# 1

# Continent–Sea Interface: a Hydrogeological Continuum



The section of land between continent and ocean is the hydrogeological continuum. Geological reservoirs containing groundwater resources do not stop at the shoreline. These formations are continuous and may be covered by less permeable formations on the continental shelf. This interface on the coast takes the form of a transition zone between freshwater and saltwater due to the difference in density, the geometry of aquifers and the heterogeneity of their physical properties as well as how the coastal aquifers are used (supply of drinking water, agriculture, tourism, industry, etc.) and also, as freshwater inputs into the ocean. The proper management of coastal aquifers inevitably involves the risk assessment of saltwater intrusion, based on geological and hydrogeological knowledge of formations, observation and alert networks, management models integrating geological, hydrogeological and geophysical data and technical management solutions. Using methods to characterize clastic sedimentary geological reservoirs by sequential stratigraphy and seismic stratigraphy both *onshore* and *offshore*, respectively, helps suggest appropriate management tools for coastal aquifers that develop within sedimentary basins. In addition, characterizing the paleo-geographic evolution of the development of carbonate platforms over the course of geological time associated with the changes in sea level and vertical tectonic movements is essential in order to establish

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conceptual models required for monitoring and managing karstic coastal aquifers. Airborne geophysics provides information about the structure and intrusion of saltwater in formations, both sedimentary and volcanic. Different examples of coastal aquifers, primarily Mediterranean, show the specificity of this continuum, characterization and monitoring tools as well as management tools.

## 1.1. Introduction

Coastal zones form an interface between the land and the sea surface. Underground, coastal aquifers in turn form a hydrogeological continuum, an interface between the ocean and continent. Groundwater flows in geological formations, usually perpendicular to the coastline, toward continental and marine outlets on the continental shelf with the release of groundwater or occasionally underwater sources.

Groundwater is found in a variety of geological formations, between the sea and land: in detrital sedimentary formations (deltas, sedimentary basins, alluviums, etc.), in karstified limestone formations (Mediterranean, Mexico, Florida, etc.), bedrock formations (Britain, Scotland, Scandinavia, etc.) or volcanic formations (Reunion, Mayotte, Caribbean, Canaries, Azores, etc.). This space between the continent and ocean is an interface between salt and freshwater. Saltwater can penetrate the continent depending on natural conditions and abstractive conditions. As its density is higher than that of freshwater, it forms below freshwater, which we call a saltwater intrusion (theoretical abrupt interface) or a transition zone (diffuse interface).

This continent–ocean interface is a zone of interest both for human societies, with more than 60% of the world's population living on the coastline less than 60 km wide, and for lagoon and marine ecosystems. This coastal zone attracts populations and tourists, both due to climatic conditions and quality of life as well as economic development (sea transport, import–export). Water resources are necessary for the development of this zone. Groundwater in aquifers of this sea–land continuum is an important source both for the supply of drinking water and for human activities (agriculture, industry, tourism, etc.). Specific ecosystems develop in the ocean or in lagoons next to groundwater outlets and may also be zones of economic interest (fishing, oyster farming, fish farming, etc.).

The Mediterranean basin and the French overseas islands are ideal for illustrating this continent–ocean interface. Three types of geological land–sea continuums are presented: sedimentary basin, karst and volcanic islands, as well as a description of the characteristics of the saltwater–freshwater interface for different geological contexts. Characterization tools, mainly geological, hydrogeological and geophysical, as well as the management of groundwater resources at this interface are also detailed.

## 1.2. Land–sea interface: from geology to the hydrogeological continuum

The land–sea interface covers 2 million kilometers of shoreline worldwide, distributed around different continents and numerous islands. Coastal zones, carbonate, volcanic (in the absence of lagoons) or bedrock, are steep except in large depressions associated with the main river basins, where large low-altitude areas occur: Rhine (Netherlands), Rhône, Garonne (France), Thames (United Kingdom), Vistula (Poland), Danube (Ukraine/Romania), Ebro, Guadalquivir (Spain) in Europe, for example.

