in Asia, its growth rates are estimated to be the highest worldwide, especially in the countries of Western Africa like Nigeria, Benin, Côte d'Ivoire and Senegal (Neumann et al. 2015).
In addition to the growing coastal zone population, changing lifestyles (higher water use per capita), agricultural expansion and economic development are causing an increase of the water demand. Urbanization is responsible for a

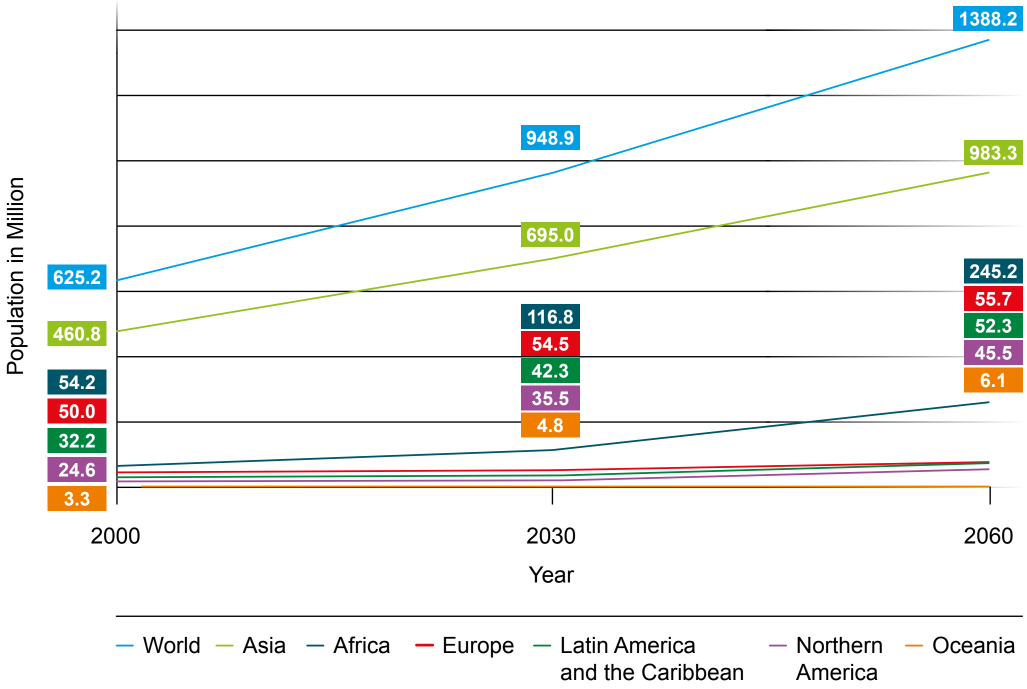


Figure 1.1: Development of the population in low-lying coastal zones (<10 m above mean sea level). Projected values are for a medium growth scenario (based on Neumann et al. 2015).

high local demand. A particular aspect of coastal zones is that the freshwater resources are at risk of salinization because of their vicinity to the ocean. Rainfall and surface waters form visible parts of the hydrological cycle, but in terms of volume, the largest freshwater resources are found underground in the form of groundwater in aquifers.

There is a multitude of processes that act on coastal aquifers (Figure 1.2). Some, like climate change or tectonic uplift, only have a noticeable impact in the long-term, but catastrophic events like tsunamis or storm surges can have enormous consequences within moments. Low-lying areas such as river deltas or atoll islands are particularly at risk, especially where land subsidence occurs (Section 2.6). In these areas a higher incidence of extreme weather events can lead to more frequent storm surges and flooding of the land surface by seawater. The safeguarding of freshwater supplies in coastal areas is thus closely connected to shoreline protection, as well as land use and urban planning.

Seawater intrusion is the displacement of freshwater in a coastal aquifer by seawater. The cause of seawater intrusion can be natural, for example a decrease of recharge or a rise in local sea level, but in the vast majority of cases, aquifer over-exploitation has been the principal driver. Just like natural

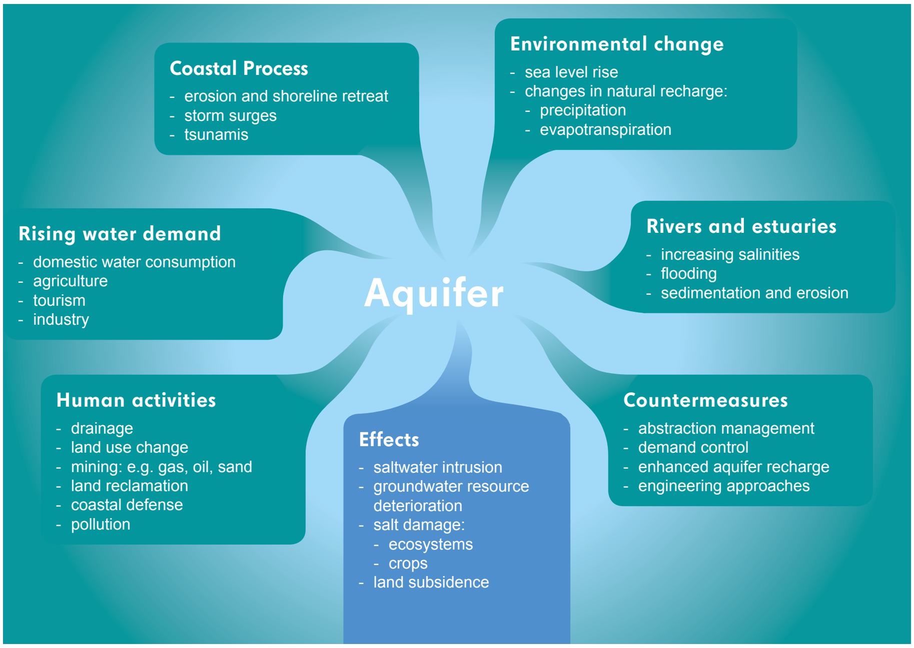
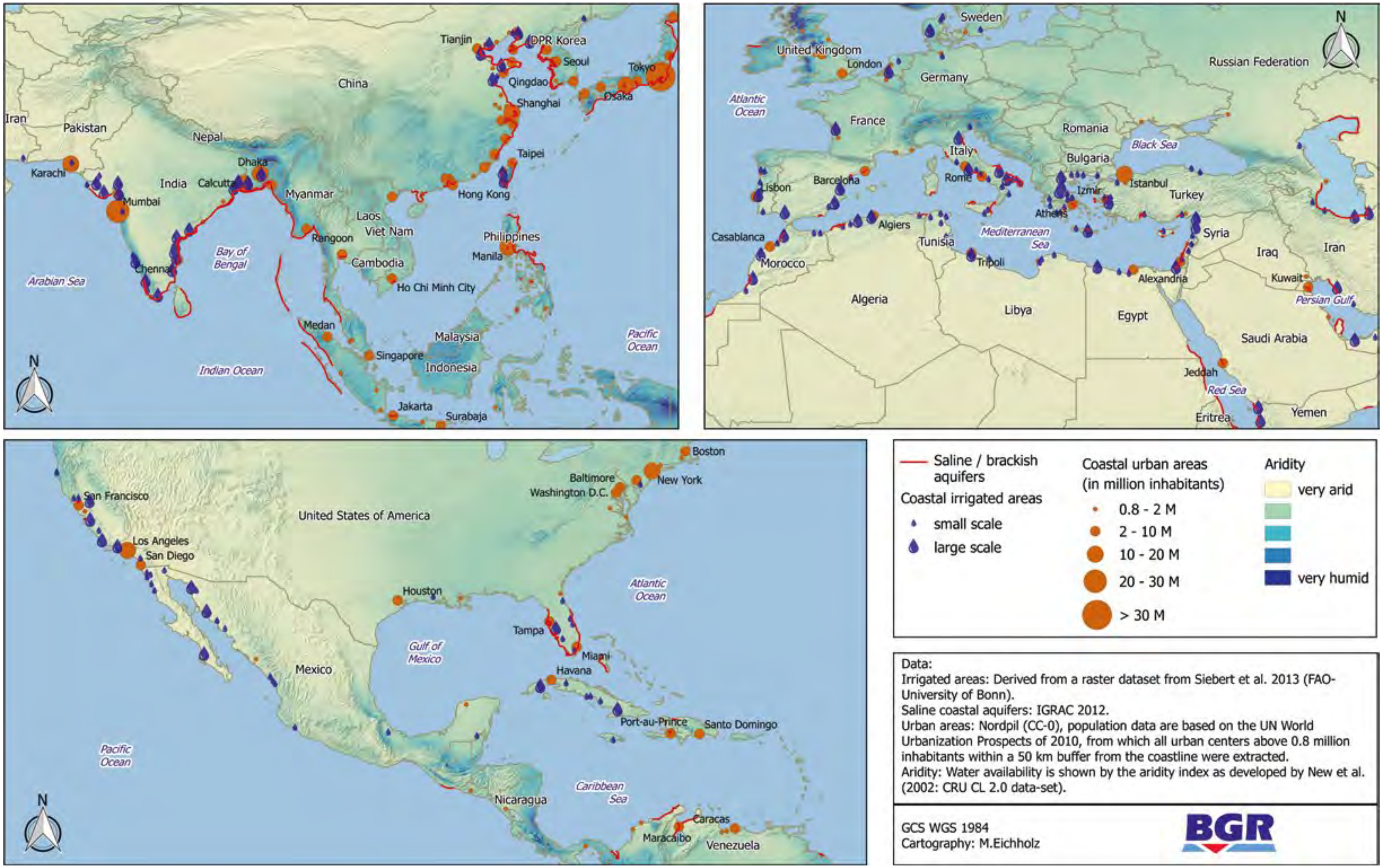


Figure 1.2: Factors influencing coastal aquifers and their effects (modified from FAO 1997).

processes, the anthropogenic drivers of seawater intrusion act on different spatial and temporal scales (White and Kaplan 2016). As groundwater salinity also affects the quality of irrigated soils, salinity control is of prime importance to the agricultural sector and the food security of the population.

Coastal water management is a highly specialized process and one of its main aims is to protect production wells from salinization. It must balance the growing demand for water with the capacity of the aquifer to deliver water of good quality, making sure at the same time that other functions of groundwater, like that of a water source to ecosystems, are not compromised. The concept of "the coastal groundwater squeeze" was coined by Michael et al. (2017) to describe the ever-growing pressure on freshwater resources in coastal aquifers. The multitude of threats and the connectedness of aquifers with various parts of the natural and anthropogenic hydrological cycle highlight the need for integrated water resources management (IWRM, Cap-Net 2010), as groundwater cannot be managed separately from other water sources.

Map 1.1 (see next page): Map of southeast Asia, the Mediterranean region and part of the Americas showing the occurrence of brackish or saline groundwater in coastal aquifers, urban centers and agricultural regions with intensive groundwater irrigation. The colors indicate the aridity index.



Data:
Irrigated areas: Derived from a raster dataset from Siebert et al. 2013 (FAO-University of Bonn).
Saline coastal aquifers: IGRAC 2012.
Urban areas: Nordpil (CC-0), population data are based on the UN World Urbanization Prospects of 2010, from which all urban centers above 0.8 million inhabitants within a 50 km buffer from the coastline were extracted.
Aridity: Water availability is shown by the aridity index as developed by New et al. (2002: CRU CL 2.0 data-set).

1.3 Global view on risk factors affecting coastal groundwater

A global assessment of coastal groundwater degradation and seawater intrusion is a difficult endeavor. It requires coherent monitoring and analysis of coastal aquifers, but such an approach is currently lacking in many of the world's coastal zones. In order to identify high-risk zones for groundwater over-extraction (or over-abstraction) and seawater intrusion, two major water demand drivers may serve as a proxy: (a) population density and urbanization; and (b) large scale groundwater-irrigated agriculture. A global review of groundwater salinity was conducted by the International Groundwater Resources Assessment Center (IGRAC) in 2009 (van Weert et al. 2009; IGRAC 2012). Based on published groundwater and proxy data, the study identified 103 coastal groundwater bodies showing seawater intrusion.

Map 1.1 on page 21 combines this IGRAC (2012) dataset with a mapping of areas with intensive agriculture where groundwater is used for irrigation, and urban centers in coastal zones in three macroregions. Intensive groundwater irrigation can be found – as expected – in coastal regions with relatively arid climatic conditions and long dry seasons on the one hand, and the vicinity of large markets for agricultural products on the other. Typical examples hereof are the agricultural areas along the coasts of California, Pakistan, India, and Northern China, as well those along the Mediterranean Sea.

Some humid coastal regions also have saline groundwater, for example in Southeast Asia. This is not always linked to seawater intrusion, and may be related to processes in the geological past when the coastline was located further inland. Also, high salinities caused by seawater intrusion during the 2004 tsunami may still persist along some coastlines of the Indian Ocean.

2. Freshwater and saltwater dynamics in coastal zones

A unique feature of the hydrology of coastal zones is the occurrence of water with distinct characteristics. On the one hand there is seawater, on the other there is freshwater that derives from sources further inland. Coastal aquifers do not differ greatly from terrestrial aquifers in terms of their physical properties, but are special in the sense that freshwater and seawater mix and interact in them. This chapter gives a brief overview of the most important hydrological aspects of coastal zones.

2.1 Salinity

Chemically, the major difference between freshwater and seawater is their salinity, which can be expressed by the total dissolved solids (TDS) concentration. The upper limit of TDS for freshwater is often taken as 1,000 mg TDS/L (Figure 2.1). Other salinity classes that are typically distinguished are brackish, saline and hypersaline, with the latter indicating water with a TDS concentration higher than that of ocean water. Average ocean water has 36,000 mg TDS/L but variations around this value occur. For example, the salinity can be markedly lower near the mouth of large rivers, or higher in warm regions with strong evaporation.

The major component of TDS in seawater is the dissolved chloride ion. There is no health limit for chloride in drinking water (WHO, 2003), but chloride is detectable by taste at concentrations over 250 mg/L. This means that a mixture of freshwater with just 1% of seawater can already be unsuitable for potable use.

The high salinity of seawater means that its density is higher than freshwater. The difference is about 2.5% for ocean water. While this difference may seem only small, it has important implications for the physical processes that determine the flow of seawater into aquifers containing freshwater. The density of seawater varies significantly between locations, being lowest in inland seas with freshwater inflow, like the Baltic Sea, and highest where evaporation forms the main water loss, like the Dead Sea. It therefore needs to be determined as part of any coastal aquifer investigation.

Figure 2.1: Subdivision of natural waters into salinity classes based on total dissolved solids (TDS) concentration in mg/L (Fetter 1994).

Freshwater 0 – 1,000
rain, rivers, lakes, groundwater

Brackish water 1,000 – 10,000
rivers, lakes and groundwater subject to evaporation or mixing with seawater

Saline water 10,000 – 36,000
rivers, lakes and groundwater subject to strong evaporation or intensive mixing with seawater

Hypersaline water 36,000 – 100,000
evaporated seawater or groundwater in discharge zones in arid regions

Brine water > 100,000
seawater or groundwater having undergone intense evaporation or dissolution of rock salt

2.2 Freshwater and seawater interaction in coastal aquifers

The ability of a geological unit to conduct water is expressed by its hydraulic conductivity. The higher the hydraulic conductivity, the greater the ease with which a unit will transmit water. Layers in the subsurface are subdivided into so-called hydostratigraphic units based on this parameter, where the more permeable layers form aquifers and the less-permeable ones form aquitards. Good aquifers are made up by coarse sand, limestone or fractured rocks, whereas aquitards comprise materials like clay, shale or mudstone.

Where fresh groundwater and intruded seawater meet in a coastal aquifer, they are separated by a transition zone (Figure 2.2). Within this zone, salinities range between that of freshwater and seawater. The location and the width of the transition zone are dependent on the characteristics of the groundwater system. When a coastal aquifer is hydraulically connected to the sea, intruded seawater forms a wedge that penetrates inland into the aquifer. This configuration is the result of the higher density of seawater compared to freshwater: A column of seawater exerts a greater pressure than a column of freshwater of the same length. Because of this, seawater can protrude into the aquifer below the land surface inland from the shoreline.

The fresh groundwater near the coast thus forms a water body that “floats” on the saline groundwater. When such a system is in equilibrium (i.e. the position of the seawater wedge remains the same), a first estimate of the thickness of the freshwater lens can be obtained with the formula:

$$\gamma=\alpha h$$

where γ is the depth of the lens bottom below sea level and h is the elevation of the water table above sea level (Figure 2.2). This relationship is known as the Ghijben-Herzberg principle. The factor α is usually around 40, due to the difference in density between standard seawater and freshwater. It must be borne in mind that, if the seawater has a different salinity than standard seawater, a different factor must be used. As illustrated in Figure 2.2, the actual position of the transition zone is normally located seaward of the position of the sharp boundary estimated with the Ghijben-Herzberg formula. Also, complicating factors like the local geology or transient groundwater processes can severely limit the application of this relationship. Nonetheless, it can provide a useful indication of the depth to the seawater wedge.

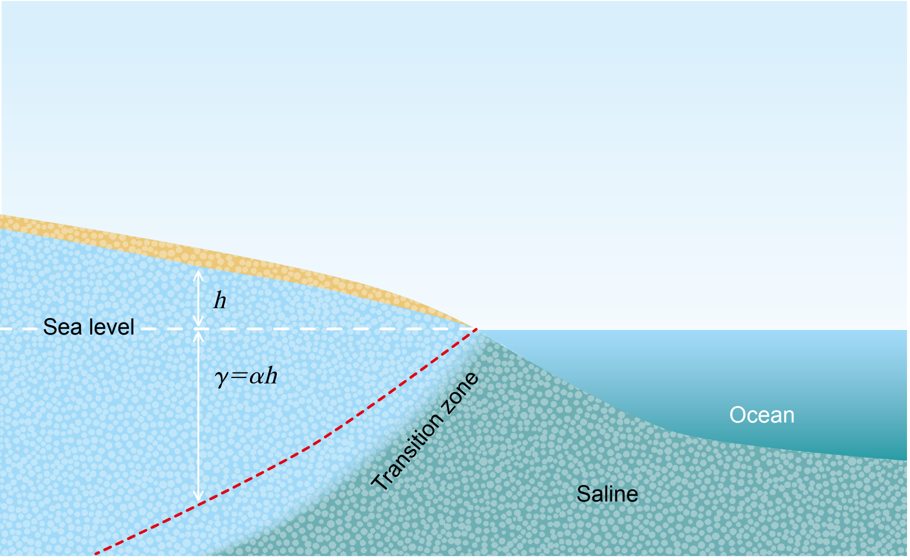


Figure 2.2: Diagram of an idealized coastal aquifer with a wedge of intruded seawater. The symbols next to the white arrows illustrate the meaning of the symbols in the Ghijben-Herzberg formula. Note that the elevation of the water table has been exaggerated for better readability. The Ghijben-Herzberg principle is based on the assumption of a sharp boundary between the fresh and saline groundwater, which is indicated by the dashed red line. In reality the transition is more gradual, and is normally located a bit more seaward than predicted by the Ghijben-Herzberg formula, as illustrated by the fill colors representing fresh and saline groundwater.

