Cambridge University Press
978-1-107-03059-6 — Coastal Hydrogeology
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1

Introduction to Coastal Groundwater Systems

1.1 Coastal Zones

Coastal zones are the areas between land and sea that are influenced by marine as well as terrestrial processes (Crossland et al., 2005). The coastal zone is a fuzzy concept for which various definitions have been proposed (Custodio and Bruggeman, 1987; Crossland et al., 2005). For example, it has been defined as the land within 100 km of the shoreline (Small and Nicholls, 2003; SEDAC, 2007; Lange et al., 2010) or the area between 200 m elevation on land and 200 m water depth offshore (Crossland et al., 2005). Even more specific is the definition of the low-elevation coastal zone (LECZ), which is understood to be the contiguous and hydrologically connected zone of land along the coast and below 10 m of elevation (McGranahan et al., 2007). This zone is of particular importance because it is susceptible to flooding by storm surges and tsunamis as well as by sea level rise.

Estimates about how many people live in coastal zones vary depending on the adopted definition and the global population data sets used. Globally, the LECZ covers 2.599×10^6 km^2, which equates to only 2.3% of the total land surface area of all coastal countries. Yet, in the year 2000, 10.9% (625 million people) of their population lived there. China, India, Bangladesh, Indonesia and Vietnam together accounted for more than half of the global LECZ population. Moreover, with 241 people km^{-2}, the population density of the LECZ was about five times the global average (47 people km^{-2}), and the population growth rates in coastal zones are significantly higher than they are in non-coastal zones (Neumann et al., 2015). Various other statistics also show that humans gravitate towards the coast. For example, based on 2003 data, Martínez et al. (2007) found that 41% of the world population, approximately 2.4 billion people, lived within 100 km from the coastline. Within this zone, the population density is highest below an elevation of 20 m (Small and Nicholls, 2003). Their attractiveness stems from the fact that coastal zones offer natural resources, notably fisheries; provide embarkation points for trade and possess endless possibilities for recreation and tourism (Merkens et al., 2016).

The geological, geomorphological and climatological conditions vary tremendously along the world's coastlines. Different combinations of these conditions make up for a wide variety of coastal zone types. Shorelines can consist of solid rocks or loose sediments, and their topography may range from low-lying flat areas to high, steep cliffs. In dry areas, deserts line the coast, but where rain is abundant or rivers bring enough water from the hinterland, lagoons and wetlands form, especially in deltas and low-lying coastal zones. Large areas may be under tidal influence, and in estuaries, seawater can penetrate tens of kilometres upstream, forming a so-called salty tide in the river channel. The shoreline may be dominated by beaches, dunes, mangroves, salt marshes, hills or cliffs.

Because they are at the interface between continental freshwater and marine saline ecosystems, coastal zones are characterised by a high biological diversity. Natural coastlines are increasingly influenced by human activities. The current rapid population growth, land use change and urbanisation are creating severe environmental problems, such as ecosystem and biodiversity loss, land degradation and pollution (Martínez et al., 2007; Shi and Jiao, 2014). It is expected that the pressures on coastal aquifer systems will become more severe as the global population continues to grow (Neumann et al., 2015).

The growth of the population in coastal areas is a main driver for a rise in water demand. Not only is the number of people rising but higher living standards also bring with them a higher consumption per person. An even stronger driver is increased food production, as irrigated agriculture accounts for most of the global freshwater withdrawal (Poore and Nemecek, 2018). A high localised water demand occurs in urban centres or where there are major industrial centres or tourist destinations.

Freshwater is a limited and threatened resource everywhere in the world, but this is particularly true for coastal areas, because their vicinity to seawater entails a high risk of salinisation of available water resources. Groundwater abstraction to meet the rising water demand often exceeds the regenerative capacity of coastal aquifers, and this causes seawater intrusion. At the same time, human activities are causing groundwater quality deterioration. Sources of anthropogenic contaminants include agriculture, landfills, wastewater and chemical spills. The combined threat of contamination from the land surface and by seawater intrusion that leads to a shrinkage of usable fresh groundwater reserves has been labelled the *coastal groundwater squeeze* (Michael et al., 2017).