Recent geological phenomena, such as glaciation and formation of reliefs, which effect sedimentary deposits and eustatic variations, have influenced the development of coastal aquifers occurring in the continent–ocean interface. During the last glaciation (≈ –18,000 years), a large part of the continents was covered with ice. Valleys were cut into rocky formations and ancient marine sediments, and then filled with fluvioglacial, fluvial, estuary, marine or even wind sediments. The Messinian salinity crisis in the Miocene (–5.95 to –5.3 million years) in the Mediterranean, isolating it from the Atlantic Ocean, significantly decreased sea level (up to 1,500 m) accompanied by salt deposits and the incision of deep valleys and karstic network development within carbonate massifs. These valleys were filled as the sea level rose with sediments, including clays and marls.

Figure 1.1 illustrates the position of the main alluvial and karstic carbonate aquifers, with the presence of the main submarine springs in the Mediterranean basin [AUR 08]. The flow rate of groundwater discharge into the Mediterranean Sea is, on average, estimated to be 43.5 km$^3$/year (29 km$^3$/year northern shore, 14 km$^3$/year eastern shore and 0.5 km$^3$/year southern shore), 10 times less than the discharge from surface water [MAR 08].

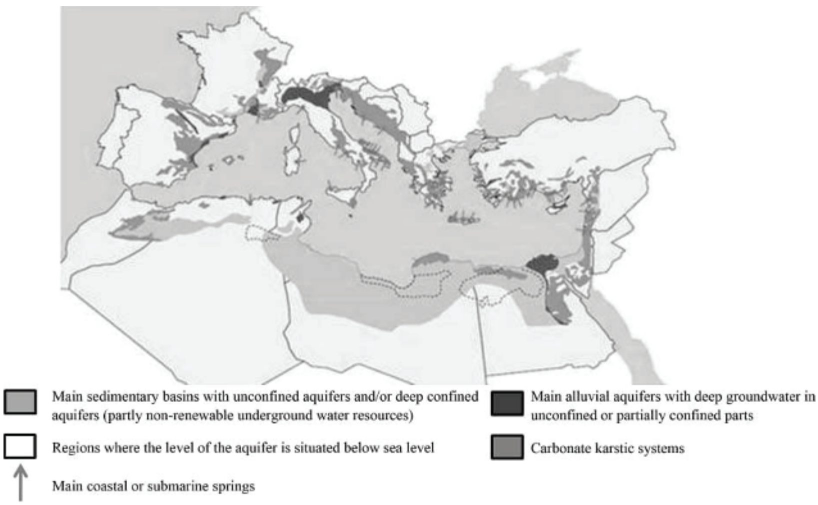


**Figure 1.1.** *Map of main coastal aquifers in the Mediterranean basin [AUR 08]*

### 1.2.1. *The continent–ocean continuum*

The continent–ocean continuum is described by considering two representative cases: sedimentary basins or deltas and carbonate platforms.

#### 1.2.1.1. *Sedimentary basins or deltas*

Mediterranean coastal sedimentary basins are good examples to show this type of continuum. Mediterranean coastal aquifers in sedimentary basins are found in Italy in the Pô plain, in Egypt with the Nile delta, in France with the Camargue plain in the Rhône delta and, to a lesser extent, along the coast of Languedoc-Roussillon from the Vistrenque plain to the Roussillon plain, all associated with the same evolution of the shelf of the Gulf of Lion and finally in Spain, with the Llobregat delta (Barcelona) or even the Ebro delta.

The geometry and three-dimensional (3D) field of hydrodynamic properties of aquifers and aquitards (semi-permeable) occur within sedimentary layers deposited over time. The occurrence of these formations can be explained using the Gilbert delta genetic model [DUV 08] (Figure 1.2).