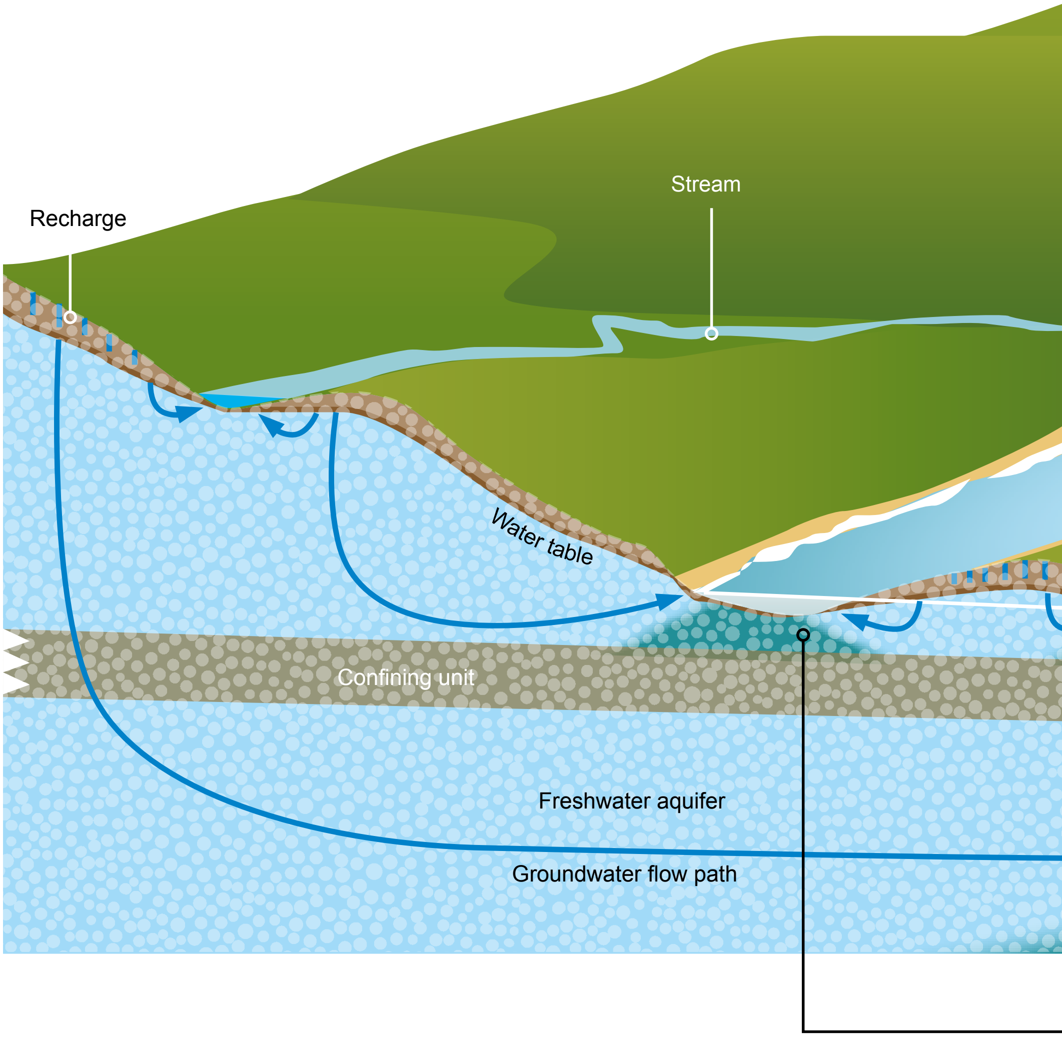
The distance to which the seawater wedge will protrude inland is a function of a number of factors:

- *Groundwater recharge and discharge processes*
- *The hydraulic properties and the geometry of the aquifer system*
- *The density difference between seawater and fresh groundwater*

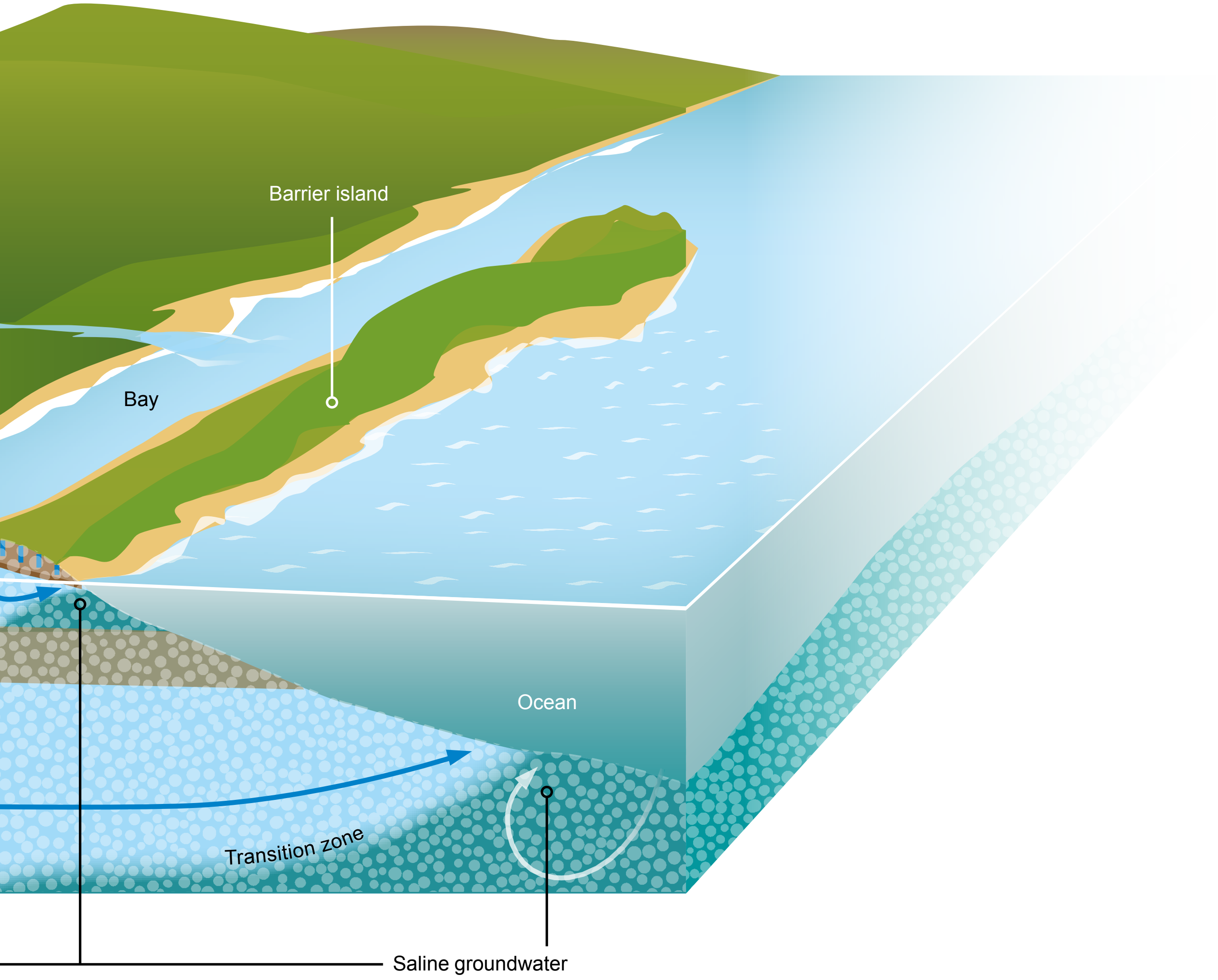
In general, the higher the seaward flow rate of fresh groundwater, the smaller the penetration of the seawater wedge into the aquifer. For the same flow rate, however, a higher hydraulic conductivity of the aquifer will result in an increased inland extent of the saltwater wedge. A higher density difference will have the same effect.

Under natural conditions without pumping, the flow of fresh groundwater is directed towards the sea (Figure 2.3). Discharge into the sea can occur in the form of localized outflow through submarine springs, or as diffuse outflow. Prior to discharging, the freshwater mixes with seawater in the aquifer, and therefore the outflow is often not purely fresh but brackish instead. The saline groundwater within the wedge is also in motion, albeit at a smaller rate than the fresh groundwater. The transition zone moves and changes shape in response to seasonal and annual variations in groundwater recharge, tidal fluctuations and longer-term sea level changes.

Figure 2.3: Interaction of freshwater and saline water in a coastal zone (modified from Barlow 2003). Fresh groundwater discharges to streams, tidal creeks, ponds, salt marshes, the bay and the ocean. A local lens of freshwater has formed beneath the barrier island.



The configuration and geometry of aquifers and aquitards control the pattern of seawater intrusion. In a multi-layered aquifer system, multiple transition zones can exist (Figure 2.3). Where an aquitard separates an aquifer from the overlying seawater, the transition zone may be located in the offshore portion of the aquifer.



2.3 Seawater intrusion

When freshwater is abstracted at a greater rate than at which it is being renewed, the lost volume may be compensated by the inflow of seawater. Wells that are in the vicinity of the fresh-saltwater transition zone are at immediate risk of salinization (Figure 2.4), in particular if the seawater is found in the aquifer beneath the well. In that case, the vertical movement of water caused by pumping can lead to what is known as up-coning of the saline groundwater, which is one of the most common causes of well salinization. Horizontal movement of seawater also occurs, but given that the distance between abstraction wells and the coastline are usually a few kilometers, the effects of horizontal seawater intrusion usually take longer to manifest themselves than the process of up-coning.

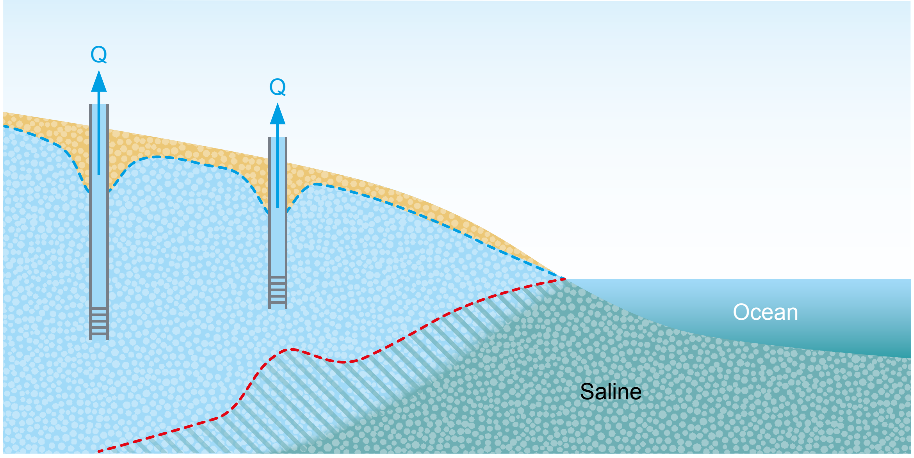


Figure 2.4: Seawater intrusion in a coastal aquifer with pumping. The well closest to the coastline causes up-coning of the intruded seawater.

Custudio and Bruggeman (1987) provided some crude rules of thumb to estimate the risk for seawater intrusion for different well types (Figure 2.5):

a. *The well is far from the coast, where the aquifer bottom is above sea level. Seawater is unlikely to intrude directly, but a high abstraction reduces the saturated thickness and the yield of the wells.*
b. *The well is far from the coast and from the natural seawater wedge, but the aquifer bottom is below sea level. Seawater intrusion is likely to reach the well when water is abstracted over a long period.*
c. *The well is close to the coast, but not located directly above the seawater wedge. There is an eventual danger of seawater contamination in the case of high abstraction.*
d. *The well is drilled over the seawater wedge. The danger of salinization is very high, even with low abstraction rates.*

Just like with the Ghijben-Herzberg formula, these rules of thumb can provide some guidance in the absence of detailed groundwater data. But as will become clear later, coastal aquifer management cannot be successful unless the complex interactions between fresh and saline groundwater are fully understood.

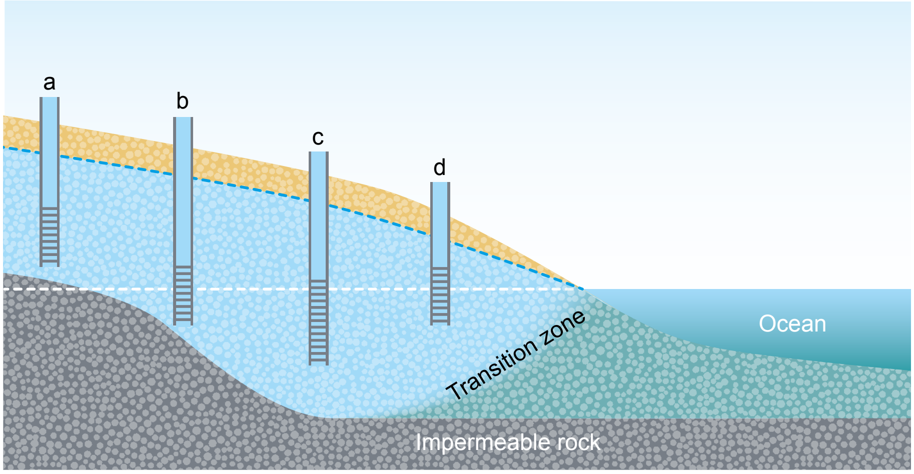
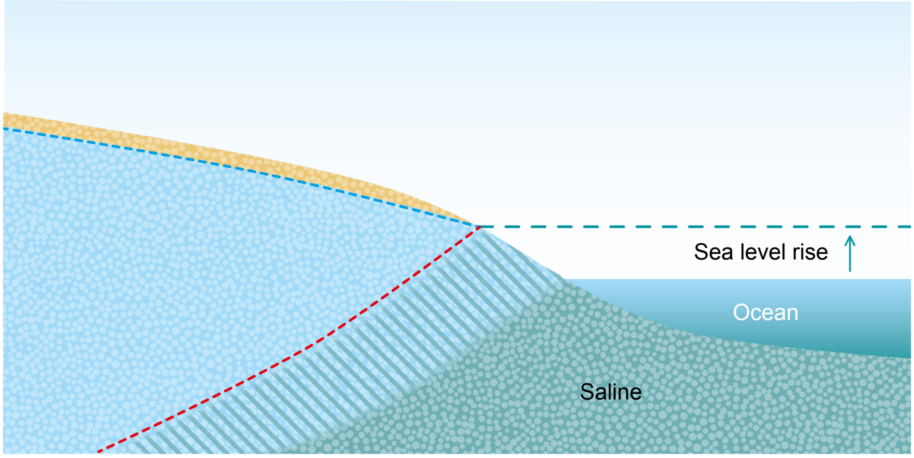


Figure 2.5: Seawater intrusion risk for different well locations. See text for more detailed information about the wells labelled a to d.

2.4 Effects of climate change and sea level rise

The Intergovernmental Panel on Climate Change (IPCC 2007) defined the vulnerability of a coastal aquifer system to salinization as the degree to which it “is susceptible to and unable to cope with, the adverse effects of sea level rise or groundwater extraction”. Not explicitly considered in this definition is the fact that changes in temperature and precipitation may lead to a change in recharge. When recharge decreases, or droughts extend for longer periods of time than under the current climate, the pressure on groundwater resources will increase, especially when higher temperatures lead to higher evapotranspiration rates and thereby an increased water demand for irrigation and domestic water consumption. On the other hand, when recharge increases, higher water tables can lead to increased storage of freshwater in aquifers. One problem faced by water managers is that future developments in weather patterns, and hence recharge and demand, are extremely difficult to forecast and are therefore highly uncertain.

Figure 2.6: Effect of sea level rise on an idealized coastal aquifer.



Sea levels are expected to increase by several decimeters along most of the world's coastlines during the 21st century. The magnitude of the impact on the availability of fresh groundwater is hard to predict a priori, and depend strongly on the local hydrological conditions. In the majority of cases, sea level rise is likely to lead to a loss of fresh groundwater due to a landward shift of the seawater wedge (Figure 2.6) and a higher incidence of flooding (Section 2.5). In some cases, however, sea level rise may lead to increased freshwater availability. This seems entirely counterintuitive but it can occur where a higher sea level enhances the storage of freshwater by lifting the water table without affecting the position of the fresh-saltwater interface. This is the case for certain atoll islands (White and Falkland 2010) if the sea level rise is not accompanied by land loss due to enhanced coastal erosion or flooding of low-lying areas. Ferguson and Gleeson (2012) contended that most coastal aquifers are more vulnerable to groundwater extraction than to predicted sea level rise. This highlights the fact that human water usage is the key driver for seawater intrusion.

While future climate change is a real and urgent concern, in many coastal aquifers the salinity distribution is partly the result of hydrological conditions that prevailed in the past. Sea levels, coastline locations and recharge rates have always been variable during the geological history. In coastal areas where the shoreline had been further inland, which had been the case in many coastal zones during the past millennia, relic seawater still resides in the aquifer system. On the other hand, during the glacial periods of the Quaternary, enormous areas of seafloor fell dry and freshwater reserves were formed. These remain preserved beneath the seafloor at numerous locations around the world. Such complexities demonstrate that predictions based on over-simplified representations of natural processes and human drivers in coastal zones can be misguided (Section 3.3).

2.5 Impacts of natural disasters on coastal aquifers

Low-lying coastal zones are prone to storm surges and tsunamis. Besides their immediate destructive impact on human lives and infrastructure, they are a threat to fresh groundwater resources. During an inundation, seawater infiltrates into the soil and contaminates the fresh groundwater (Villholth and Neupane 2011). Topographic depressions and large-diameter dug wells are especially vulnerable because seawater pools in these and does not flow back to the sea after the catastrophe (Figure 2.7). The impact is highest for unconfined aquifers. Deeper, confined aquifers are relatively better protected against short-term risk but may also suffer negative consequences in the long term (Cardenas et al. 2015).

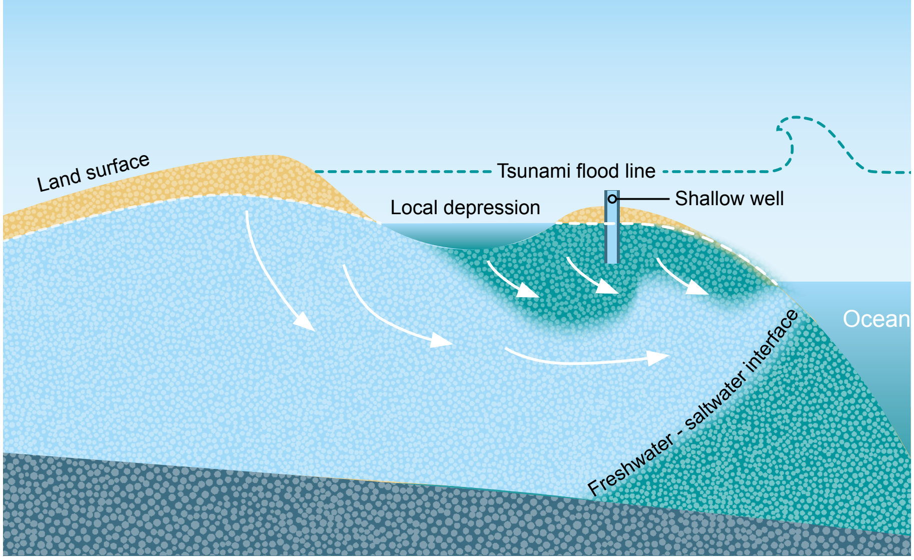


Figure 2.7: Idealized graphic showing seawater inundation caused by a tsunami. During the tsunami seawater fills local depressions and open dug wells and contaminates the groundwater (modified from Villholth and Neupane 2011).

Groundwater salinization was reported after the 2004 tsunami in India, Sri Lanka and Indonesia (Villholth and Neupane 2011). In Indonesia, the tsunami caused the contamination of thousands of shallow water wells in the coastal region of the Province of Nanggroe Aceh Darssalam in northern Sumatra (Siemon and Steuer 2011). The earthquake damaged the reticulated water supply system and many new drillings were unsuccessful in finding potable water due to the lack of knowledge about local hydrogeological conditions. The water supply was thus seriously compromised. Geophysical airborne investigations showed that saline water was present several kilometers inland nine months after the catastrophe (Figure 2.8).

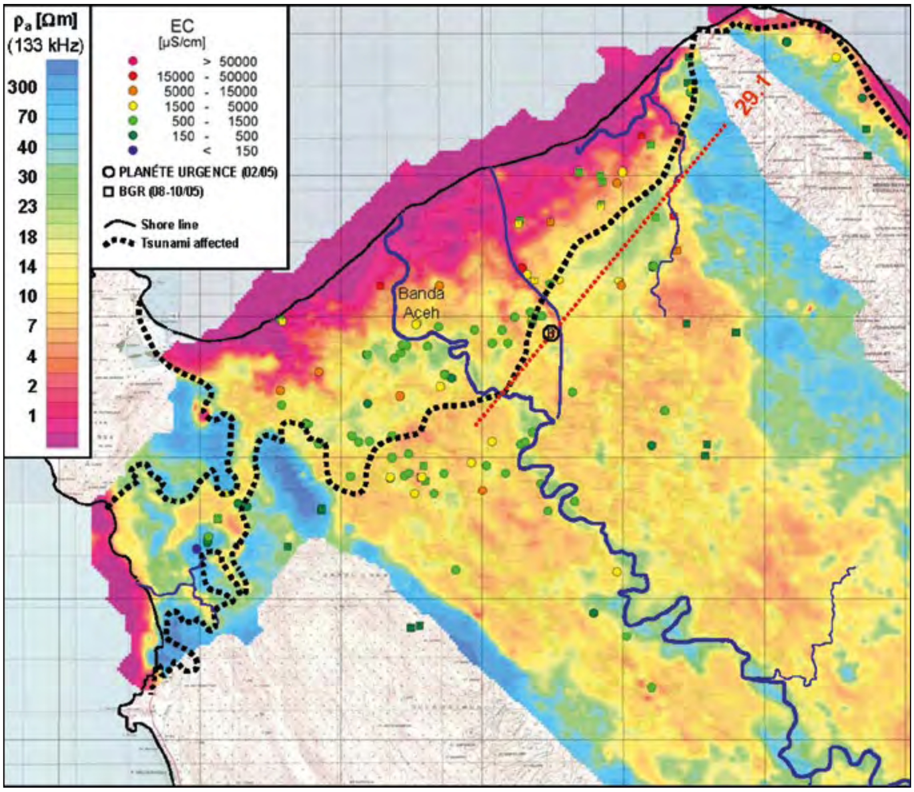


Figure 2.8: Electrical resistivity of the shallow groundwater in the northern part of the Banda Aceh survey area nine months after the tsunami in 2004. Low resistivity values indicate a high groundwater salinity. Water conductivity samples (colored dots and squares), maximum extent of the tsunami flooding (dashed black line) and main rivers (blue lines) are plotted on top (Siemon and Steuer 2011).