From a hydrogeological perspective, coastal zones are usually understood to be the regions where fresh groundwater of meteoric origin and saline waters of marine origin meet and interact. The extent of a coastal zone varies according to the type of problem being addressed and the study objectives, so it depends on the relevant groundwater processes and is not defined on the basis of a general distance, elevation or boundary. If the tidal effect is the topic of investigation, then the study area comprises the onshore area where the tidal effect is significant, which can be a few hundred metres to a few kilometres away from the coast (Merritt, 2004). To understand the regional flow in a complicated coastal multi-layered aquifer–aquitard system, however, usually a comprehensive groundwater regime, which stretches from the recharge to the discharge areas, has to be included (Figure 1.1). In some cases, the discharge area may be offshore and could even extend all the way to the edge of the continental shelf (e.g. Wilson, 2005).

Coastal zones evolve by the interplay of geological processes such as tectonic movement and sea level change, as well as erosion and sedimentation. In more recent times, humans have become a dominant geological agent by executing large-scale land reclamations,

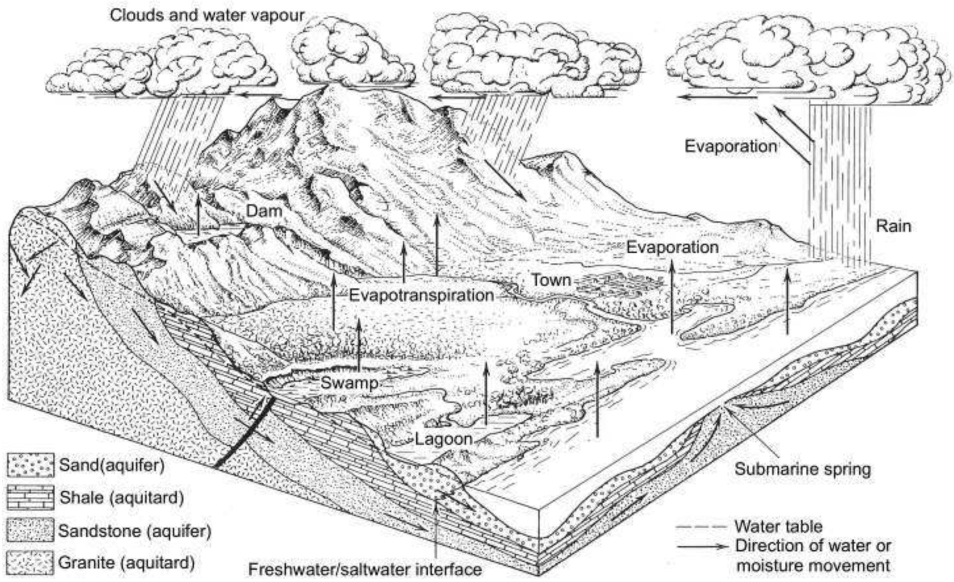

Figure 1.1 The hydrological cycle in a coastal zone. In a natural coastal environment, groundwater flows into the sea by diffuse discharge or concentrated springs, located either along the coastline or in the seabed. The focal points for discharge are outcrops of a confined aquifer or fracture or fault zones. Modified from Todd (1980).

dredging, damming rivers and building coastal defence structures. These processes change the coastal landscape directly or indirectly by impacting the natural erosion and deposition processes. The rate of change by anthropogenic interventions is typically much faster than it is for geological processes, although natural catastrophic events like earthquakes or flood waves can have almost instantaneous impacts.

1.2 Coastal Hydrogeology

Hydrogeology is a branch of geology that deals with the occurrence, movement and chemical state of groundwater, as well as the chemical and physical reactions between water and rock. The study of groundwater and fluid-rock interaction below the seafloor is called *marine hydrogeology* (Fisher, 2005). Traditional hydrogeology excludes the ocean realm and might therefore be equivalently called *terrestrial hydrogeology*. Because marine hydrogeology is not concerned with freshwater resources for human use, its scope is less applied than terrestrial hydrogeology. Instead, it focusses more on topics such as global geochemical cycles, the role of groundwater in ocean floor geochemical processes and the importance of fluid flow for the energy budget of the oceanic crust (Fisher, 2005; Judd and Hovland, 2007; Becker and Fisher, 2008; Kummer and Spinelli, 2009).