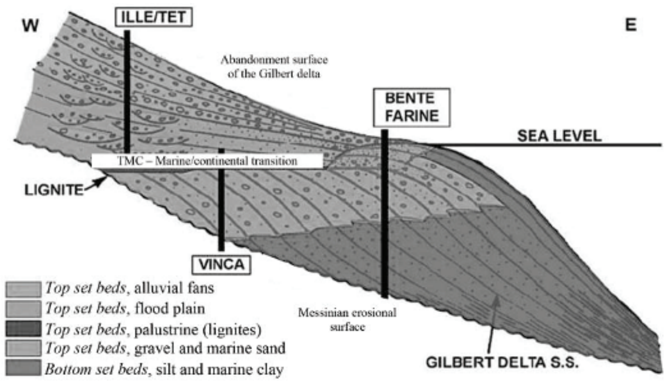


**Figure 1.2.** *Genetic model of the filling of a Pliocene river. Distribution of features in a Gilbert delta and characteristic surfaces (according to Clauzon et al. 1990, in [DUV 08])*

As we pass from the Pliocene (–5.3 to –1.35 million years) to the Quaternary (–1.35 million years to present), sedimentary deposits, generated through the active erosion of watersheds situated upstream of deposition zones, prograde toward the center of the basin. At the base of the Gilbert delta, the sedimentary prisms are composed of silt and clay, from upstream to downstream. The top section of marine prisms is characterized by the presence of gravel and sand.

Marine prisms are overlaid by lacustrine layers and sediments from floodplains and alluvial fans. The sediment layers, which are deposited in the accommodation space in the basin, are influenced by erosion and transport of solids in the water as well as by sea level variations and vertical movements (subsidence in the basin, vertical movements associated with tectonics).

Restoring geometries of sedimentary layers is an important stage in the study of coastal aquifers occurring in alluvial depositions or sedimentary basins. Sequential or genetic strategy is an essential tool for analyzing the development of sedimentary layers along a land–sea continuum, using drilling data, observations of outcrops as well as geophysical data (seismic profiles). Sequential stratigraphy is defined as a method that defines a chronostratigraphic framework on a global scale based on accurate dating of time lines among discrepancies of eustatic origin (variation in sea level), which restrict genetic sediment units [VAI 91]. This method was applied to the Roussillon plain (South of France) [DUV 08, AUN 07] (Figures 1.3 and 1.4), and to the Llobregat delta (Spain) [GAM 09].

From a hydrogeological point of view, the Roussillon plain is a groundwater body subdivided into two vertical sections, namely the quaternary aquifer of a generally unconfined aquifer and confined aquifer if covered by impervious silt over 5 m deep in the coastal zone, composed of quaternary alluvial deposits and the deep Pliocene aquifer (Figure 1.5). The continental fluvial–lacustrine Pliocene deposits show superposition of permeable lenticular sandy layers within a less permeable clay matrix; the most permeable layers are located at the top of the prisms, along with arkosic sand. At the base of the continental pliocene deposits lies plastic clay, which forms the upper part of the marine pliocene deposits giving them a confined characteristic. The marine pliocene sediments partly composed of micaceous clays and silts are generally less permeable, but there are still local variations in characteristics, with lightly compacted sandy sections which form good aquifers. The base of the marine pliocene sediments, with blue marl, is impervious. Due to its architecture and geometry, this aquifer is heterogeneous: the hydraulic conductivity of different aquifer terrains as well as the position of the freshwater/saltwater interface can strongly vary [AUN 06]. Finally, the underlying aquifer is the sandy marine pliocene aquifer, separated from the continental Pliocene aquifer by layers of lignites and plastic clays resulting from depositional environments of flood plains or wet lands; these layers are not continuous throughout the area. The sandy marine pliocene aquifer develops within sediments of prograding prisms of the delta in the distal part of the basin. This aquifer, in theory, is not in direct contact with the sea; however, certain sections are affected by mineralization associated with chlorides. The origin of this mineralization is quite probably due to contamination from being hydraulically connected to the quaternary aquifer by defective boreholes. Without pumping, the hydraulic load of the sandy marine pliocene aquifer is greater than that of the continental pliocene aquifer [AUN 06].