Salinization of shallow groundwater also occurs after storm surges like those during typhoon Haiyan on Samar Island, Philippines in 2013. The seawater surge reached 7 m above mean sea level and led to contamination of the upper aquifer by seawater infiltrating from the land surface. The deeper confined aquifer was mainly contaminated via poorly-sealed tube wells. The salinity decreased significantly after 8 months, but given that salinities in the shallow unconfined aquifer are expected to remain high for several years, the risk of contamination of deeper freshwater remains.

Figure 2.9 shows the effects of the 1962 storm flood on the groundwater salinity in the northern German island of Baltrum. An important aspect is that the contamination of the freshwater is fast because the seawater sinks downward in the form of salt fingers because it has a higher density than the freshwater. But this density difference becomes smaller with time due to mixing effects, which means that the salt fingers do not sink any further and have to be flushed out by the natural lateral groundwater flow. So while the destruction of the resource is rapid (weeks to months) the restoration to natural salinity levels is very slow by comparison (years).

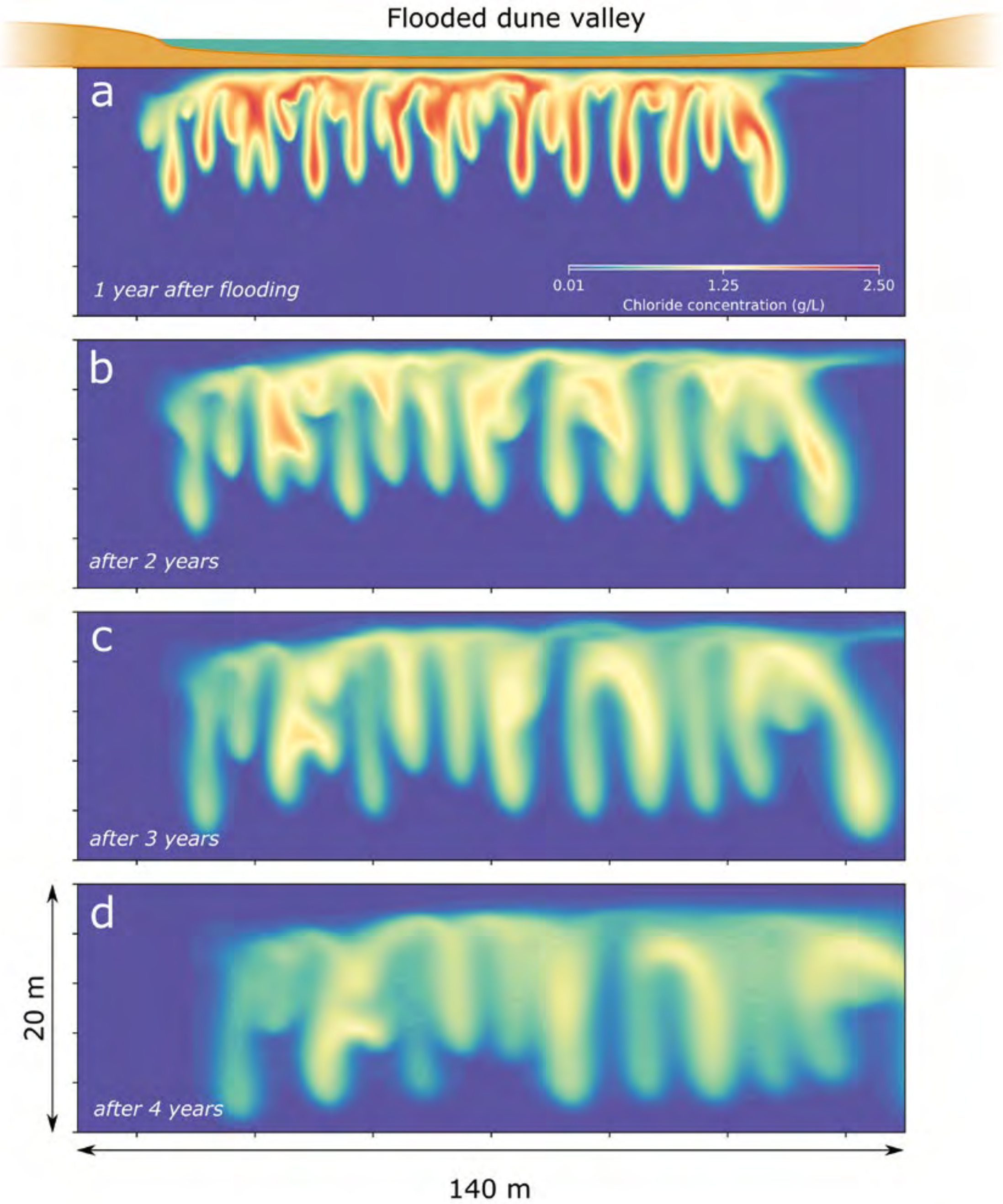
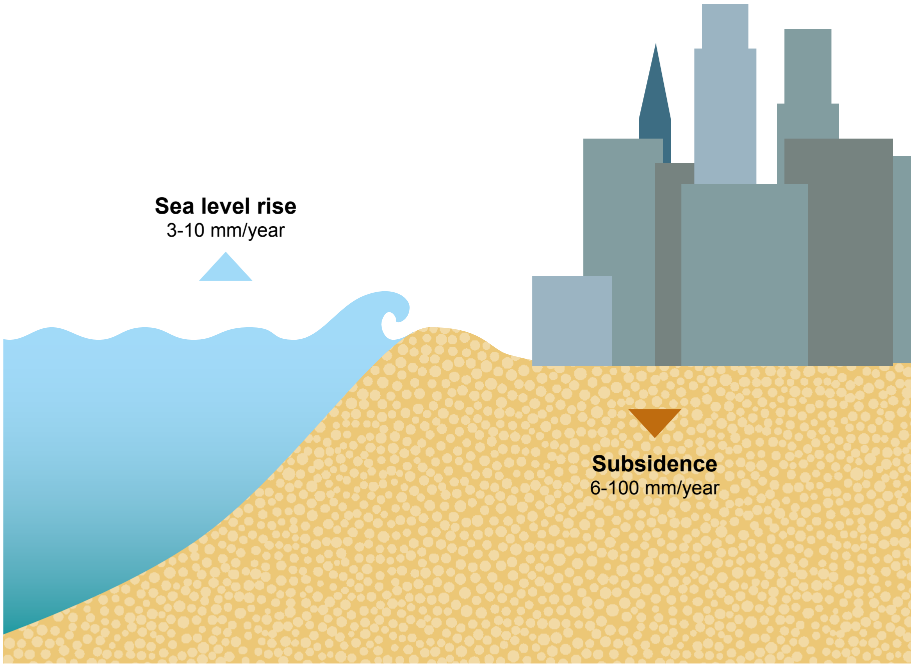


Figure 2.9: Cross sections showing modelled chloride concentrations following the inundation of a 100m wide dune valley by seawater on the German island of Baltrum during the 1962 storm flood. Colors indicate the concentration of chloride after (a) 1, (b) 2, (c) 3 and (d) 4 years since the flood.

2.6 Land subsidence

A lowering of the land surface relative to sea level can be another trigger for seawater intrusion (Figure 2.10). Coastal zones that are prone to land subsidence are those with extensive subsurface layers of clay and peat. Roughly, half a billion people live in delta regions threatened by land subsidence (Syvitski et al. 2009). The leading cause is the loss of structural support of the rock grains in the subsurface, which is primarily due to the removal of groundwater by excessive pumping (USGS 2016). Another cause of land subsidence is the lowering of the water table by land drainage, which can be responsible for massive oxidation of soil organic carbon in peat areas.



Climate change

Accelerated sea level rise
Extreme weather events

Socioeconomic development

Urbanization and population growth increased water demand

Figure 2.10: Cumulative effects of sea level rise and land subsidence (based on Deltares 2015)

Rapidly expanding urban areas require huge amounts of water for domestic and industrial water supply, which often leads to over-exploitation of groundwater resources. In the city Dhaka in Bangladesh for instance, continuous large scale extraction currently causes groundwater levels to fall by 2–3 meters per year (Deltares 2015). The extraction of groundwater causes severe land subsidence, and similar conditions occur in other coastal cities like Jakarta (Indonesia), Ho Chi Minh City (Vietnam), and Bangkok (Thailand). Current global mean sea level rise is around 3 mm/year. This rate is expected to increase in the future (IPCC 2013), but still it remains rather small compared to subsidence rates of 6–100 mm/year in some coastal megacities (Figure 2.11). This highlights once more the fact that human actions are the key risk factor for seawater intrusion.

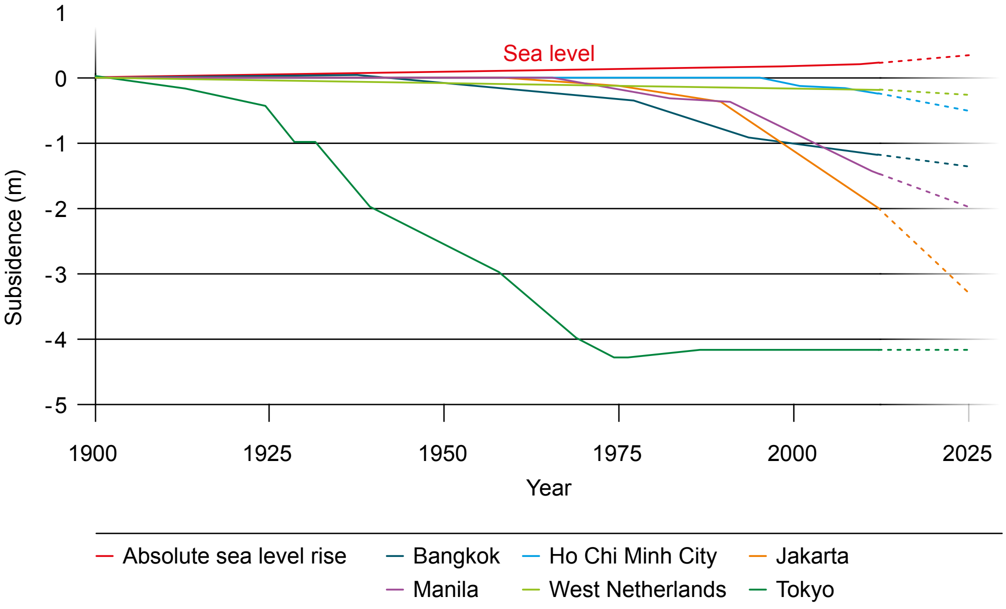


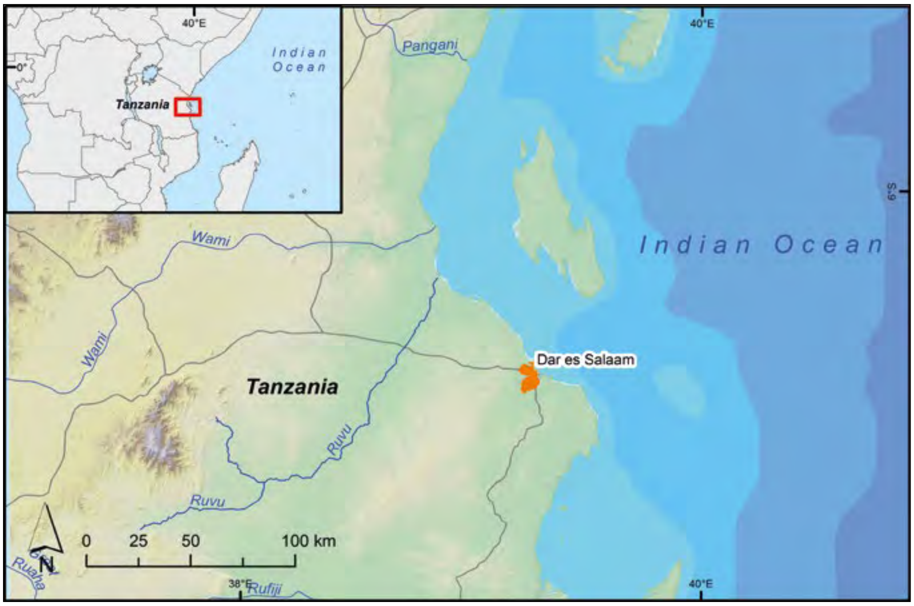
Figure 2.11: Absolute sea level rise and average land subsidence for several coastal cities (note that subsidence can differ considerably within a city area, depending on groundwater level and subsurface characteristics (Deltares 2015).

3. Water management challenges in coastal zones

Human activities impacting on coastal groundwater systems are manifold and go beyond water withdrawal from coastal aquifers. Land subsidence was already mentioned in the previous section, but land use change, river modification and mining are also important drivers of seawater intrusion (Figure 1.2). Case studies from different coastal regions are presented in this chapter to illustrate the diverse impacts of human activities and the ensuing water management challenges in coastal zones.

3.1 Rapid population growth (Dar es Salaam, Tanzania)

Map 3.1: Location map Dar es Salaam, Tanzania



Background

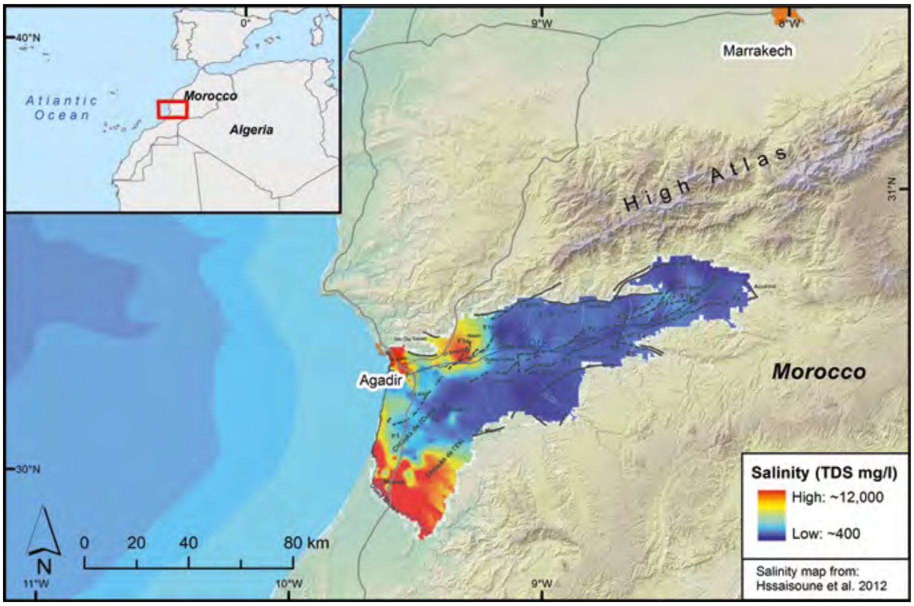
Dar es Salaam (Map 3.1) is one of Africa's fastest growing urban centers. While the population of Dar es Salaam was 128,000 in 1957, it currently numbers around 4.1 million. It is likely to achieve 'megacity' status – more than 10 million inhabitants – by the early 2030s (African Development Bank 2014). According to Skinner and Walnycki (2016) 51% of the population of Dar es Salaam was served with piped water in 2013. This water is mainly taken from the nearby Ruvu River and from the Kimbiji aquifer, an aquifer that is up to 600 m deep. The remainder of the population – mostly living in informal and low-income settlements not connected to public networks – obtain their water from the shallow aquifer under the city. Seawater intrusion has occurred in the city center close to the coast, where chloride concentrations exceed the WHO drinking water standard of 250 mg/l.

Consequences

Rapid urbanization causes seawater intrusion in two ways. On the one hand, massive land use change due to the spreading of new settlements and urban infrastructure in the coastal plain reduces the infiltration of precipitation, and thus the freshwater recharge of the shallow aquifer. On the other hand, abstraction from the shallow aquifer is rapidly increasing to meet the higher demand (Sappa and Luciani 2014: 466). Up to 10,000 unauthorized boreholes are currently tapping the shallow aquifer.

To address the problems, several interventions are necessary concerning water services, urban development and environmental planning. An extension of the piped water supply network can substitute uncontrolled and illegal water extraction from the shallow aquifer. However, it will take years to build a network that delivers drinking water to all settlers. Even if the network would reach the poor quarters, the connection and running costs may be unaffordable for the poorest, who may therefore opt to continue to use groundwater. Institutional reform is necessary to control and manage all different sources of water. All central (surface water and deep aquifer) and decentral (shallow aquifer) water sources need integrated and conjunctive management (Sappa and Luciani 2014). At the time of publication, piped water and the shallow aquifer were being managed by different institutions. For sustainable management that prevents further seawater intrusion, a single coordinated institutional umbrella is necessary. The management should be data-driven, which requires systematic monitoring of the shallow aquifer, as well as the fluctuations in water supply and consumption (Skinner and Walnycki 2016).

3.2 Expansion of irrigated agriculture (Souss-Massa Basin, Morocco)



Salinity map from: Hssaisoune et al. 2012

Map 3.2: Salinity (TDS) of groundwater resources in the shallow aquifer (Hssaisoune et al. 2012).

Background

The Souss-Massa Basin, located on the Atlantic coast in central Morocco, is a key area for the economic development of the country due to its highly productive irrigated agriculture and tourism industry. Agricultural development has increased significantly since the 1980s and has become strongly export-oriented. In 2008, the Moroccan government implemented the Green Morocco Plan ("Plan Maroc Vert"), which is the overarching sectoral development plan for agriculture. The plan involves an annual investment of 1 billion US$ from 2008 to 2020 to improve production and increase exports of agricultural products. This places additional pressure on the limited water resources. The Souss-Massa Basin is currently the second most productive agricultural area of Morocco, especially for vegetables and citrus fruits. The cultivated area amounts to 160,410 ha, of which about 50% are irrigated (Choukr-Allah 2016). The region has an arid climate with a mean annual precipitation of around 250 mm (Bouchaou et al. 2008). Rainfall is increasingly irregular. Water is predominantly sourced from groundwater and from surface water stored in seven dammed reservoirs. The water demand for agriculture exceeds the sustainable supply capacity by far.

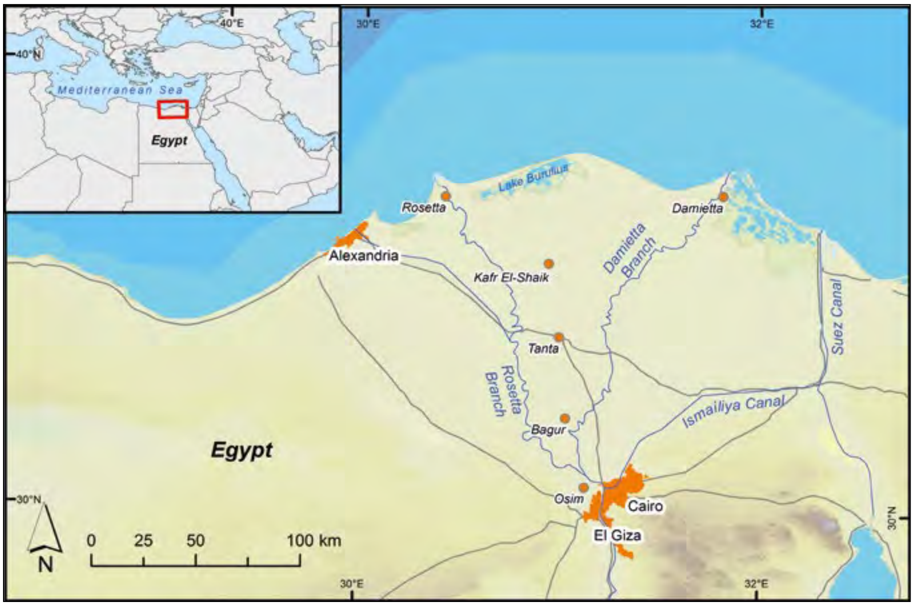
Consequences

The situation in the Sous-Massa Basin illustrates the challenges of combining agricultural expansion with sustainable groundwater management. Groundwater abstraction has caused water levels to drop by between 0.5 to 2.5 m per year, and salinity has increased. Salinization is not only linked to seawater intrusion but also to up-coning of old seawater trapped in the aquifer and dissolution of evaporite minerals. At the same time, groundwater nitrate concentrations are rising because the application of fertilizers (Bouchaou et al. 2008). The shallow aquifers in the western part of the basin show the highest levels of salinity (Map 3.2).