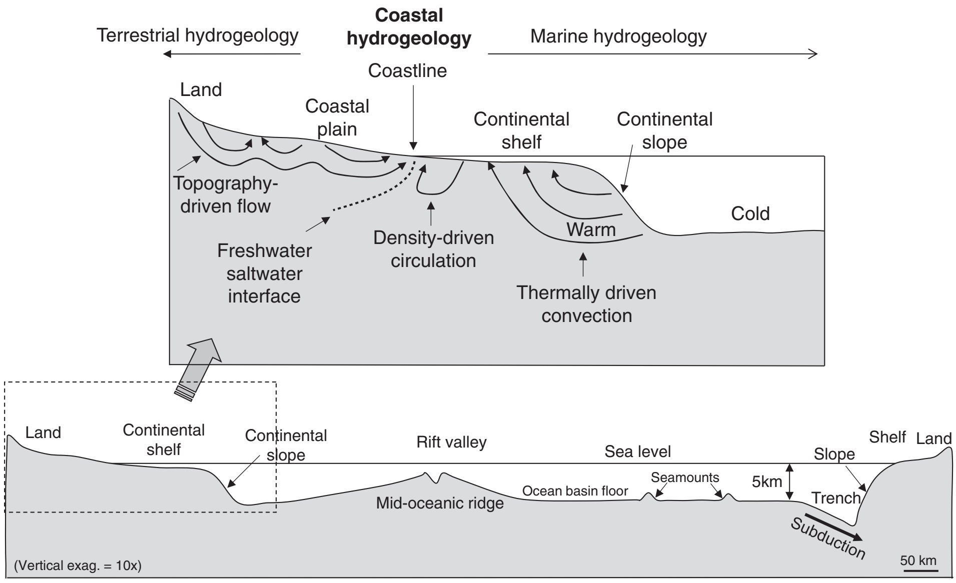

Figure 1.2 Sketch of an ocean basin with inset showing the geographic areas covered by terrestrial hydrogeology, marine hydrogeology and coastal hydrogeology. Inset modified from Wilson (2005).

The physiography of coastal areas was important in determining early human migration patterns (Armitage et al., 2011), and numerous archaeological excavation records testify to human occupation dating back thousands of years (Gaur and Vora, 1999; Zong et al., 2009). These human activities have led to early groundwater exploitation in coastal aquifers. At an early Neolithic Hemudu culture site near the mouth of the Yangtze River in China, a 5600-year-old wooden well was unearthed (Jiao, 2007). This pre-historic well suggests that the people who lived there knew that groundwater had a better and more stable quality than the river water influenced by the tides. Coastal hydrogeology did not become established as a scientific specialisation, though, until the first decade of the twentieth century (Houben and Post, 2017). Nowadays coastal hydrogeology forms one of the most important frontier topic areas in groundwater science, one reason for this being that such a large portion of the world's population lives in coastal areas, giving rise to excessive pressure on water resources, particularly on groundwater. Further human interventions along the coast, such as land reclamation and deep foundations of buildings, as well as natural factors, such as long-term sea level changes, also modify the natural coastal groundwater flow system and the interaction between seawater and groundwater. The resulting groundwater-related resource, environmental and engineering challenges call for enhanced understanding of coastal groundwater systems, as well as solutions to the emerging problems (Michael et al., 2017; Post et al., 2018c). This offers unprecedented novel research opportunities.

There are no clear-cut boundaries between terrestrial, coastal and marine hydrogeology. Geographically, the scope of coastal hydrogeology may stretch offshore to the continental shelf, where the coastal aquifers discharge, or landward to mountainous areas, which provide recharge to the coastal aquifers (Figure 1.2). Coastal hydrogeology comprises a wide variety of topics, including sea level–induced groundwater level fluctuation, submarine groundwater discharge, seawater intrusion, groundwater-dependent coastal ecology, impact of anthropogenic activities on coastal groundwater regimes, palaeo-hydrogeology and groundwater management.