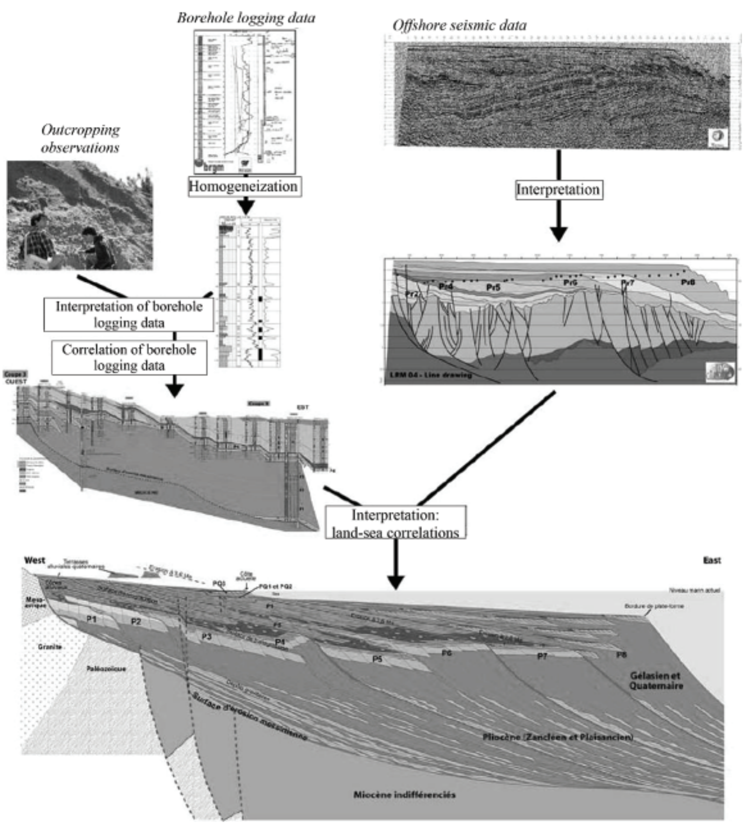


**Figure 1.3.** *Methodology for the sea–land interpretation and correlation of Pliocene and Quaternary sedimentary formations [DUV 08]*