In order to also reduce the demand, a key objective is to increase irrigation water-use efficiency by promoting and subsidizing drip irrigation systems that replace flood and sprinkler systems (Closas and Villholth 2016). The water management authority developed an IWRM plan for the basin and designed legislation that aims to shift agriculture towards increased water efficiency and control of groundwater extraction. However, compliance and enforcement of new regulations remain a challenge in the context of the ambitious agricultural development of the basin (Choukr-Allah et al. 2016).

3.3 Unregulated groundwater use and knowledge gaps (Nile Delta, Egypt)

Map 3.3: Location map Nile Delta, Egypt



Background

Irrigated agriculture in the Nile Delta (Map 3.3) is of vital importance for Egypt's economy. It provides work to more than 2 million people, and about 65% of the country's irrigated surface is concentrated here (Molle et al. 2016). Although irrigation water is sourced primarily from the Nile River, groundwater use is on the rise (Figure 3.1). The number of registered wells has sharply increased in recent years (Table 3.1). While just over 32,000 wells were officially registered in 2016, it is estimated that the real number may be as high as 73,000 (Molle et al. 2016). Especially when surface water supplies decrease, a growing number of farmers use groundwater to overcome scarcity (El-Agha et al. 2017). Historical records show a continuous increase in the abstraction rates between 1981 and 2010.

Table 3.1: Development of the number of wells in the Nile Delta from 1952 to 2016 (Molle et al. 2016)

Year	Number of wells
1952	5,600
1991	13,000
2011	22,905
2016	32,054

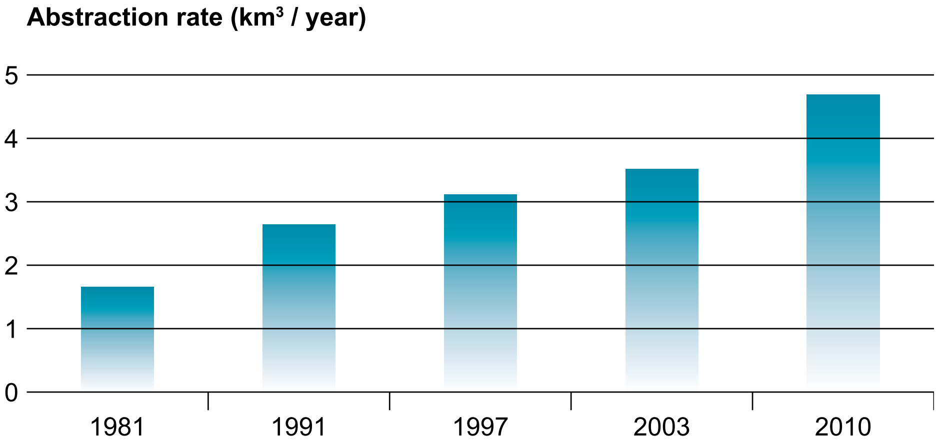


Figure 3.1: Abstraction rates versus time in Nile Delta (adapted from Mabrouk et al. 2013)

The subsurface of the Nile Delta hosts a large aquifer system that consists of unconsolidated sediments (Leaven 1991). The risk of seawater intrusion and possible up-coning of deep saline groundwater limits the volume of freshwater that can be withdrawn. Yet groundwater use in the Nile Delta is largely unregulated. Although there are permit procedures for well development, many farmers are not aware of these procedures and the registration of agricultural wells is still an exception (El-Agha et al. 2017).

Consequences

Due to lacking groundwater monitoring data, different conceptual models of the aquifer have been proposed, and this precludes the development of a sustainable groundwater management concept. Some have taken the view that a single body of intruded seawater extends up to 100 km inland from the Mediterranean coastline (e.g. Sherif et al. 2012), while others contend there are several disconnected bodies of saline groundwater that have different origins (Kooi and Groen 2003). This is exemplified by the two cross sections in Figures 3.2 and 3.3, which portray two contrasting conceptual models of the same system. Despite the orientation of the profiles being different (north-south versus east-west), they clearly show different insights from different investigators about the same system.

Such a discrepancy is obviously problematic, as a proper conceptual understanding of the aquifer system forms a prerequisite for effective management. Moreover, without it, predictions of future developments by numerical models cannot be relied upon. There is the risk of a significant deterioration of the freshwater resources if groundwater abstraction continues to increase unchecked (Dawoud 2004).

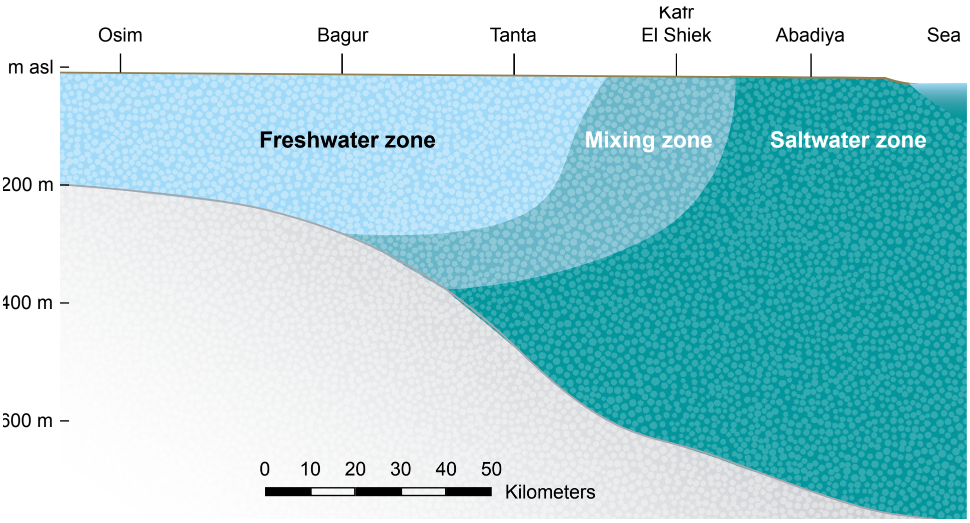


Figure 3.2: Hydrogeological north-south cross section through the Nile Delta according to Farid (1985). This conceptual model considers solely seawater intrusion as source for saltwater.

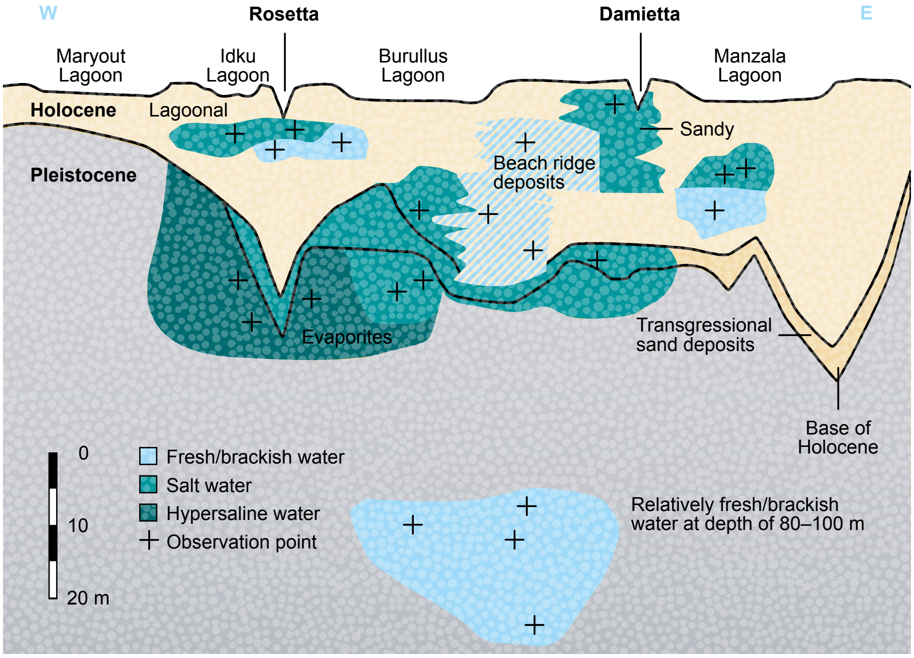
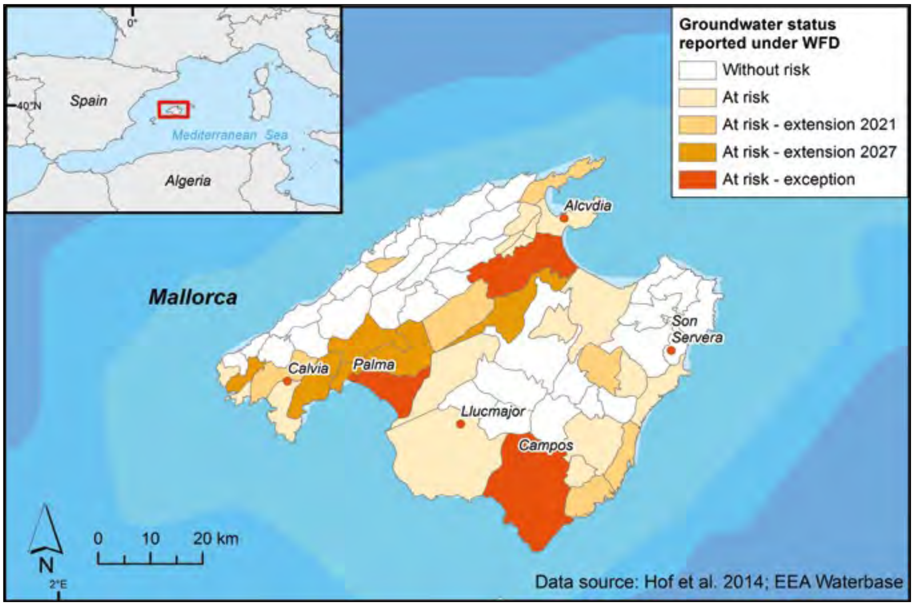


Figure 3.3: Hydrogeological conceptual model of the Nile Delta according to Kooi and Groen (2003). Rather than a single pervasive body of saline groundwater as in Figure 3.2, this depiction of the groundwater system assumes that the distribution of groundwater salinity is geographically more localized and that the origin of dissolved salts may have multiple origins besides seawater intrusion. The gray shading is used to emphasize the paucity of data.

3.4 Groundwater for a tourism hot spot (Mallorca, Spain)



Map 3.4: Location map Mallorca and groundwater status reported under the European Water Framework Directive (WFD)

Background

The coastal aquifers of the Mediterranean region are highly susceptible to seawater intrusion due to a combination of factors, most importantly the high water demand during the dry summer months and the high permeability of the aquifers. Problems are particularly severe on islands, where availability is constrained by their size.

The water-related problems of the Balearic Islands of Spain typify those of many Mediterranean regions that have experienced significant economic development during the recent decades. On the island of Mallorca, the tourism industry has grown extensively and in 2015 the island received almost 10 million visitors (Agència de Turisme de les Illes Balears 2016), which is more than 10 times the number of residents (Deyà-Tortella et al. 2016). Tourism is an important driver for urbanization along the coastline, and accounts for up to half of urban water use. While agriculture used to be the largest consumer of water on the island, urban water use now accounts for most of the consumption.

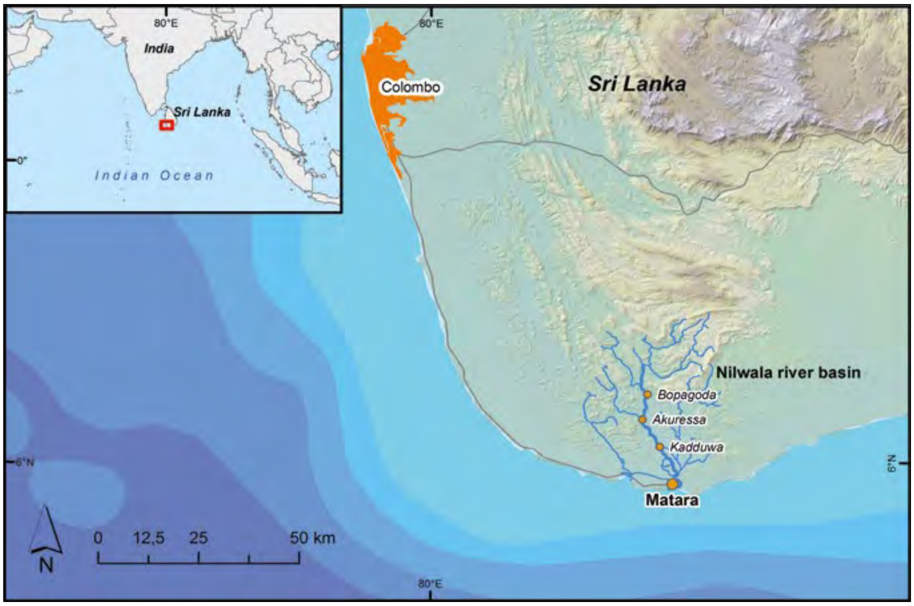
The rainfall on Mallorca is unevenly distributed throughout the year. Almost half of the total annual amount falls in September and October, while almost no rain falls from June until August (Garing et al. 2013). The total exploitable ground- and surface water reserves amount to 227 million m³/year, which is only just enough to meet the demand of 210 million m³/year for the island as a whole (Hof et al. 2014). Groundwater supplies three quarters of the demand, the remaining demand is covered by the reuse of treated wastewater, desalinated seawater and surface water.

Consequences

The strong reliance on groundwater to meet the local demand near the coast has resulted in widespread seawater intrusion (López-García and Mateos Ruíz 2003), and conflicts have arisen over the use, protection and management of the groundwater resources (Karim et al. 2008). One fifth of the groundwater bodies have been classified as severely over-used according to the Groundwater Directive of the European Union (Hof et al. 2013, Map 3.4). Accordingly, the Hydrological Plan of the Balearic Islands (PHIB) adopted in 2013 foresaw in abstraction limits. After a change of government these constraints were relaxed, however, because of the negative financial impacts of such measures on the tourism and agricultural sectors.

The adoption of water saving measures has helped to bring down the urban water use between 2005 and 2012 somewhat. The record tourist numbers since 2016 (Reuters World News May 30, 2016), resulting from fears over terrorism in other Mediterranean holiday destinations, may negate the savings gained. Without additional measures, freshwater resources thus remain at risk, and future water stress may become even more severe as climate change effects are expected to lead to less rainfall and higher temperatures across the Mediterranean region (Milano et al. 2013).

3.5 The effect of sand mining (Nilwala river basin, Sri Lanka)



Map 3.5: Location map Matara, Sri Lanka.

Background

River discharge and morphology are important factors that control the salinity of water in coastal zone rivers. Both are influenced by natural processes, such as rainfall as well as sedimentation and erosion, and human activities, such as dam construction and dredging. In southern Sri Lanka, riverbed sand mining has increased rapidly over the last 25 years (Figure 3.4). Main drivers of the high demand for sand are economic growth and the reconstruction of the 2004 tsunami damage (Pereira and Ratnayake 2013). A watershed strongly affected by sand mining is the Nilwala River (Map 3.5). The increased extraction of sand since 1997 has led to a lowering of the riverbed. Since 2008, the Nilwala's riverbed is 4.5 m below sea level in the estuarine reach near Matara, and does not reach sea level until 28 km upstream near Akuressa. As a result, seawater can move upstream during the dry season when the river discharge is low.

Consequences

The drinking water supply of Matara relies on the aquifers beneath the coastal plain. In the last 20 years, water supply wells located next to the Nilwala River have shown increasing salt concentrations and had to be moved further upstream. While the main production well used to be 8 km from the shore, it is currently located in Kadduwa (Map 3.5), more than 18 km inland (Piyadasa and Naverathna 2008). Agriculture and ecosystems in the region are also affected by increased salinity of the river water. For example, there are reports that 5,000 ha of paddy fields had to be abandoned (Weerasekera 2014).

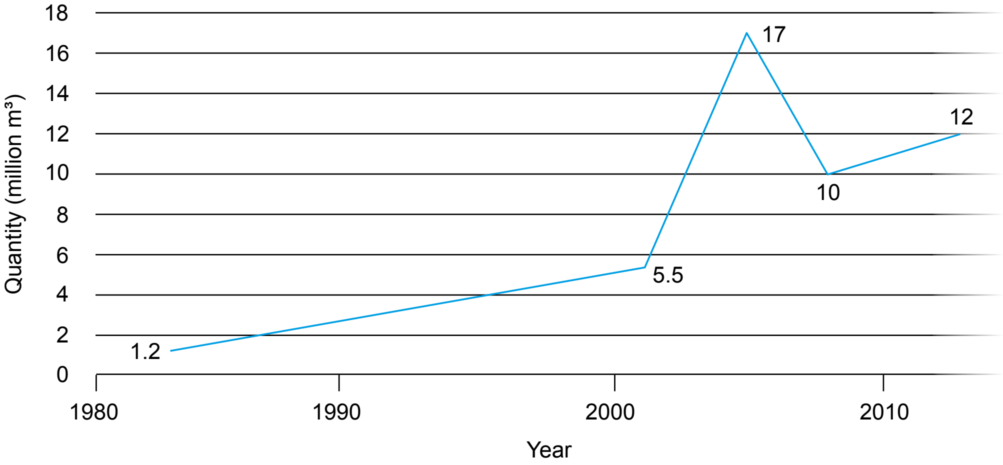


Figure 3.4: Estimated extraction of sand in Sri Lanka in million cubic meters

Efforts to reduce sand mining are undertaken by the Sri Lankan Water Partnership together with partners from academia, civil society and international organizations. Given that legislation to control sand mining exists but that compliance is fairly low, the focus is on raising awareness at law enforcement agencies such as the police and regulatory authorities for the environment and mining sector (Pereira and Ratnayake 2013).

4. Sustainable groundwater governance and management in coastal zones

As the examples in the previous example have shown, seawater intrusion is a key challenge for groundwater management in coastal zones. It is a problem that cannot be addressed merely by technical interventions. The following chapter explains why it is important to have groundwater governance in place when designing effective solutions to seawater intrusion problems. The role of monitoring for groundwater management will also be discussed.

4.1 Groundwater problems and governance

Groundwater resources – regardless of whether they are near the coast or inland – pose some general governance challenges which are linked to groundwater's 'invisibility'. Groundwater management is an urgent issue because the decreased predictability of rainfall and runoff patterns increases the dependence of economies and livelihoods on groundwater almost all over the globe. Often, this results in growing pressure on groundwater due to over-extraction and pollution. The Groundwater Governance-Global Framework for Action (FAO 2015), a joint international initiative led by the FAO, in a global diagnosis of groundwater governance, identified six key governance deficiencies:

- *Inadequate leadership from government agencies*
- *Limited awareness of long-term groundwater risks*
- *No measurement of groundwater resource status*
- *Non-performing legal systems on groundwater*
- *Insufficient stakeholder engagement in groundwater management*
- *Limited integration of groundwater in related national policies*

In many regions, well construction and pumping have for decades been considered as private enterprises, and the exploitation of the resource by individuals has been done without consideration of and coordination with other users (van Steenbergen et al. 2015). A joint management of the resource requires changes not only to administrative procedures but also to peoples' perception of the resource. Yet, unlike surface water, groundwater processes are more difficult to observe and quantify. For coastal areas, the complex hydrogeological processes at the saltwater/freshwater interface are thus not easy to visualize for non-experts.

Definitions of governance:[1]

From an academic perspective, groundwater governance describes the set of formal and informal rules, norms and institutions that govern the development and use of groundwater. This includes all structures and processes of decision-making, planning and implementation of groundwater development and management that are in place in a particular region. Thus, groundwater governance is negotiated (formally or informally) between various actors, and

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[1] *Based on definitions from OECD (http://www.oecd.org/governance/oecd-principles-on-water-governance.htm) and GWP (https://www.gwp.org/en/learn/iwrm-toolbox/About_IWRM_ToolBox/)*

hence embedded in regional and local power relations. Good governance is a normative concept. Generally, it refers to governance systems focused on economic, ecologic and social sustainability based on transparent, equitable and participatory decision-making and management processes.