1.3 Coastal Groundwater Systems

Coastal aquifers have some unique characteristics compared to other aquifers. These include variable-density flow with freshwater and seawater as two end-members, groundwater level fluctuations in saturated zones and airflow in unsaturated zones induced by tidal fluctuations, groundwater chemical zoning due to seawater and fresh groundwater mixing and associated chemical processes, submarine groundwater discharge as an important flux and chemical exchange between the land-sea interface and transient but slow changes of the system in response to natural factors like sea level change and anthropogenic factors such as large-scale land reclamation along the coast.

Because of the great diversity of coastal landscapes and geology, as well as the anthropogenic influences impacting them, there is no such thing as a typical coastal groundwater system. Nonetheless, there are certain communalities. The first is that, somewhere in the subsurface, terrestrial groundwater meets intruded seawater. The distinct salinity difference between the two water types, albeit that the details vary per region (Section 5.2), is a feature of all coastal groundwater systems. The second is that, because of its higher salinity, the seawater has a higher density than freshwater; generally, it is greater by approximately 2.5%. Albeit modest, this difference has extremely important consequences for the groundwater flow processes. It gives rise to the typical wedge shape of a body of intruded seawater and makes it so that under equilibrium conditions, the seawater protrudes inland from the coastline (Chapter 6).

The quintessential depiction of a seawater body in a coastal aquifer is displayed in Figure 1.3. Because of its higher density, the seawater extends inland from the coastline and is wedged between the bottom of the aquifer and the overlying freshwater. The ratio of the densities of freshwater and saltwater is one of the primary controls on the position of the boundary between the two water bodies. A dynamic equilibrium exists when the position of the saltwater wedge does not change. The word *dynamic* is meant to indicate that the groundwater is not stagnant: the freshwater flows towards the sea, and as is explained in Chapter 6, a (slow) circulatory flow exists within the saltwater wedge (Figure 1.3).

Figure 1.3 also makes clear that the separation between fresh and saline groundwater is never completely sharp; instead, the two are separated by a zone with gradually varying

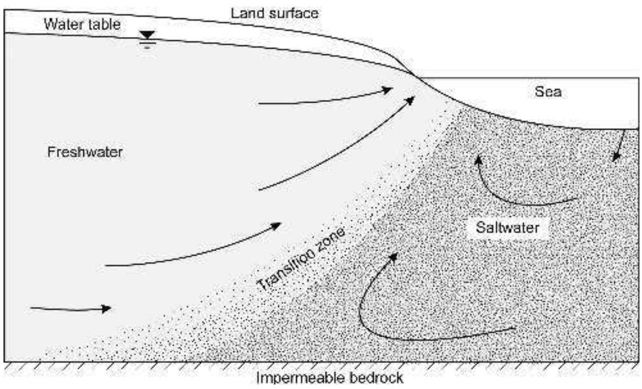

Figure 1.3 Idealised depiction of a wedge of seawater intruded into a coastal unconfined aquifer. The saltwater is separated from the fresh groundwater by a transition zone in which the salinities gradually change from freshwater to seawater values. From Cooper et al. (1964).

intermediate salinities, which is called the *transition zone*, *mixing zone* or *zone of diffusion*. Transition zones can be only a few decimetres wide, but some can reach up to tens of metres in width. If the transition zone is very narrow (relative to the thickness of the freshwater-filled portion of the aquifer), it is sometimes referred to as the *interface*. In this book, this term is reserved, though, for the sharp boundary that is assumed to exist for the purpose of simplifying the mathematical treatment of seawater intrusion problems. Seawater and freshwater are sometimes separated by zones of brackish water that extend over many kilometres that form when the coastline shifts. In that case, it becomes hard to identify the limits of the transition zone, and the concept loses its meaning. The processes that lead to the different kinds of salinity distributions are discussed in Chapters 6 and 8.