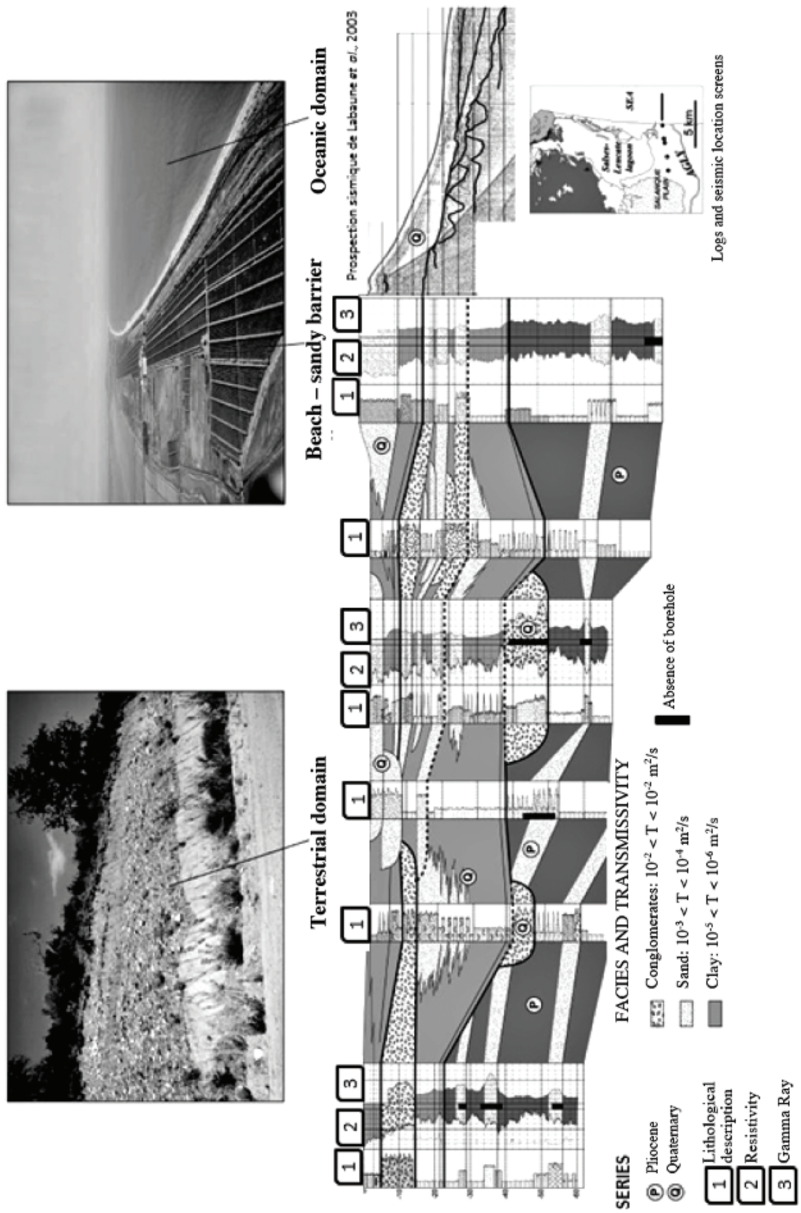


**Figure 1.4.** *Correlation between Quaternary and Pliocene deposits in the continental and oceanic domain, interpreted in terms of hydrogeological characteristics [AUN 04]*