Groundwater over-exploitation in coastal zones is related to a set of natural and socio-economic processes that encompass both supply and demand sides. Regions with low surface water availability and (semi-)arid climates are generally dependent on groundwater. Water availability is often aggravated by climate variability and long-term change or groundwater pollution and changes in land use. Changing precipitation and runoff regimes make that groundwater is favored as a resource as it is perceived to be more resilient to climate variability.

Irrigated agriculture is a major driver of groundwater over-exploitation, alongside rapid population growth and urbanization, and water-intensive economic activities like large-scale tourism. Furthermore, the protection of groundwater-dependent ecosystems is a rising concern not only for biodiversity conservation but also for local economies, especially where ecosystems have an added value (e.g. as tourist destination).

Groundwater over-exploitation and the resulting seawater intrusion in coastal aquifers aren’t new problems. Several management approaches have been developed and tested around the world (Chapter 5) which include control of groundwater extraction as well as technical measures such as barriers and managed recharge. Evaluations of management methods has revealed that their effectiveness “depends on the degree of compliance with legislation and policy instruments and conflicts between regulators and groundwater users are common” (Werner et al. 2011: 1838). This highlights the importance of good governance structures and processes that enable the implementation of sustainable management practices and policies for coastal aquifers. Several coastal regions have made important progress by reforming water laws and administration, while others are still underway to form joint and effective action in aquifer management.

4.2 Observed problems in coastal groundwater governance

Several studies identified governance problems of coastal aquifers in different regions and development contexts (Table 4.1). In southeastern Spain, coastal aquifers are regarded as crucial to support intensive agriculture for European markets. Growing demand and climate variability has provoked over-exploitation and saltwater intrusion has occurred in many aquifers of the region. Among the efforts to reduce groundwater abstraction has been the development of alternative water sources via desalination and inter-basin water transfers. Farmers still preferred groundwater though because the overall final costs are lower, as the change to an alternative water source often requires significant investments in a farm's water distribution network (Custodio et al. 2016).

Table 4.1: Summary of governance problems found in the three regions discussed in this chapter.

SE-Spain *(Custodio et al. 2016)*	– Inadequate monitoring, control and administrative means – Lack of detailed studies – Inflexibility of legal instruments for water rights allocation and difficulty to align them with social interests and common values – Insufficient consideration and fostering of water user participation – Excess of paternalism in governmental institutions – Scarce political will
East Africa *(Comte et al. 2016)*	– Poor participation of local stakeholders and knowledge – Lack of centralized groundwater information – Development projects do not take into account local conditions – Mismatch of management criteria and technical criteria
Coastal California *(Brown et al. 2016, Nelson 2012)*	– Low participation of weaker and disadvantaged groups in groundwater decision-making due to lack of trust, knowledge, and/or resources – Inequitable groundwater decision-making – Water agencies see themselves as water supplier, not as water managers or stewards – High reliance on non-mandatory methods of extraction control

A study of coastal aquifers in three east-African countries (Comte et al. 2016) – the Comoros Islands, Kenya and Tanzania – revealed the challenge of matching effective groundwater management with abstraction well development that is fine-tuned to specific hydrogeological conditions of the respective coastal aquifers. Projects by international development agencies supported groundwater development in the three regions. In all cases there was a preference for the construction of deep, high-yield boreholes. These wells were supposed to be managed more efficiently via economies of scale than traditional shallow, large diameter wells. However, in the long-term the deep wells showed higher levels of salinity than the shallow wells. The findings show that the development of coastal groundwater needs to take into account local hydrogeological conditions and requires specific collaborative governance schemes able to coordinate and regulate many wells.

In the coastal region of California, multi-stakeholder inclusion in decision-making is a key element of sustainable groundwater governance as required by the Sustainable Groundwater Management Act of 2014 (Brown et al. 2016). However, in reality, economic, social and cultural barriers determine the engagement of the different stakeholders. A study by Nelson (2012) identified that (a) limited technical background knowledge, (b) limited trust in the powerful actors present in multi-stakeholder-platforms as well as (c) limited resources (e.g. of time and money) to participate in the meeting were obstacles to the active participation of weaker groups of water stakeholders (e.g. smallholders, farm workers).

A common element in all studies is that a considerable gap exists between legal framework and regulatory requirements and their implementation. An increased understanding of what really governs coastal groundwater decision-making is necessary to close this gap.

4.3 Understanding the actors in coastal groundwater governance

Every coastal region has its own specific configuration of relevant actors that have an interest in coastal aquifer management. Table 4.2 gives a generic overview on actors that are frequently involved in coastal groundwater governance.

This wide range of actors adds to the challenges of managing the environmental, social, economic and political processes of a region. In addition, many coastal economies are increasingly part of a globalized system that defines opportunities and constraints far beyond the influence of regional decision-making. For example, groundwater use of export-oriented agriculture depends on global markets, as in the case of the Souss-Massa region in Morocco (Section 3.2). The prices and demand on these markets often are central variables in the decision-making of farmers, which has consequences for water management.

Table 4.2: Example of different actor groups that have a stake in coastal groundwater.

Water supply and use	Drinking water supplier – Large utilities – Domestic supply (decentral) Water treatment / reuse – Sewage and wastewater treatment facilities – Desalination plants – Aquifer recharge facilities Water user groups – Domestic water user groups – Large commercial consumers (e.g. tourism) – Industrial water users Agriculture – Large farms – Smallholders
Public administration	Municipality – Public services – Environmental protection – Health authorities – Land-use administration Regional authorities – District administration – Water authorities – Agricultural services National authorities – National water board – Regulating authorities – Sector ministries
Politics and interest groups	Councils and parliaments (legislative bodies) Political parties and politicians Interest groups – Business associations – Farmer associations – Unions – Environmental protection organizations
Financing institutions	Public trusts and funds Development agencies and banks Private investors and financing institutions
Other institutions	Universities Consulting-business Drilling and well-construction companies International organizations

4.4 Towards a governance system for sustainable coastal groundwater development

The Groundwater Governance-Global Framework for Action (FAO 2015) summarized the following five basic principles for sustainable groundwater governance:

1. *Joint management of groundwater and other water resources in order to achieve water security and ecosystem health*
2. *Conjunctive management of groundwater and land resources*
3. *Co-governance of subsurface space (e.g. mining, infrastructure)*
4. *Vertical integration between local and national level*
5. *Coordination with macro-policies from other sectors*

A governance system ensures that all these principles can be implemented, not overnight, but as a permanent process which needs to be continually adapted to the specific conditions of each coastal area.

Bringing together actors with different, sometimes conflicting interests is an art. Different institutions have developed guidelines and learnt lessons that help to get participation in place (e.g. World Bank 2003). Approaches that help to put the train on the right track, as well as best practices to learn from, are discussed below.

Consideration of groundwater as a shared public resource

The definition of groundwater as a public resource is a basic principle of sustainable groundwater governance. It is important in two ways: in legal practice and in public perception. Private ownership of groundwater is a major obstacle to sustainably govern groundwater as a common resource (Mechlem 2016: 3). Even though some countries still consider groundwater as a private resource linked to land ownership, the concession of groundwater use rights is more and more becoming the prevailing legal practice. Changes in legislation need a lot of time and tenacity. Moreover, even when legal changes occur, adapting the public perception of coastal groundwater as a vulnerable resource remains vital for the long-lasting implementation of sustainable groundwater use and management. Although changing the “water paradigm” of a region is complex endeavor, some successful examples can be found (see box on the right).

Almeria, Spain: Awareness raising for groundwater protection

The program Acuiferos del Poniente (aquifers of Poniente) existed in the southeastern coastal region of Almeria, Spain between 2008 and 2012. It brought together the regional Andalusian water council, the public ACUAMED company in charge of Spain’s hydraulic infrastructure, the National Institute of Geology and Mining and the groundwater users association of the region. The objective of program was to support the sustainable management of aquifers. To this end, it promoted the reduction of groundwater extraction from the deeper coastal aquifers, the replacement of the reduction by alternative water sources, and the increase of pumping from the shallow aquifers of the region. Part of the program was the diffusion of groundwater information at different levels to raise awareness of the critical water situation of the region. The campaign focused on three groups. To the professionals and decision-makers of the agricultural sector, the problem and impacts of groundwater over-exploitation were presented at regional trade fairs. The topic was also introduced into the curriculum of agricultural training institutions. A second focus group was the education sector: the program – in collaboration with the regional educational authority – developed didactic materials for use in primary and secondary schools and trained teachers to integrate the topic in their curriculum. A third part of the campaign was aimed at the general public: an exhibition showing the groundwater situation and its challenges toured through various towns of the region. The exhibitions were promoted in mass media and accompanied by opening talks with local stakeholders. Altogether about 20,000 persons participated in the awareness activities of the program. This made the program an important step to trigger change in the attitude of water users towards sustainable groundwater management.

Source: Agencia Andaluza del Agua (2009)

Adaptive governance and participation

A major lesson learnt from the discussion on proper (ground)water management is that traditional command-and-control-approaches prescribed by external technical experts generally fail to solve to complex groundwater issues such as over-extraction and seawater intrusion. Especially those measures that need actors to change their practices – for example farmers to reduce pumping – will hardly work if the relevant stakeholders do not have ownership of the defined rule. Consequently, integral and participatory approaches constitute the state-of-the-art in groundwater management as laid out in international principles and guidelines, like the European Water Framework Directive or OECD Principles on Water Governance. Adaptive management is meant to be an iterative cycle (Figure 4.1), in which policies and management measures are constantly revised and adjusted to changing conditions and uncertainty (Pahl-Wostl et al. 2007). The definition of the problem, the design and revision of policies and decisions to work on the problem are part of a joint process with participation of all relevant stakeholders. The main objective of this process is to increase the quality of decisions but also their acceptance and implementation. Another aspect of stakeholder participation is the process of social learning facilitated by the exchange between actors with different perspectives. Social learning builds on the insight that the entire collection of views from different angles is greater than the sum of its parts.

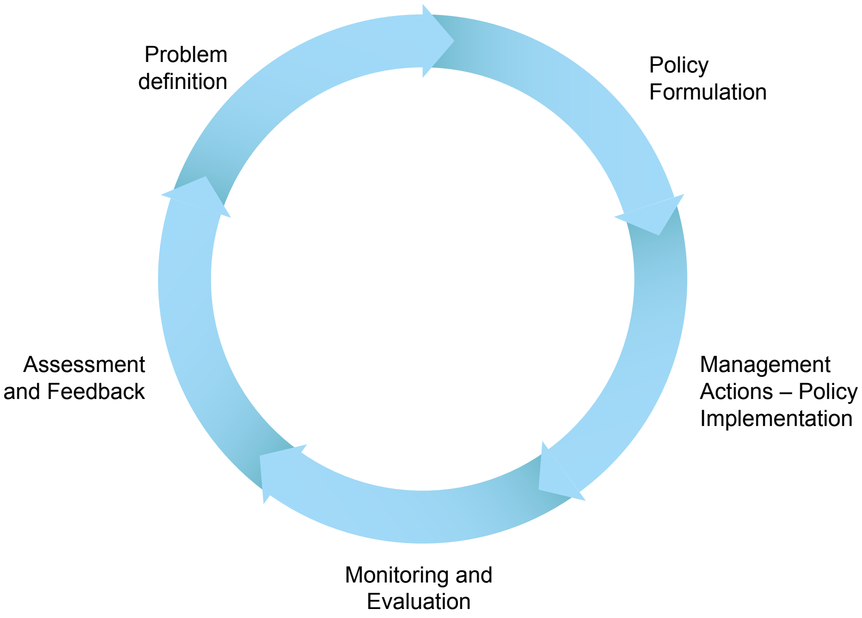


Figure 4.1: Iterative cycle in the adaptive management process (Pahl-Wostl et al. 2007)

Oman: Groundwater demand management via pre-paid energy supply

The Batinah coastal area of Oman hosts about 53% (74,000 ha) of the country's farmland irrigated with groundwater. Irrigation water is pumped from about 100,000 wells, of which 74% run on electricity. The aquifers of the region are currently under serious pressure as the extraction exceeds the safe yield and saltwater intrusion is occurring in various zones. The government of Oman decreed several measures to protect the aquifer and regulate groundwater use, including the delineation of protection zones, and drilling and pumping restrictions. The legislation also determined sanctions and fees. To reduce the extraction rates of existing wells, authorities allocated a water quota to each farm based on their acres of irrigated land. As the direct flow measurement of pumped water is quite expensive, a system to control pumping energy consumption through a prepaid energy supply system was designed.

For that purpose, the water quotas are converted into pumping energy equivalents, taking into account the depth of the well and the capacity of the pumps. The prepaid meter stops energy supply once the groundwater extraction exceeds the allocation. To avoid critical water stress, the meter warns of low credit and emergency credit. The quota-based approach allows the farmer also to sell or buy quotas, rewarding water-saving irrigation and giving flexibility to bigger farms.

The system's central database stores water and energy quotas as well as information on farm size and crop types. Before irrigating their fields, farmers have to charge their energy credit in order to activate the energy-smartmeter connected to their pump. The purchase of energy credits is possible with an online tool or cell phone. During the buying-process, the system checks the farmer's energy account for any remaining energy quota as well as their bank account for sufficient funds. The system can also generate warnings in the event of excessively high or low consumption rates.

The approach has been tested in a field study with 40 water users. Crucial for the success and acceptance of the water and energy quotas has been the inclusion and active participation of stakeholders, mainly farmers, in the process. This included explaining of the quota allocation formula and the technical details of the billing procedures.

Source: Zekri (2009)

Adaptive management especially fits into the context of coastal aquifers as seawater intrusion processes are slow and hard to forecast, and affect many actors in the coastal regions. However, in order to succeed, the participatory approach has to be accepted by the relevant actors and embedded in the institutional policies of the authorities in charge. Groundwater governance concepts also highlight the importance of “socializing” groundwater among stakeholders (Moench et al. 2015). This process operates in two directions. In the one, water managers try to reach a common understanding with water users about the long-term effects of aquifer over-exploitation and threat of seawater intrusion. This aims to raise awareness about the vulnerability of groundwater resources and promotes the concept that compliance with sustainable groundwater management plans and principles is in the groundwater users' own interests. In the other direction, groundwater managers may benefit from an increased understanding of groundwater´s relevance means for the economic activities and livelihoods of the groundwater users. By focusing more on the objectives of groundwater uses in terms of the productive outcomes (Moench et al 2015: 25), new and unconventional ways to manage aquifer over-exploitation become thinkable. For example, a holistic water management approach can support farmers in finding a way to cope with crop losses that they may suffer by not pumping irrigation water from the aquifer during a drought. Other examples of support mechanisms include formal and informal water markets, crop and drought insurance programs, or food for work-programs (Moench et al. 2015).

4.5 Monitoring of coastal aquifers – cornerstone of management and governance

Good governance forms the enabling environment for a proper and careful management of coastal groundwater. The basis of such management is the knowledge about what is managed. This includes static data, like aquifer properties, but also dynamic data like groundwater recharge and abstraction rates. A well-designed monitoring system and database from a further prerequisite for the enforcement of regulatory instruments like well licensing and abstraction permits.

Data that indicate the state of the groundwater resources include measurements of water levels as well as the groundwater salinity and chemical composition. Water level measurements and water samples for chemical analyses require a network of observation wells and, because they provide direct access to the groundwater, these monitoring efforts are called direct methods. Salinity data can also be inferred from geophysical measurements made at the land surface or the sky, and these are called indirect methods. Which method or combination of methods is applicable to an area depends on the local conditions such as the geology, the dynamics of the groundwater flow processes (e.g. variations of recharge, tidal fluctuations, pumping), the scale of the system (depth and geographical extent) and the salinity distribution.

For surficial aquifers that receive recharge from rainfall, meteorological records of precipitation and evaporation provide the basic information to infer the recharge rates. The flow in coastal zones can be complex though and recharge to an aquifer may derive from sources other than rainfall, such as rivers, or upward flow from a deeper aquifer. An integral appraisal of the flow components is therefore the first requirement for a proper assessment of the salinization processes.

In areas where groundwater is abstracted, falling water levels are a first indication of the risk of seawater intrusion. Seawater may already start to flow towards the wells before water levels drop below sea level, because seawater has a higher density than fresh groundwater. Water levels alone are therefore not enough to assess the risk of salinization, and salinity monitoring near pumping wells must always be done as well.

4.5.1 Salinity

Salinity can be deduced from measurements of the electrical conductivity of groundwater. This is because the higher the salinity of water, the more electricity it can conduct. Because electrical conductivity is relatively easily measured, for example using handheld devices, it is a quick and cost-effective method to determine changes of salinity over distance and time. The electrical conductivity of seawater is much higher than that of fresh groundwater so seawater intrusion is recognizable as a significant increase in the values of electrical conductivity. The dissolved chloride (Cl^-) concentration is also a powerful indicator of seawater intrusion, because it is many times higher in seawater than in freshwater. Unlike electrical conductivity, however, it can not easily be measured in the field, and samples must be brought to a laboratory to measure its concentration.

Geophysical methods are well suited to provide an overview of the spatial variability of the salinity of groundwater. Different techniques exist and instruments may be operated at the land surface, at sea, or from the air (Figure 2.8). The principle of the method is that the electric or magnetic field that is measured is influenced by the electrical properties of the subsurface, which is a strong function of the salinity of the groundwater. It is, however, also partially determined by the nature of the rocks, and therefore, the electrical conductivity (or the reverse, the resistivity) is not easily converted to a groundwater salinity value. Despite this limitation, geophysical methods are used frequently to investigate coastal aquifers.

4.5.2 The “ideal” monitoring well

The salinity distribution can change over short distances, both horizontally as well as vertically. Aquifers near the coast are likely to be characterized by a distinct change of salinity with depth (Figure 4.2) and a single well to characterize the salinity distribution is insufficient. Instead, several observation wells

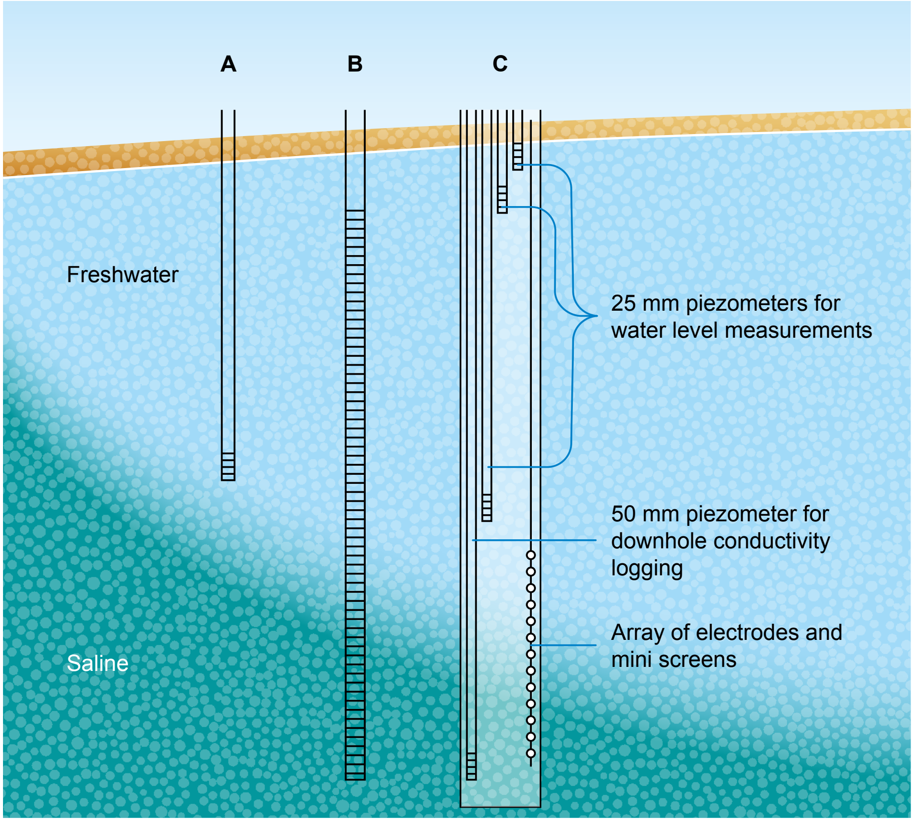


Figure 4.2: Schematic cross section of a coastal aquifer with three different observation well designs. (A) single well with short well screen in freshwater zone, (B) single well with long well screen in the transition zone; (C) sophisticated multi-level observation well with electrode system (Kamps et al. 2016).

are required to provide information on the depth-dependence of the groundwater salinity, which adds to the cost of the investigation. This information is indispensable, however, as monitoring at the wrong depth may result in seawater intrusion going unnoticed. Wells with long screens (several meters or more) are sometimes used to investigate the characteristics of the seawater-freshwater mixing zone, but their use should be avoided because the flow of water through the borehole disrupts the natural conditions in the aquifer and may result in local salinization of the freshwater lens.