1.3.1 Sedimentary Aquifer Systems

Aquifer systems consisting of alternations of various types of sediments form complex hydrogeological settings because the permeability of the geological units is highly variable (e.g. Jiao et al., 2010; Saha et al., 2014). Clay layers can be virtually impermeable, whereas coarse-grained strata can conduct groundwater with greater ease. The permeability is also determined by the degree of consolidation and cementation of the sediments. Coastal plain aquifer systems are typically composed of several aquitards and aquifers, and the sequence generally dips and thickens towards the sea. Owing to past sea level variations, the sediment facies shift between marine and terrestrial types. When sea level was high, deposition of finer-grained sediments dominated where full marine conditions existed, forming strata of clay-rich deposits. When sea level was low, such marine deposits became weathered and eroded, and at the same time, fluvial, aeolian and lacustrine sedimentation resumed, which, depending on the flow conditions, resulted in the deposition of sediments with a range of grain sizes.

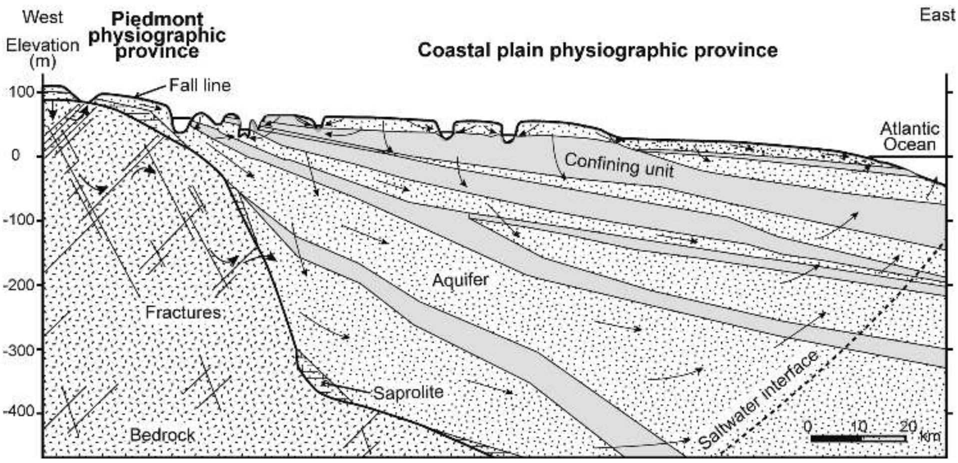

Figure 1.4 Hydrogeological cross section of the Virginia Coastal Plain Province as an example of a sedimentary coastal plain aquifer system. Modified from Nelms et al. (2003).

Alternations of these depositional environments in time resulted in complex, inter-layered fine- and coarse-grained sediment sequences. Individual aquifers, usually consisting of sand and gravel, are separated by aquitards dominated by clay and silt. The degree of aquifer connectivity and inter-aquifer groundwater fluxes are determined by variations of the extent, thickness and lithology of the aquitards (Cherry et al., 2004). In the presence of aquitards that prevent the downward flow of seawater, fresh groundwater flow originating on land may extend offshore, or have done so in the geological past (Post et al., 2013). Conversely, seawater can become trapped inland when low-permeability strata prevent it from migrating (Miller, 2000). The effect of changing flow patterns over (geological) time in combination with the lithological variability gives rise to complex and sometimes counter-intuitive groundwater salinity patterns.

Some coastal plain aquifer systems are volumetrically dominated by clay-rich layers. When aquifers in such systems are extensively exploited, a large part of the abstracted water derives from the aquitards, and the pressure decrease causes land subsidence as the sediments compact (Chen et al., 2003a; Phien-wej et al., 2006; Guo et al., 2015). The processes within aquitards can also exert a control on the chemistry of the adjacent aquifers by releasing salts and ammonium (Mastrocicco et al., 2013; Wang et al., 2013; Colombani and Mastrocicco, 2016) or arsenic and arsenic-mobilising solutes by natural consolidation or in response to pumping (Erban et al., 2013).