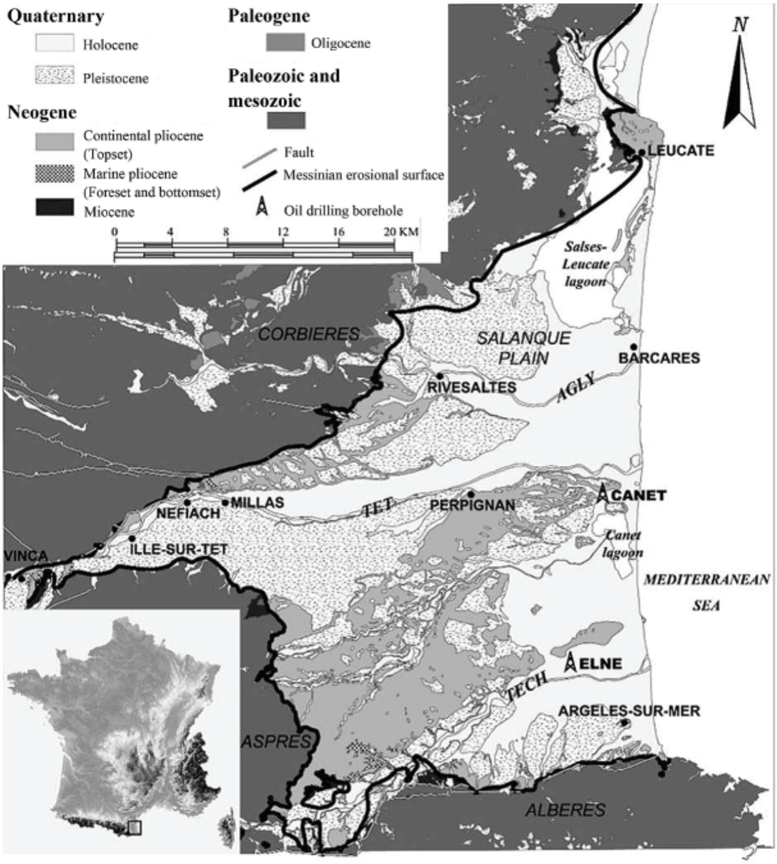


**Figure 1.5.** *Simplified geological map of the Roussillon basin and the geophysical location [AUN 04]*

From stratigraphic and hydrogeological data, a diagram helps propose a hydrogeological conceptual model (Figure 1.6) as well as an interpretive hydrogeological profile from west-east [AUN 07] to represent the characteristics of aquifers within aquitards (Figure 1.7). The groundwater level of the Quaternary superficial layer (TQ and PQ) in general follows the topography; this aquifer is recharged by precipitation, exchanges with rivers and drainage canals for irrigation of the plain for agriculture. Upstream of the basin, the quaternary surface aquifer recharges confined aquifers of sandy pliocene prisms 1 and 2. In addition, due to the thinness of palustrine and clay layers, the flows are divided equally among the three first sandy pliocene prisms. Approximately 15 km from the shore, the lower hydraulic conductivity of sandy pliocene prisms and the increase in the granulometry of the continental pliocene deposits favor flows within continental channelized systems. The problem of the saltwater–freshwater interface begins not only in the coastal zone, but also in the offshore zone. Knowledge of the geometry and permeability of geological layers of the offshore domain is essential to determine the vulnerability of water resources. The hydrodynamic properties of slightly permeable and semi-permeable layers are central to this issue. In addition, downstream, i.e. along the coast, hydraulic heads are greater within deep aquifers than within shallow aquifers. Natural drainage is ascending. The difference in water heads between each aquifer is metric. Due to exploitation of the deep resource by drilling, the local hydraulic water head of the underlying aquifer may decrease, due to inversion of the hydraulic water head gradient (vertical leakage).

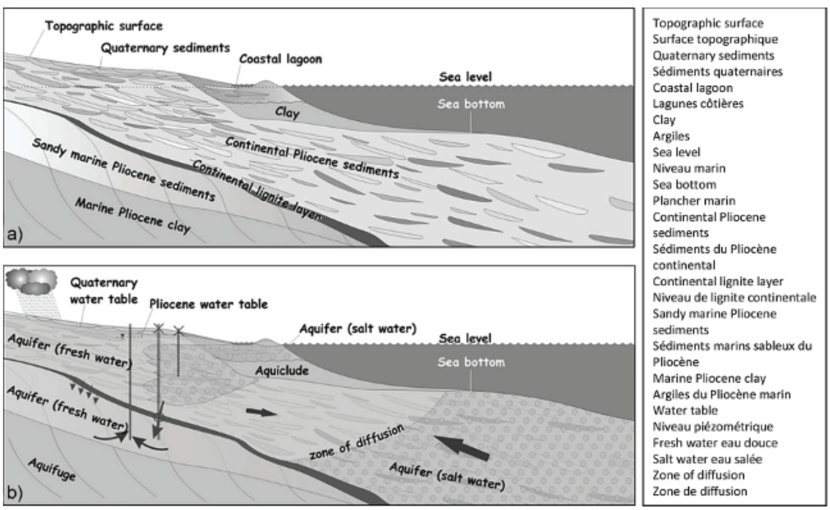


**Figure 1.6.** *Interpretive geological a) and hydrological b) sections of the Roussillon plain orientated west-east [AUN 07]. Vertical drainage associated with an inversion in hydraulic gradient is shown in the hydrogeological section. Vertical drainage takes place via continental sandy formations with lignite or via faulty drilling sites*