Short well screens are preferred instead and can either be installed in the same borehole, provided that effective seals are used to prevent cross-borehole contamination, or in separate boreholes. Well configuration C in Figure 4.2 shows an example of one of the most advanced monitoring systems as used by the Amsterdam Water Supply Company (Waternet) in the Netherlands. It has 3 piezometers and a series of 13 closely-spaced mini-screens and electrodes with which the location of the transition zone can be determined very accurately. Sophisticated well designs such as in this example may not be feasible everywhere. Yet it shows the importance of taking the vertical dependency of salinity into account. Good guidance for the development of a coastal aquifer monitoring plan is given by the FAO (1997).

4.5.3 Water chemistry

A comprehensive analysis of the chemical composition of the water can reveal important information about the progress of seawater intrusion. For example, when seawater displaces freshwater in an aquifer, cations will be exchanged between the solid particles and the water. The chloride (an anion) in the seawater-freshwater mixture is not affected. Even if a small fraction (< 1%) of seawater mixes with freshwater, the sodium (Na^+) will already be exchanged for other ions like calcium (Ca^{2+}). This means that before seawater intrusion becomes apparent as a significant salinity increase, the Na/Cl ratio will already start to decrease noticeably (Figure 4.3). This ratio may therefore be used as an early-warning indicator of seawater intrusion. Care must be taken though because other hydrochemical processes may also cause ionic ratios to change.

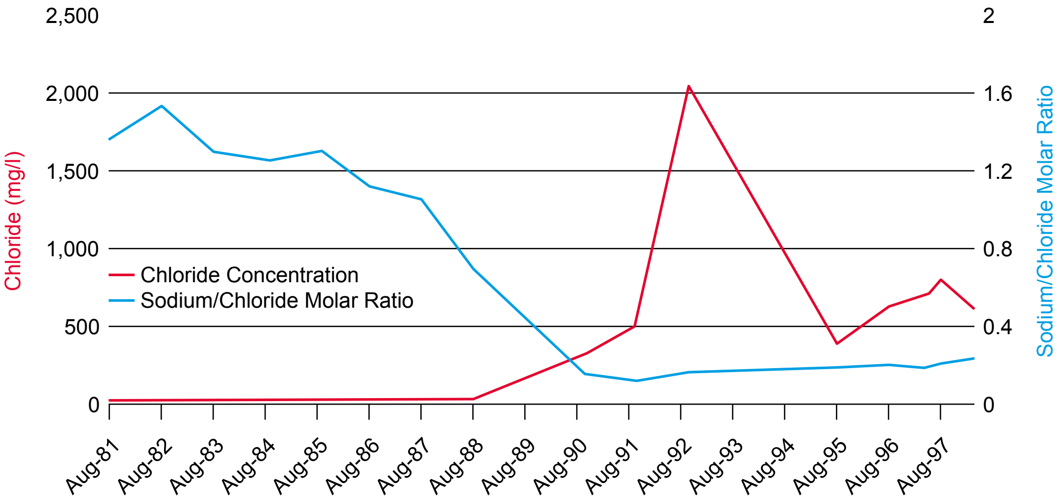


Figure 4.3: Graph showing the change of the chloride concentration and the Na/Cl ratio of a well affected by salinization in California, USA (HydroMetrics 2008).

Comprehensive chemical analysis also aid in establishing the origin of saline groundwater. The source of dissolved salt in groundwater is not always seawater and interpretation may be ambiguous if other sources are present. These may include:

- *Old seawater trapped in stagnant parts of the groundwater system*
- *Atmospheric dust and sea spray*
- *Evaporite rocks*
- *Irrigation return flow*
- *Anthropogenic sources*

A large variety of chemical substances in groundwater can be used to identify the salinity source. Isotopes of water and its solutes can contribute as well, and can also provide information on the age of the groundwater. In areas that experienced a complex geological history, understanding the processes that cause salinization can be challenging.

5. Strategies and solutions

This chapter presents examples of groundwater management strategies that have proven to be effective to prevent and control seawater intrusion. These have to focus on the aquifer itself, but also consider groundwater as an integral part of coastal water resources management. As the conditions in each coastal region are different, site-specific solutions are required.

The management approaches described in this chapter can be classified into four different categories:

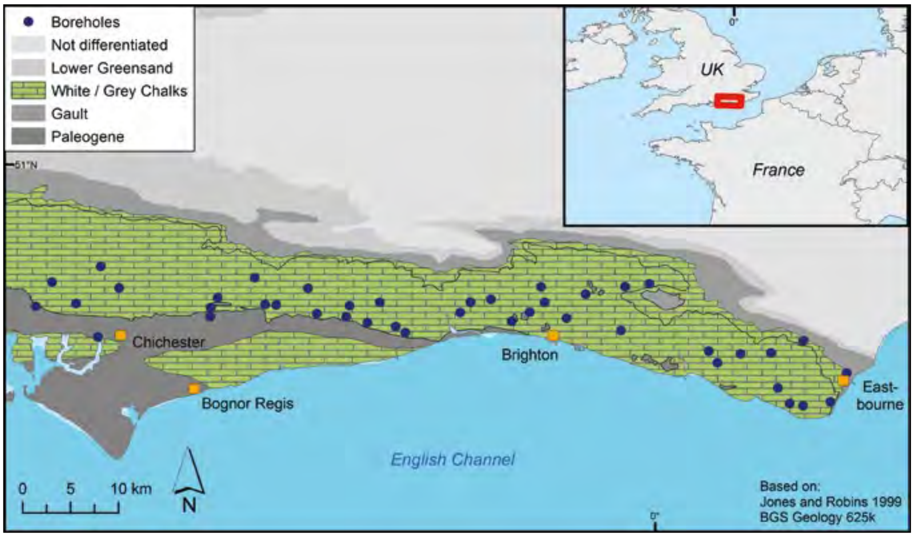
- *Optimized groundwater abstraction approaches (Section 5.1)*
- *Demand control approaches (Section 5.2)*
- *Enhanced aquifer recharge approaches (Section 5.3)*
- *Engineering approaches (Section 5.4)*

All strategies in this chapter are illustrated by selected cases from different coastal regions in the world. For each case the nature of the problem, the technology and the implementation of the control measure is described.

5.1 Optimized groundwater abstraction approaches

This section presents two cases that illustrate the role of abstraction management strategies to prevent seawater intrusion. These require detailed knowledge of the groundwater system and understanding of the dynamics of the transition zone between seawater and freshwater. The examples underline the importance of well-designed monitoring networks that provide the necessary data to quantify the relationships between groundwater recharge rates, abstraction and salinization processes. The case of South Downs in England is an example of a long-term management strategy that has been evaluated and modified from time to time. The importance of numerical modelling is exemplified by the case study of Kiribati. It follows that successful groundwater management is a highly-specialized task that requires the close collaboration of hydrogeologists and other specialists such as engineers, responsible agencies and decision makers.

Case 1: Alternating pumping wells (South Downs, England)



Map 5.1: Location map South Downs, England, showing basic geology and public water supply boreholes (Jones and Robins 1999).

Introduction

The limestone aquifer in the coastal area of the South Downs in England (Map 5.1) supplies about 70% of the water demand of the area. It is susceptible to seawater intrusion but due to the fissured nature of the chalk, a well-defined wedge of intruded seawater has not formed. Instead, the distribution of groundwater salinity is highly irregular, and inland wells may have higher salinities than ones nearer to the coast. The salinities also vary with time and respond to changes in water level, tides and abstraction.

Management approach

Groundwater is being abstracted from a total of 46 wells, and the total amount withdrawn is 25% of the recharge on average. During dry years though, this percentage can exceed 60% (Robins et al. 1999). Because of resultant salinization problems a sophisticated abstraction policy was introduced as early as 1957. Coastal boreholes are preferentially pumped during the winter months, intercepting freshwater outflows but allowing the water levels in the inland boreholes to recover (Figure 5.1). During summer the situation is reversed, with inland boreholes being pumped to utilize the groundwater storage that built up over the winter months (Robins et al. 1999).

The net result of this policy has been an effective rise in the water levels around the inland boreholes, and thus a considerable increase in available storage and abstraction potential. A 33% increase in abstraction could be achieved with a simultaneous rise in average groundwater levels of 1.6 m. This provided sufficient increase of the water levels to restrict seawater intrusion and led to a widespread reduction of the groundwater chloride concentrations. During the drought from 1988 to 1992, when winter rainfall was 20% lower than the long-term average, some water uses were not permitted and water levels fell, but supply could be maintained.

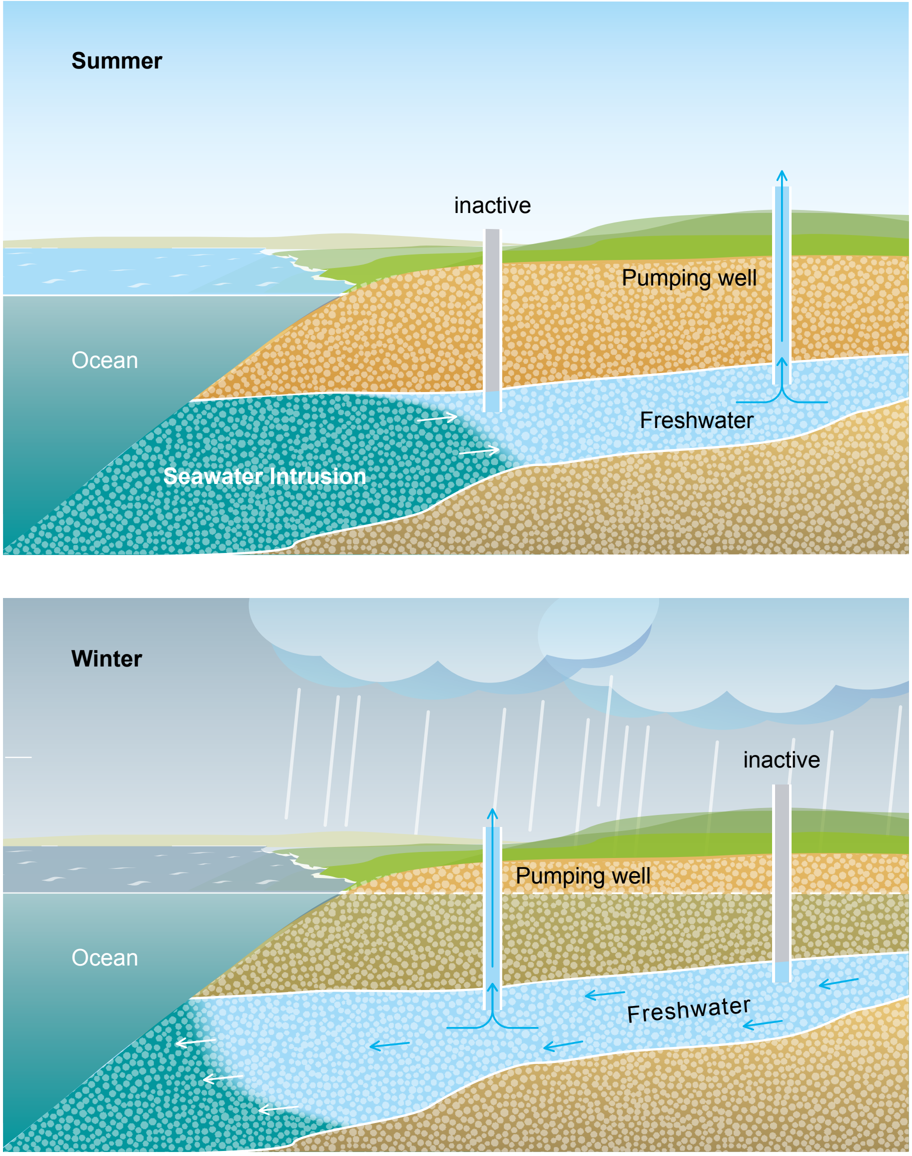


Figure 5.1 Schematic illustration of the principle of alternating abstraction wells to prevent seawater intrusion. In summer, when recharge is low, groundwater is pumped further inland only to prevent seawater intrusion. In winter, when recharge occurs, the water can be pumped near the coast, allowing groundwater levels further inland to recover.

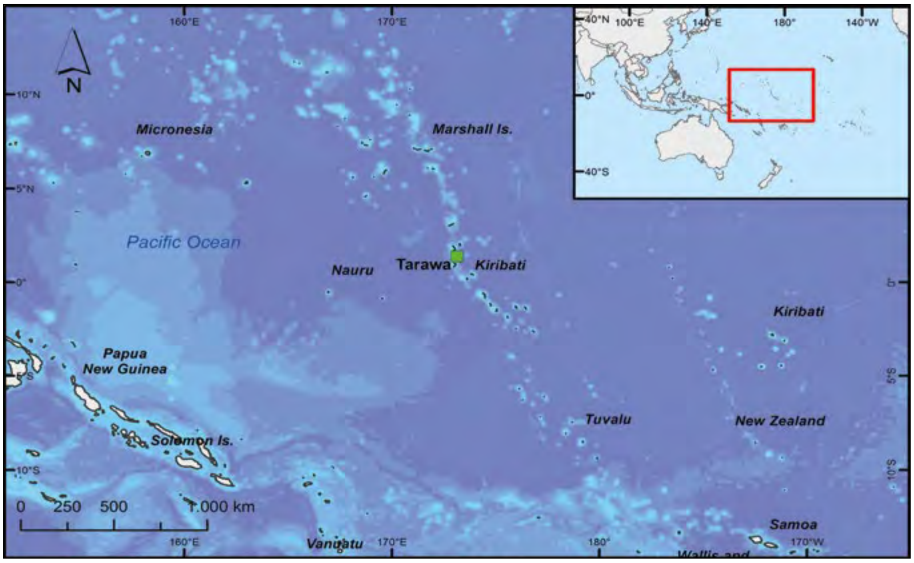
Results

Problems related to the implementation of the management scheme were mainly of an operational nature. For example, the linkage between sources posed some difficulties, and there were high financial and energy costs associated with the transport of water over large distances. This meant that not all policy recommendations could be followed, and a lack of feedback from the operational side made it difficult to assess to what degree the recommendations were being implemented.

Despite these problems, the management scheme has clearly been successful in safeguarding the freshwater supply. The factors that contributed to this success can be considered as key factors for a successful implementation of management strategies in other coastal areas as well. They include:

- *A sound conceptual understanding of the aquifer system with sufficient hydrogeological data, which was updated when new data became available (Robins and Dance 2003).*
- *Effects of the abstractions were closely monitored by determining chloride concentrations and water levels in observation wells.*
- *Abstraction was controlled by a clear policy and licensing system.*

Case 2: Water management system for a hydrogeological system (South Tarawa, Kiribati)



Map 5.2: Location map Tarawa, Kiribati

Introduction

In atoll islands, the water supply is largely reliant on a lens of fresh groundwater ‘floating’ on a body of brackish water. The Republic of Kiribati is a country in the Central Pacific region (Map 5.2) that consists of 33 atolls spread across an area of approximately 5 million km². With a population of almost 60,000 people in 2015, the southern part of the Tarawa atoll is the main urban area in Kiribati. The residents are supplied with water sourced from the freshwater lenses on Bonriki and Buota Islands.

The Bonriki lens was declared a water reserve in 1977. Abstraction of groundwater started in the 1970s and was expanded in the decades that followed. To reduce the risk of saltwater up-coning, the abstraction is by means of a system of horizontal wells, called infiltration galleries. The number of galleries grew from initially 4 to 22 in 2003, and the abstraction rate that is currently considered to be sustainable is 1,660 m³/day.

The status of the lens as a water reserve means that settlement, sand and gravel mining and agriculture are forbidden. The enforcement of these regulations has been problematic, and as a result, there is a high risk of contamination of the freshwater. Ongoing pumping also makes the lens more vulnerable to salinization during droughts, and therefore the current management practice of a constant abstraction rate is being reassessed (Galvis-Rodriguez et al. 2017).

Management approach

The state of the lens is monitored by means of a system of observation wells from which every three month the salinity is measured every three months. The rainfall is measured daily, and with these data, the response of the lens to rainfall and abstraction can be established. The data show that since the 1980s the lens has become thinner, and that the salinities of the abstracted water nowadays show a stronger response to rainfall than in the past.

One of the future management approaches that is currently considered involves a dynamic pumping regime, in which wells are turned on and off depending on the rainfall and the salinity of the abstracted groundwater. Based on pre-defined salinity threshold criteria a well may be turned off during a drought period, and turned on again if the salinity of the groundwater remains below a certain level for a certain period of time. As a consequence, less water can be supplied from the freshwater reserve, but at the benefit of the long-term sustainability of the lens.

The reduced availability of groundwater during a drought means that other water supply options, such as desalinized seawater or rainwater, will be required. To assess the socio-economic impacts, the future availability of groundwater needs to be known, and this can be estimated based on numerical modelling. Within the framework of the CAIA project (Galvis-Rodriguez et al 2017), a numerical model of Bonriki Island was developed and calibrated to the dataset of existing salinity measurements. The calibrated model was then run 30 years into the future, based on certain assumptions about future rainfall patterns, land use and abstraction.

Using the model, different management scenarios were tested and compared to a base case scenario for an assumed future rainfall distribution. In the base case, two 3 year droughts occur and land use remains unchanged. It was compared to a scenario with management rules, where wells that exceed an electrical conductivity (EC, a measure of groundwater salinity) threshold of 1,000 μS/cm are switched off, and remain off until the EC drops below 900 μS/cm. Figure 5.2 shows the development of EC over time. It can be seen that without additional management, current abstraction rates could lead to regular exceedance of the threshold limit of EC = 1,500 μS/cm, which is the level still accepted by the community for potable water. The adaptive management scenario indeed reduces the impact of drought on the salinity of the pumped water.

Results

Based on the numerical simulations, a set of future management options has been recommended to the government of Kiribati. At the time of writing of this publication, the decision-making process was still ongoing. The study also made clear that other developments can have significant impacts on the freshwater lens. The clearing of coconut trees for example to make room for a photovoltaic power plant in September 2015, has led to an increase of groundwater recharge, which is beneficial to the lens (Galvis-Rodriguez et al. 2017).

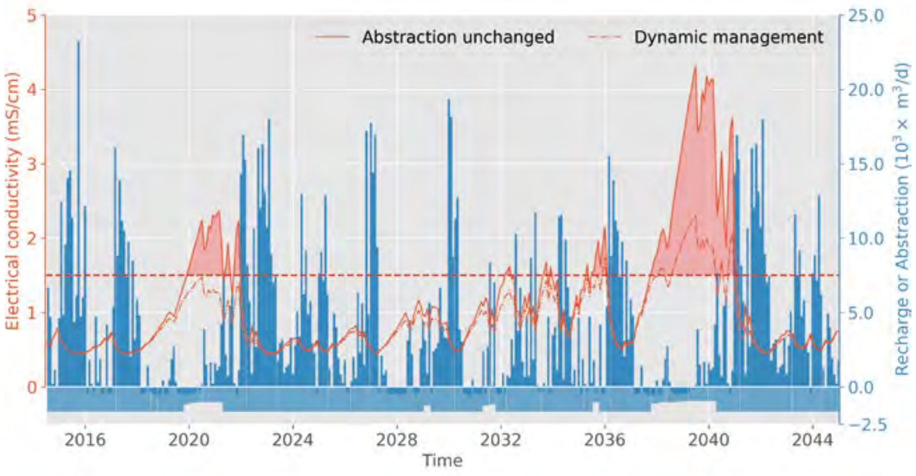


Figure 5.2: Simulation of different water management options. A constant abstraction rate of 1,660 m³/d often leads to a high electric conductivity of over 1,500 µS/cm, whereas reduced abstraction during droughts mitigates salinization but at the expense of reduced water availability.