An example of a flow regime in a sedimentary coastal aquifer system is depicted in Figure 1.4. Overall, the flow is approximately horizontal on a regional scale. In the hinterland recharge areas, where the aquifer system is dominated by permeable materials with active groundwater flow, the vertical component of flow is downward. Near the shoreline in the coastal plain, the vertical component of the flow can be upward, and springs and seepage zones may be formed in topographic depressions and near the shoreline. Depending on the topography, geology and recharge, groundwater flow rates vary but are on the order of metres per year (Back et al., 1993).

In coastal areas with a flat topography and low-energy depositional environments, such as slow-flowing water and stagnant lagoons, deposition of fine-grained sediments prevails. Where this is the case, the permeability of the aquifer system generally decreases towards the coast as the proportion of finer-grained materials increases in this direction. As a result, flow becomes progressively more sluggish, especially in the deepest part of the system.

The bedrock that underlies the sedimentary strata (Figure 1.4) can be any type of hard rock, e.g. igneous, metamorphic or consolidated sedimentary rock (Anderson, 1978; Wang and Jiao, 2012). The bedrock is usually not the focus of coastal hydrogeological studies because it is considered to have too low a hydraulic conductivity to be of relevance, or because of practical reasons, such as the bedrock being too deep or too rigid to drill boreholes into. However, studies have shown that the bedrock can play an important role in the geochemistry of the overlying aquifer system (e.g. McIntosh et al., 2014).

1.3.2 Limestone Aquifers

Limestone aquifers consist of carbonate minerals. There is a wide variety of limestone types, and their textures and grain sizes are therefore highly variable. Fine-grained marine limestone can have a very low permeability, whereas bioclastic limestone with lots of shell or coral fragments can have many voids that make it permeable. Limestone aquifers are special in the sense that the carbonates dissolve relatively easily as groundwater flows through them. As such, they develop porosity, and permeability increases with time. Since initially, a pristine limestone has a relatively low permeability, groundwater flow will be preferentially along faults and fracture zones, which means that dissolution features will be aligned with such zones of preferential flow. The enhanced permeability due to the dissolution of the rock reinforces this, and as a result, conduits of various size develop. Carbonate rock aquifers that have developed extensive dissolution networks are called *karst aquifers*.

Water flow velocities and volumes inside these features can become high, and flow often resembles that of rivers rather than the slow flow of groundwater through the fine pores of a sedimentary aquifer. Discharge is often localised and in the form of springs, which are sometimes located offshore (Stringfield and LeGrand, 1971). The salinity distribution tends to be highly irregular, as some parts of the subsurface are subject to rapid flow, whereas groundwater can be quasi-stagnant in the less-weathered, less-permeable parts. The seasonal variability of the groundwater salinity can be very high in the permeable parts of the system. Well-studied coastal limestone aquifer systems include those in Florida, USA and Yucatan, Mexico (Barlow, 2003; Bauer-Gottwein et al., 2011), the karst regions of the Mediterranean (Fleury et al., 2007) and carbonate islands, including atolls (Vacher, 2004).

Karstification can be more significant near the water table, where flow is dynamic and groundwater is rich in carbonic acid. The water table elevation in coastal aquifers is controlled by sea level, which has fluctuated over geological time (Section 8.2). Some studies have demonstrated that the position of the zone of karstification in coastal limestone is strongly related to the past sea levels (Audra et al., 2004; Fleury et al., 2007).

1.3.3 Hard Rock Aquifers

Hard rock aquifers are made up by igneous rocks and metamorphic rocks. Just like in limestone aquifers, the flow in hard rock aquifers is mainly localised around faults and joints (Park et al., 2012a), but because the chemical weathering processes in hard rocks are much more sluggish than they are in limestone, the porosity and permeability development is not as pronounced. Instead, permeability distributions in hard rock systems are largely controlled by tectonic processes that result in mechanical weathering by fracturing. Hard rock aquifers are among the least productive aquifer systems, and their strong geological heterogeneity makes them difficult to investigate.