5.2 Demand management approaches

Good water resource governance needs to ensure that the demand is commensurate with the capacity of the natural system to deliver water for human needs. Apart from minimizing the risk of over-exploitation, keeping the demand as low as possible has several other advantages, such as the reduced energy and monetary costs for water supply, less need for wastewater treatment and higher water availability of water-dependent ecosystems. The demand for groundwater can be reduced by the introduction of water tariffs, well licensing, and allocation limits or by setting incentives like subsidies for efficient irrigation technology or other water-saving technologies. Some examples were given earlier in Chapter 4. The case study presented in this section further illustrates this for a rapidly developing coastal region in China.

Case 3: Managed groundwater demand (Tianjin, China)

Map 5.3: Location map Tianjin, China

Introduction

The coastal zone of Bohai Sea is located more than 100 km southeast of the capital Beijing (Map 5.3) and is one of the most rapidly developing regions in China. With a population of around 15 million people (2013) and limited water resources, it is one of the water-scarcest regions of China. The city of Tianjin has annual renewable water resources of only 160 m³ per capita (Zhang et al. 2008). The economic development and population growth of the last decades has intensified the exploitation of groundwater resources (Hu et al. 2009). This led to pumping rates that exceeded the recharge by far and caused seawater intrusion into some of the coastal aquifers (Shi and Jiao 2014). Salinity problems affected the water supply of some 400,000 people and circa 8,000 irrigation wells were shut down (Shi and Jiao 2014: 2813). Some farmers continued to use groundwater for irrigation, which led to soil salinization and a reduction of farm yields by up to 60% (Chunmei 2000). Apart from seawater intrusion, groundwater abstraction resulted in land subsidence. The urban area of Tianjin was the most affected with an average annual subsidence of more than 10 cm in 1981. Due to measures taken in the 1980s, the subsidence rate decreased to 20 mm/year (He et al. 2006: 394) but by 2000 the cumulative subsidence since 1960 nonetheless measured approximately 3 meters in Tianjin city (Xu et al. 2009). Altogether, water availability and problems related to water (over-)abstraction are considered to be a major constraint to development (Song et al. 2011).

Groundwater demand reduction measures

Several measures have been implemented by the government to control groundwater abstraction, including:

- *Restrictions on groundwater abstraction and borehole drilling*
- *Setting water tariffs*
- *Reduction of the per-hectare water demand for irrigation*
- *Substitution of groundwater by alternative sources, such as water imports from other basins, wastewater reuse and seawater desalination*

Groundwater pumping was completely prohibited in the urban area of Tianjin in 1987. Water users had to apply for permission from a municipal authority. At the same time a tariff system was introduced which was modified in 1998 and 2002 (Table 5.1) to meet the policy goals and to promote water conservation efforts. Initially the agricultural sector – the largest water user – remained exempt from tariff charges and abstraction regulations (Kataoka 2010) and the obligation to introduce efficient irrigation technologies. In 2006, water metering was introduced for farmers in some areas. The regulation of agricultural water demand represented the greatest challenge.

Table 5.1: Water tariffs in Tianjin (Xu and Zhang 2006 cited in Kataoka 2010)

Year	For township enterprises (CNY/m³)	For petroleum and chemical corporations (CNY/m³)	Other enterprises (CNY/m³)
1987	0.05	0.12	0.0968
1998	0.50	0.50	0.50
2002	1.30 (in areas with tap water available: 1.90)		

The growing demand in Tianjin was met by wastewater reuse, water transfer from other basins and seawater desalination. Wastewater reuse in the industry increased from 40% in the 1980s to 74% in the 1990s.

A major water transfer project that diverts water from the Luan River to the city of Tianjin was completed in 1983. Due to water scarcity in the Luan basin, water has been diverted from the Yellow River instead since 2004 (Kataoka 2010). Additionally, the South-North Water Transfer mega-project diverts freshwater from the Yangtze River in southern China to the more arid and industrialized northern plains where cities like Beijing and Tianjin are located (Shi and Jiao 2014).

Results

The large water transfer projects since the 1980s have been especially important in decoupling Tianjin's huge economic growth from groundwater abstraction (Figure 5.3). In urban areas, groundwater decline and its adverse side effects – land subsidence and saltwater intrusion – have slowed down or even reversed (IGES 2007). Groundwater abstraction is now strongly regulated and effectively forbidden in the most critical areas. The implementation of water-saving technologies in agriculture and industrial production has increased (Zhang et al. 2016). However, drought periods continue to challenge the region's water resources and may increase the reliance on groundwater.

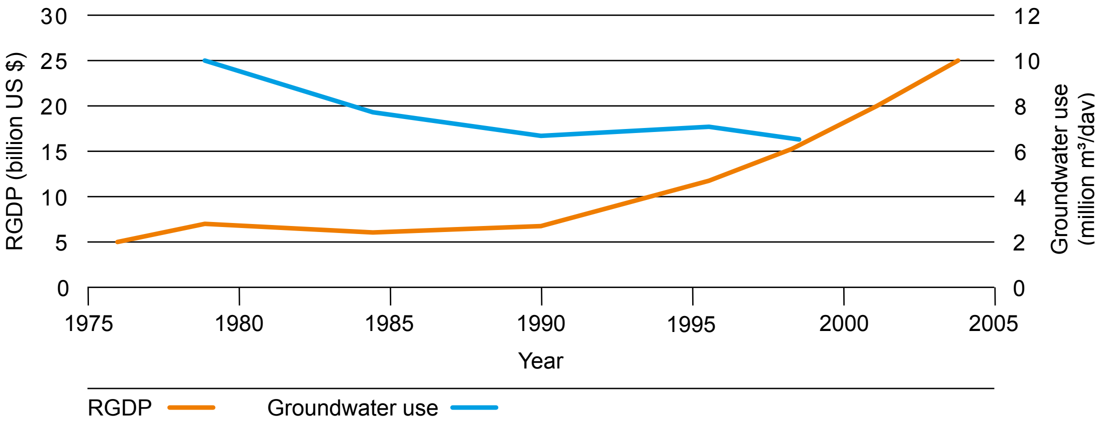
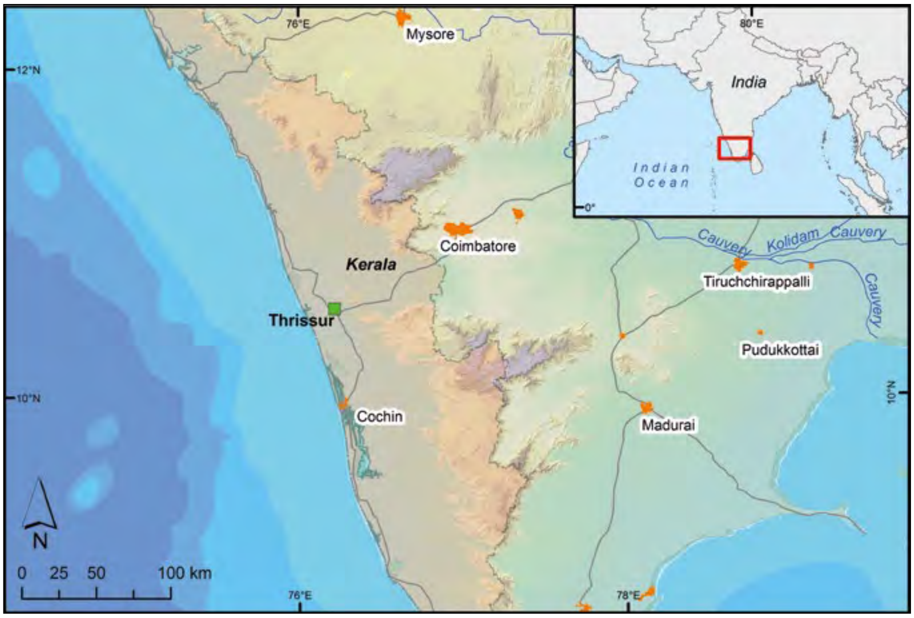


Figure 5.3: Regional gross domestic product (RGDP) and groundwater use (IGES 2007).

5.3 Enhanced aquifer recharge approaches

There are multiple measures that can be taken to enhance groundwater recharge. Some are linked to urban and land-use planning, like open space planning or decentralized stormwater infiltration. Moreover, changes in land cover may have beneficial side-effects for groundwater recharge, as for example the clearing of vegetation that has a high water use, if be socially and ecologically acceptable (also see case 2, Section 5.1). Underground storage of excess water when it is available is another approach, which is applicable especially in climatic environments characterized by distinct wet and dry seasons. During the wet season the water surplus can be injected into an aquifer and is stored there for use in the dry season. For successful implementation, it is important to have good knowledge about the storage and recovery capacity of the target aquifer, potential water quality changes and the harvesting potential based on precipitation data. This section presents two case studies of artificial recharge. The first (Kerala, India) is low-cost and can be implemented at the household level with simple technological means. The second (southwest Netherlands) requires more sophisticated technology and higher investments, and is meant to increase irrigation water availability at farms.

Case 4: Rooftop rainwater harvesting for dug wells (Kerala, India)



Map 5.4: Location map Kerala, India.

Introduction

In Kerala, on the southwestern coast of India (Map 5.4), around 80% of the households rely on groundwater. The water is sourced from shallow wells, which occur at a density of up to 400 wells per km² in the coastal region of the state. Despite the high annual rainfall of about 3,000 mm, which is concentrated in two monsoon seasons, there is limited groundwater recharge because the soil has a low infiltration capacity. Therefore the water table falls, and 70% of the shallow wells run out of water, during the dry summer months (Planning Commission-Government of India 2008). This has also resulted in saltwater intrusion along lagoons and tidal rivers, with illegal sand mining from coastal riverbeds intensifying the problem.

Technology

The high amount of rainfall during the monsoon months forms a high potential for water storage. In 2008 the Mazhapolima project (www.mazhapolima.org) developed infrastructure to harvest the water from rooftops and divert it into open wells with the aim to store it in the aquifer (Figure 5.4). Prior to injection, the water is passed through a filter made of sand and charcoal or through a textile filter made of nylon or cloth. Once the well is filled with water, it seeps into the surrounding aquifer. Since the start of the Mazhapolima project in

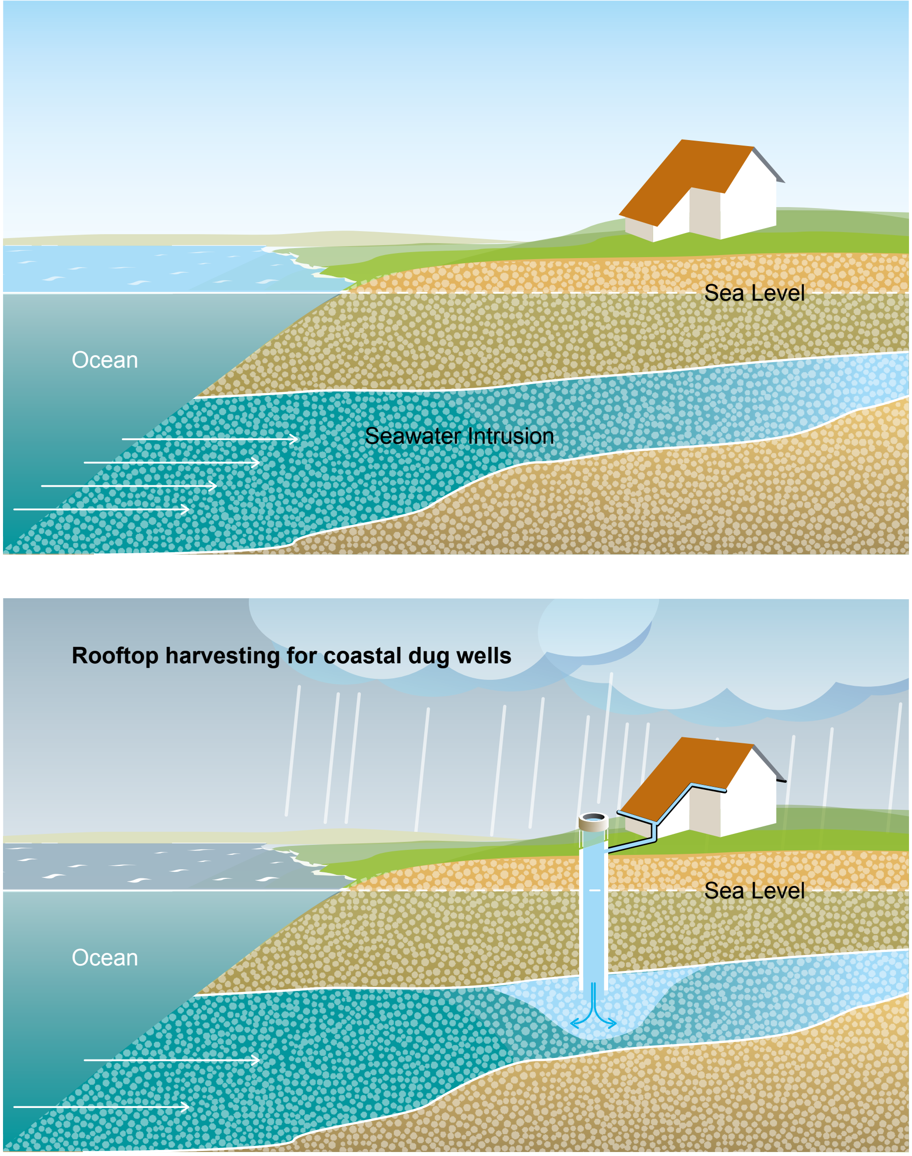


Figure 5.4: Rooftop water harvesting and infiltration into dug wells. When the salinity of the infiltrated water is lower than that of the aquifer, a local improvement of the groundwater quality may be achieved.

2008, 20,000 harvesting units have been installed. The costs for each unit range, depending on the type of filter, between 75 US$ (textile filter) to 100 US$ (sand and charcoal filter, Raphael 2014). In coastal regions the salinity of the infiltrated water is lower than the ambient groundwater, thus leading to a groundwater quality improvement near the wells (NITI and UNDP 2015).

While the dug wells facilitate the infiltration of rainwater into the aquifer they may also become pathways for aquifer contamination. There have been reports of wells that were used as dumpsites for wastewater, with the effect of bacterial contamination of the recharged water (NITI and UNDP 2015). Therefore, sound capacity building and monitoring of the water along the process (ambient groundwater, source water for infiltration, recovered water) and technical infrastructure (filters, wells) in the households are crucial for the success and sustainability of this approach. This includes an up to date and geo-referenced register of wells and infiltration facilities as well as the provision of knowledge resources to handle the dug wells, also when they are no longer being used as infiltration wells. Promotion of this approach should be coordinated with competent water authorities, or accompanied by programs to strengthen groundwater-user groups who are able to care for the protection of the aquifer (Chapter 4).

Case 5: Innovative freshwater lens management (Zeeland, the Netherlands)

Map 5.5: Location map Zeeland, the Netherlands.

Introduction

A large part of the Netherlands is at or below the seawater level. Groundwater resources in the country's coastal zones are therefore affected by salinization (Oude Essink et al. 2012), which poses a central challenge for the management of agricultural and drinking water supply. Climate change, sea level rise and land subsidence will place additional stress on freshwater, especially during summer. Brackish and saline groundwater is often found at shallow depths. In these areas, the water availability for agricultural activities depends on freshwater lenses that are formed by infiltrated rainfall in brackish or saline aquifers (Oude Essink et al. 2012). The lenses vary in thickness from > 50 m in dune areas, 5 to 20 m in fossil sandy creeks, to 1 to 2 m in polder areas.

Aquifer Storage and Recovery (ASR) can enlarge local freshwater lenses. The main advantages in comparison to surface water storage are that ASR requires a much smaller surface area (Zuurbier et al. 2013a) and that the water is not subject to evaporation. Especially in coastal zones with saline or brackish groundwater, the application of ASR requires high hydrogeological expertise, accurate knowledge on the aquifer characteristics as well as investments in technology and infrastructure. The recovery of stored freshwater can be negatively affected by lateral flow, density effects and dispersive mixing, as these reduce the amount of injected water that can be recovered. In the greenhouse area within the South Western Delta of the Netherlands (Map 5.5), innovative recharge technologies are being developed (Veraart et al. 2017)

Technology

The Freshmaker is a system that enlarges the freshwater lens during the winter by injecting freshwater from a nearby water ditch through a 70 m long shallow horizontal well (Figure 5.5). A second, deeper horizontal well continuously intercepts the underlying saline groundwater and discharges it into another ditch. The enlarged freshwater lens can thus be used for irrigation in the sum-

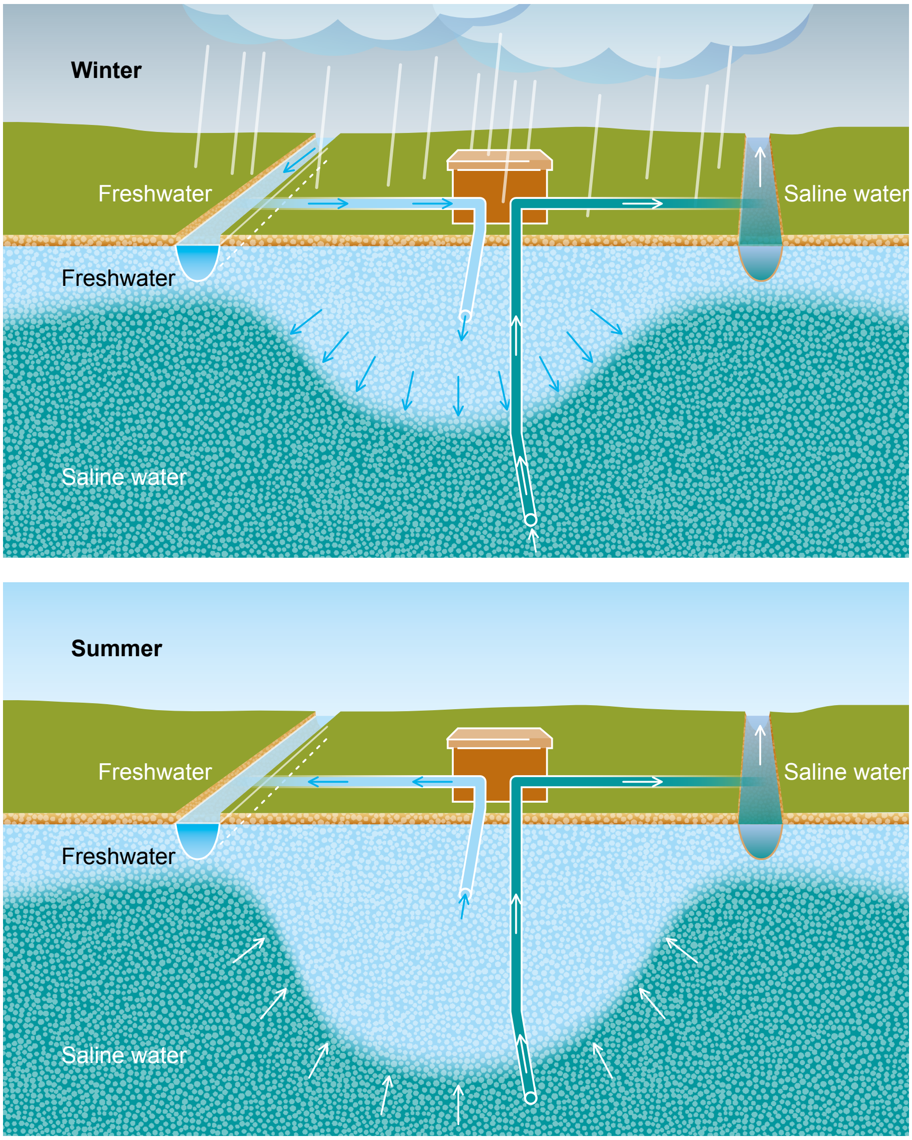


Figure 5.5: An artificial freshwater lens within the saline groundwater with available freshwater being infiltrated during the winter months and used for irrigation during the summer months.