In rocks of volcanic origin, fissures sometimes give the material a high porosity and permeability. Weathering and soil formation make the permeability generally higher near the surface. Flow directions are highly dependent on the orientation of the fissures and the occurrence of impermeable structures such as dykes (Custodio and Bruggeman, 1987). The high degree of structural control on the flow patterns makes it hard to draw generalisations about the hydrogeological behaviour of these systems, and the characterisation of the interaction of freshwater and seawater within these systems remains a challenge.

1.4 Coastal Groundwater Chemistry

1.4.1 Salinity

Salinity is a measure of the total amount of solutes, or more exactly, the sum of the masses of all the individual ions in the water. Absolute salinity is defined as the ratio of the mass of dissolved material in water to the total mass of water (Millero et al., 2008) and is often also referred to as the salt mass fraction. The absolute salinity of standard seawater, which is a carefully defined reference water composition in oceanography, is exactly 35.16504 g kg^{-1}. Since the absolute salinity is tedious to measure due to analytical difficulties, a so-called practical salinity has been defined, which is based on measurement of the conductivity, temperature and pressure of seawater. It is not often used by hydrogeologists, but it is important that they understand its definition so as to avoid confusion when interacting with oceanographers. The practical salinity, which is a dimensionless quantity, of standard seawater is 35.

In hydrogeology, the amount of dissolved ions is most commonly expressed by the mass of dissolved material per litre of water, which is referred to as the total dissolved solids (TDS) concentration, and the unit is mg l^{-1} or g l^{-1}. At 25°C, standard seawater has a density $\rho = 1.02334$ kg l^{-1}, so its TDS is $35.2 \times 1.02334 = 36.0$ g l^{-1}. As the density is a function of temperature, a TDS expressed per unit of solution volume can change as the temperature changes. The absolute salinity is invariant with temperature. *Salinity* and *TDS*

Table 1.1 *Salinity Classes Based on Total Dissolved Solids (TDS) Concentrations*

	TDS (mg l^{-1})	Description
Fresh	0–1000	Sufficiently dilute to be potable; includes rain and is found in rivers, lakes and groundwater
Brackish	1000–10 000	Too saline to be potable; found in rivers, lakes and groundwater subject to evaporation or mixing with seawater
Saline	10 000–36 000	Less than or equal to seawater; found in rivers, lakes and groundwater subject to strong evaporation or intensive mixing with seawater
Hyper-saline	36 000–100 000	Significantly more saline than seawater; found in evaporated seawater or groundwater in discharge zones in arid regions
Brine	>100 000	Seawater or groundwater having undergone intense evaporation or dissolution of rock salt

Note. Descriptions after Post et al. (2018b).

are often used interchangeably, but as the above discussion shows, this is strictly not correct.

Groundwater is often divided into salinity classes (Table 1.1), mainly as an aid in interpreting hydrochemical data or simply for the purpose of discussion. The TDS concentration is often used to define salinity boundaries, but chloride concentrations are sometimes also used (Stuyfzand, 1989). Based on the suitability for human consumption, a TDS value of 1000 mg l^{-1} is usually regarded as the upper limit of freshwater (Alley, 2003). The upper limit for saline water in Table 1.1 is standard seawater, but depending on the salinity of local seawater, it may be more meaningful to set the boundary at a different value.

1.4.2 Sources of Salinity

Besides seawater intrusion, different sources of salt can lead to freshwater salinisation in coastal aquifers. Van Weert et al. (2009) distinguished between three different origins of saline groundwater: (1) marine, (2) natural terrestrial and (3) anthropogenic terrestrial (Table 1.2). Groundwater of multiple origins may form mixtures in coastal aquifers.

Within the class of marine sources of groundwater, connate saline water is the seawater that was trapped in the rock that formed underwater. These rocks may be sedimentary but can also be oceanic basalts, for example. The connate seawater thus has the same age as the rock. Marine transgression groundwater formed when the coastline was further inland and the sea level was relatively high compared to the land surface in the geological history (Chapter 8). It is thus younger than the rock of which it occupies the pore space. The length during which connate or transgression waters can be preserved depends mainly on the permeability of the host rock and the