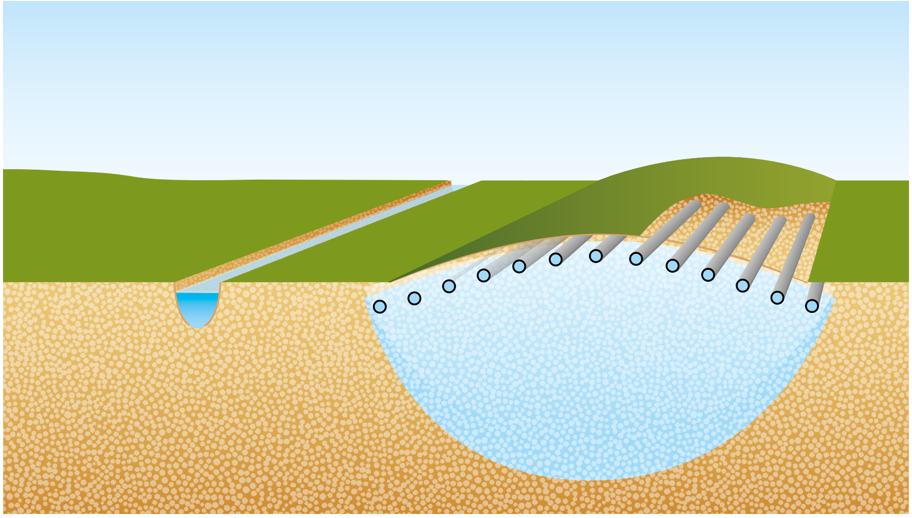


Figure 5.6: Creek ridge infiltration system. Freshwater is infiltrated into creek ridges through a drainage system at 1.20 m below ground level and enlarges a freshwater lens that is used for irrigation in dry periods.

mer (Zuurbier et al. 2013b), when irrigation water is in short supply. During a field trial, the fresh-salt interface was displaced downward from an initial depth of approximately 5 m down to the depth of the deep well. An additional freshwater volume of 4,200 m³ was thereby created. During the abstraction phase, the fresh-salt water interface moved up without reaching the upper well (Zuurbier et al. 2014). The estimated cost of water produced using this system is 0.35 €/m³, (Vink et al. 2010), whereas the local agricultural water service provider charges 0.60 €/m³.

In flat low-lying coastal areas, former tidal creeks can become slightly elevated above the surrounding land because they are filled with sandy sediments that are less prone to subsidence than the clay deposits in the adjoining area. Because of their higher elevation and higher permeability than the adjacent clay soils, some of these creek ridges contain a freshwater lens between 10 and 15 meters thick. In one such a freshwater lens in the southwestern part of the Netherlands (Zeeland province), water was injected to enlarge its volume during a trial in 2013. The infiltration was done via multiple tile drains at 1.2 m below the surface, which covered the entire width of the lens (Figure 5.6). An extensive monitoring network was designed to understand the groundwater processes and optimize the performance of the system. During the first month of the project, the groundwater level rose by 0.5 m and the fresh-salt interface moved downward by 15 cm.

5.4 Subsurface engineering approaches

Subsurface engineering solutions to prevent seawater intrusion are mostly cost-intensive and require a complex technical infrastructure. Therefore, they have seen limited uptake and only a few detailed descriptions exist in the literature. Two of these are presented here: hydraulic barriers (Los Angeles, USA) and underground dams (Shandong, China).

Case 6: Injection wells and hydraulic barriers (Los Angeles, California)

Map 5.6: Location map Los Angeles, California and locations of hydraulic barriers (Johnson 2007a)

Introduction

In southwestern Los Angeles County, two aquifer systems (the Central Basin and West Coast Basin, Map 5.6) are located adjacent to the Pacific Ocean. Groundwater abstraction from the early 1900s to the 1950s caused water levels to drop below sea level, allowing saltwater to intrude, rendering several wells out of service and threatening the usability of this major water resource. From the mid-1950s to mid-1960s, groundwater management agencies took regulatory and technological measures to stop the intrusion and control the overdraft. Given that the demand and the existing groundwater abstraction rights exceeded the natural recharge, artificial recharge schemes and fresh-water injection wells were established (Johnson and Whitaker 2004). A sophisticated monitoring and management program secures the quantity and quality of the resource. The successful implementation of these schemes makes that groundwater from both basins continues to be intensively used.

Technology

Groundwater in the area occurs in confined aquifers. Lines of injection wells along the coast create a hydraulic barrier that prevents seawater intrusion (Figure 5.7). Three lines of injection wells were built between 1953 and 1971 (Table 5.2), with wells reaching up to a depth of up to 213 m. In addition to the injection barriers, the Water Replenishment District (WRD) is also artificially enhancing groundwater recharge through sprinkler fields located in eastern part of the aquifer (Map 5.6).

Initially only treated potable freshwater was injected, but since 1995 this has been gradually replaced by treated wastewater (Chang 2013). For the years 2017/2018, the three seawater barriers are expected to require a total of 37.744 million m³ of water, and 86% of this amount is planned to be covered by recycled water (WRD 2017). Simulation models were used to optimize the injected water volumes and to identify optimal locations for new injection wells (Bray and Yeh 2008).

Barrier project	West Coast	Dominguez Gap	Alamitos Gap
Date started	1953	1971	1966
Overall length (km)	14.5	9.5	3.2
No. of injection wells	153	94	43
No. of observation wells	300	257	220
2012 injection amounts (million m³)	14.618	5.347	6.415

Table 5.2: Selected key metrics for the seawater intrusion barrier projects in Los Angeles (Chang 2013)

Results

Through the injection barriers further salinization of the groundwater was prevented. Moreover, owing to the advanced treatment of municipal wastewater, the barrier projects are close to being completely operated with recycled water and thus independent from imported freshwater. Groundwater thus continues to contribute about 40% of the water supply of the area (Johnson and Kirk 2012). However, great technical and financial efforts as well as the ongoing coordination between various institutions are required to maintain the scheme. For 2018, the WRD expected water replenishment costs of 25.6 million US$ (WRD 2017) for the three barriers. Future challenges, like an increasing demand, water quality protection and renovation of the aging infrastructure may further increase the costs (Johnson 2007b).

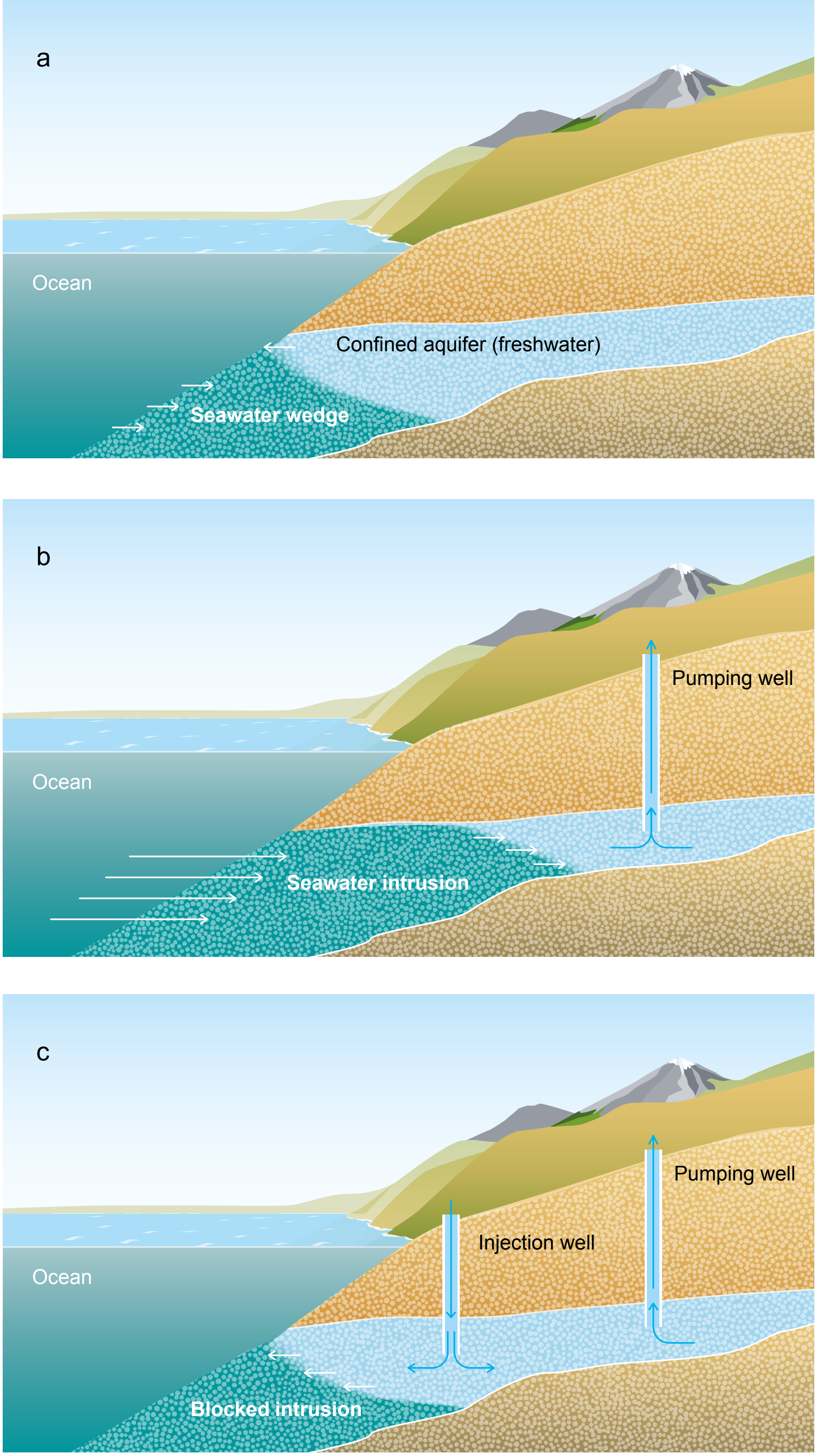
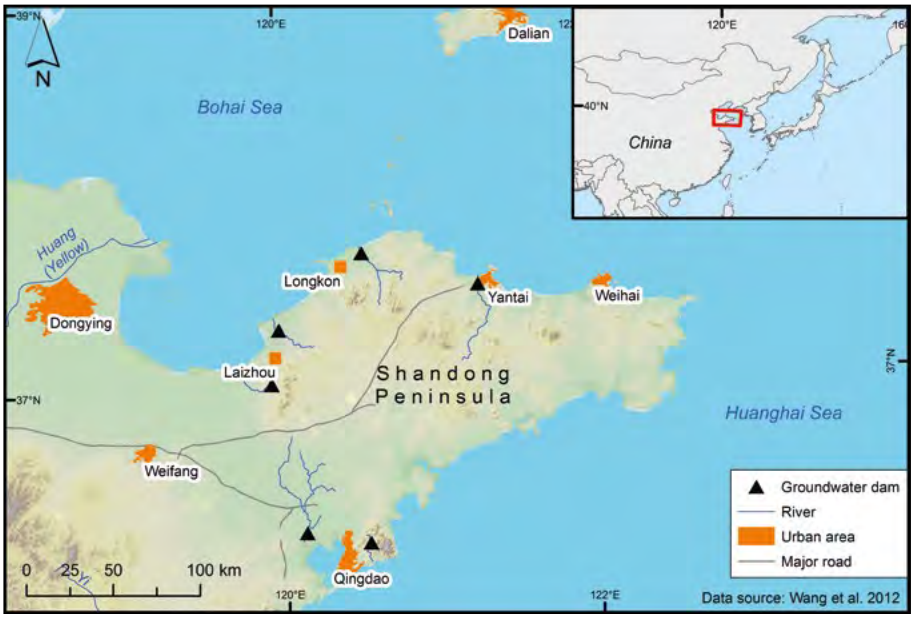


Figure 5.7: Seawater intrusion and barrier wells: a) Natural condition where fresh groundwater flows towards the ocean and there is minimal intrusion; b) Excessive pumping draws the water level below sea level causing seawater intrusion; and c) Injection wells build up pressure so that the water levels rise above sea level, blocking seawater intrusion. (Johnson 2007a)

Case 7: Salinity barriers (Shandong, China)



Map 5.7: Location map Shandong, China and location of groundwater dams (Wang et al. 2012).

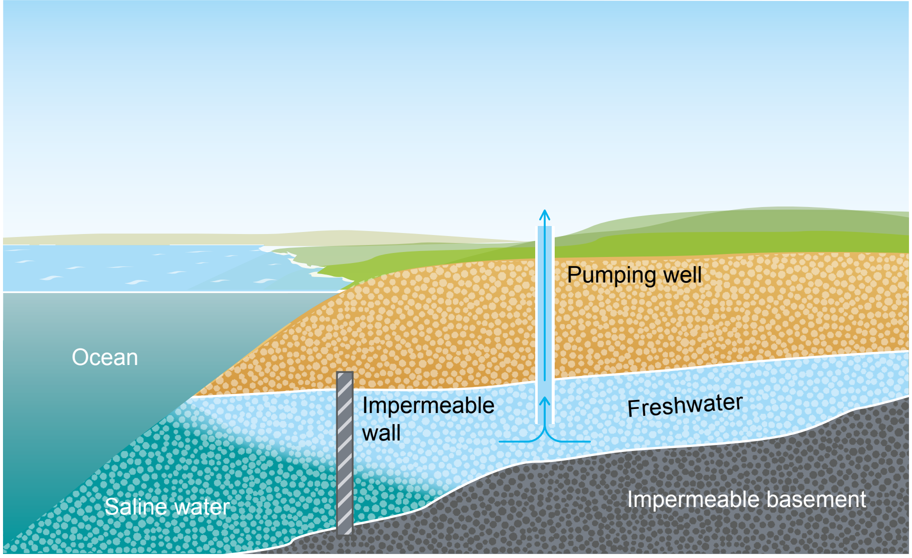
Introduction

Shandong Province is located at the southern end of the Bohai Sea on China's east coast. It has a land area of 157,100 km² and hosts a population of 95 million, about half of which live in urban centers, including 12 cities with more than 1 million inhabitants. The province's main water sources are river water (about 54%) and groundwater (about 44%). 90% of the rainfall falls during the summer monsoon period, and with an average annual water availability of less than 320 m³ per capita, the region is considered water scarce (Wu and Tan 2012). In 2006, the water shortage was more than 10% of the water resources annually available (Kutzner et al. 2006) and the growing economy let to an increased demand. Since the 1980s groundwater resources had been massively overused and a regional water level depression with an extension of 20,000 km² had developed, reaching the coastal area and causing seawater intrusion (Monninkhoff et al. 2010). As described in Section 5.2, case 3 seawater intrusion not only affected the potable water supply, but also agricultural production because of soil salinization.

Technology

To prevent further intrusion of seawater, eight underground dams have been constructed in the Bohai Sea area. The barriers have been constructed by injecting cement at high pressure into the underground to create an impermeable wall resting on an impermeable geological layer (Ishida et al. 2011). While the dams serve as a barrier for seawater intrusion, they also create an underground reservoir for the abundant monsoon rains (Figure 5.8). Infiltration wells, trenches and ditches have been built upstream from the dam to increase groundwater recharge.

Figure 5.8: Cross section of an underground dam (Ishida et al. 2011).



Results

The underground dams have been effective in reducing seawater intrusion and increasing the local water availability. In the case of the Wang River underground reservoir near Laizhou, where an underground dam was completed in 2004, the average groundwater level rose up to 3.3 m, and the area affected by seawater intrusion was reduced by 68% (Wang 2012). The underground reservoir can store more than 32 million m³ of water, which has considerably enhanced regional water security and sustains several economic and agricultural activities of the province.

The construction of underground groundwater reservoirs and seawater barriers requires good hydrogeological knowledge and monitoring data. Furthermore, reliable data and projections of water availability and water demand are crucial for an adequate design and operation. Certain conditions require special attention or preclude the application of the technology. In karst aquifers, for example, underground barriers may increase spring discharge or flood cave systems. Also, water quality implications have to be assessed (Ishida et al. 2011).

6. Concluding remarks

Coastal regions host a large share of the world’s population and economic activity, and a reliable water supply forms the basis for their future development. Groundwater plays a major role herein, but is at the risk of salinization by seawater intrusion. The primary driver is aquifer over-exploitation, which also causes land subsidence, thus adding to the salinization risk. Flooding of low-lying coastal zones is another cause for seawater intrusion that may increase in the future when sea levels rise.

As this handbook has shown, only good groundwater governance can minimize the threats to freshwater reserves in coastal aquifers. This first of all relies on knowledge of groundwater processes and the state of the freshwater resources, both of which require targeted and sustained data collection and management. An efficient and strong institutional framework is necessary to coordinate the monitoring process and use the available data to develop policies and legislation. Involvement of all stakeholders is essential to the success of solutions to water management problems.

The principal management aim should always be to keep the demand for water as low as possible in a coastal development scenario that is collectively decided on by all actors (Figure 6.1). Because population and food demand are still growing in most regions of the world, a reduction of water use per capita and per hectare is essential. Fundamental steps towards efficient water use are systematic monitoring of water extraction and metering of water consumption. Economic incentives like subsidies for water-efficient technologies in irrigation, industrial production and households, can be effective instruments to promote water saving. At the same time, strict enforcement of water allocation limits is a prerequisite.

Well-managed groundwater can provide an important share of the coastal water supply, as illustrated by the example from South Downs, England (Section 5.1, case 1) and Tarawa, Kiribati (Section 5.1, case 2). Artificial recharge technologies, like the sophisticated ones in the Netherlands (Section 5.3, case 5) or relatively simple solutions like in Kerala, India (Section 5.3, case 4), can be implemented to store excess water when it is available. Diversifying the sources of water increases resilience to water scarcity. A sustainable provision of alternative water sources must be in place when the agreed-upon demand exceeds the supply of the natural system. These sources can be manifold. Desalination and wastewater are presently emerging as complementary sources of water. Coupling of the energy-intensive desalination process with renewable energy generation, increase the economic and environmental viability of this technology.

With the emergence and growth of coastal megacities, water transfers from other watersheds have been realized in several countries, such as for the city of Tianjin, China (Section 5.2, case 3). Such schemes are costly and may have negative environmental impacts. Physical or hydraulic barriers to prevent seawater intrusion may complement the management strategy as the examples of Los Angeles (Section 5.4, case 6) and the Bohai Sea area show (Section 5.4, case 7).

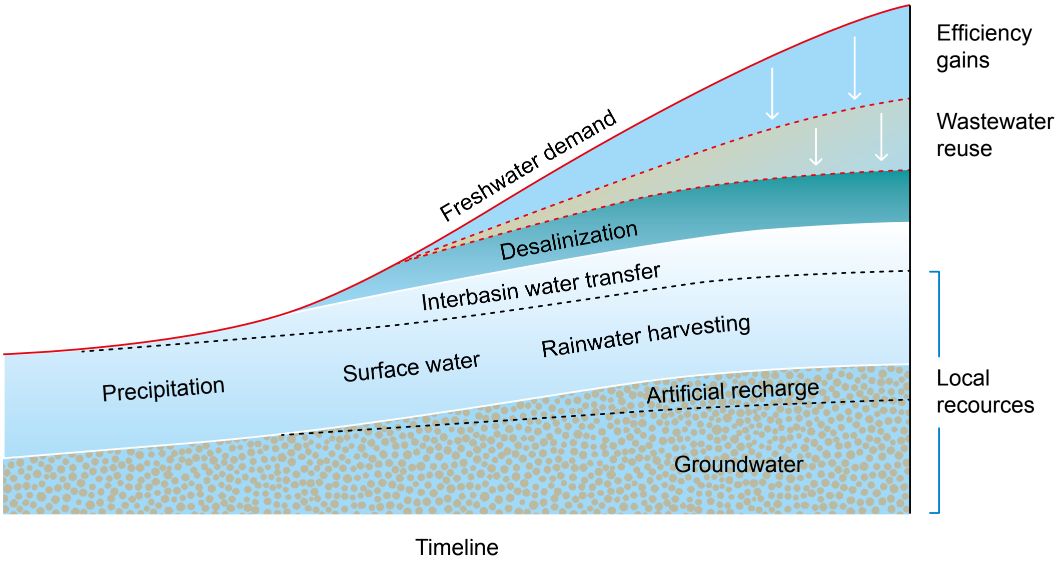


Figure 6.1: Overview of the development of coastal water supply options

The factors that affect coastal aquifers are dynamic and diverse. Ongoing demographic and natural transformations mean that rigid water management processes must be abandoned in favor of adaptive approaches. These should not be limited to the water sector only, and they have to cross boundaries between public administrations and academic disciplines. Science should thereby inform new policies. The limited capacity of groundwater systems to meet water demand necessitates a re-thinking of water supply, which should be based on innovative solutions and a diversification of water sources. Water availability should be a guiding principle in economic development and spatial planning, and the focus should not only be on direct human needs but also on the health of ecosystems. This balancing act will be a delicate one in many coastal regions, but it will have to be faced in order to meet the challenges brought by the rapid changes of the 21st century.

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Spatial data references

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Additional sources are cited specifically within the maps.

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