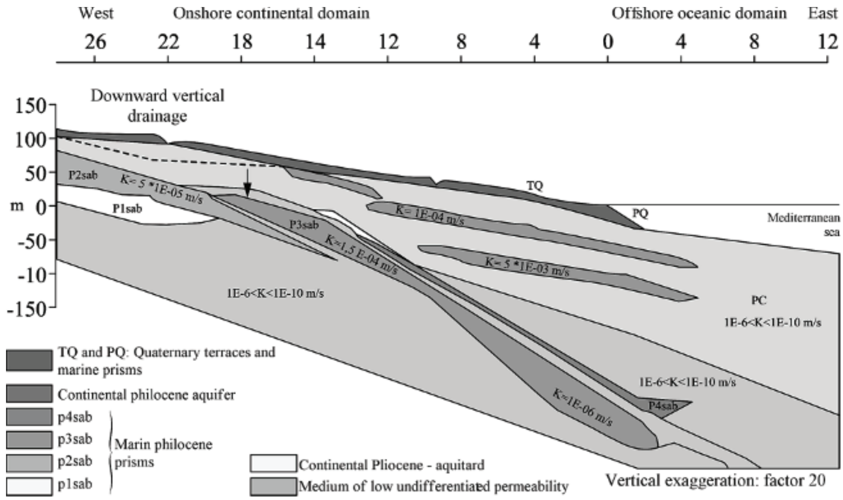


**Figure 1.7.** *Interpretive hydrogeological section of the Roussillon plain orientated west-east (adapted according to [AUN 04])*

### 1.2.1.2. *Carbonate platforms*

Carbonate platforms giving rise to potentially karstified coastal carbonate massifs are present in many sites around the world: Mexico, Florida in the Americas, China and Vietnam in Asia, Spain, France, Italy, Croatia, Greece, Turkey, Syria, Libya in the Mediterranean basin, the Parisian Basin, London Basin, or even Ireland in Europe, for example.

Due to the many changes in sea level [HAQ 87] over geological time and, in particular, since the Miocene [BLA 02, HAL 84, ROU 92], it appears that the sea level variation has had more influence on the development of coastal karstic aquifers than more localized tectonic movements with slower dynamics. The evolution of karstic aquifers and their functioning differ depending on the increase or decrease in sea level. Over periods of relatively low sea level, the karstic springs are therefore situated above sea level. The increase in the resulting karstification potential makes possible the development of a new karstic conduit network, connected to the pre-existing karstic network as well as to the new base level [FOR 89]. On the other hand, an increase in sea level causes submersion and the potential fossilization of karstic networks.

The location of submarine springs and submerged karstic conduits indicates the existence of sea level variations along the coast. Throughout the Quaternary, the lowest sea level was 120–140 m lower than the current sea level. During the interglacial period, the sea level was close to the current sea level. These variations have been recorded along all coasts. Moreover, karstic conduits located at significant depths disagree with the lowest sea levels of the ice age take place along in the Mediterranean basin:

– the Port-Miou conduit network (France) has been explored up to a depth of -172 m [ARF 06a, CAV 06];

– the karstic network of the Fontestramar spring (France) has been explored up to a depth of –164 m [AUN 03, BRA 97]; in Chekka (Libya), the deepest spring is located at a depth of 110 m and 150 m below the sea level below the sea level [BAK 07b, ELH 06, KAR 67]; in Almyro of Eraklion (Crete), the marine intrusion has been identified at a depth of 500 m below the current sea level, implying karstification at depth [ARF 02, ARF 04, ARF 06a].

These depths are not consistent with the lowest sea levels of the last ice age. Consequently, developments of coastal karstic systems at depth in the Mediterranean are associated with an event of a much greater magnitude, the Messinian salinity crisis [CLA 82, ROU 99, ROU 06]. Approximately 5.35 million years ago, at the end of the Miocene, there was a significant decrease in sea level due to the closing off of the Mediterranean from the Atlantic Ocean and a high evaporation rate was recorded in the Mediterranean. This geological event allowed the incision of valleys and the development of vertical karstic conduits [BLA 95] below the current sea level, often located below Pliocene sediments, as well as significant evaporite deposits. Depending on the local geological conditions, the karstic conduits may be obstructed or open to the sea.

The development of Mediterranean karstic systems is shown in Figure 1.8, reconstructing the development of an east Corbières system and the Fontestramar-Fontdame karstic system, whose outlets border the Salses Leucate lake (Eastern Pyrenees, South of France).

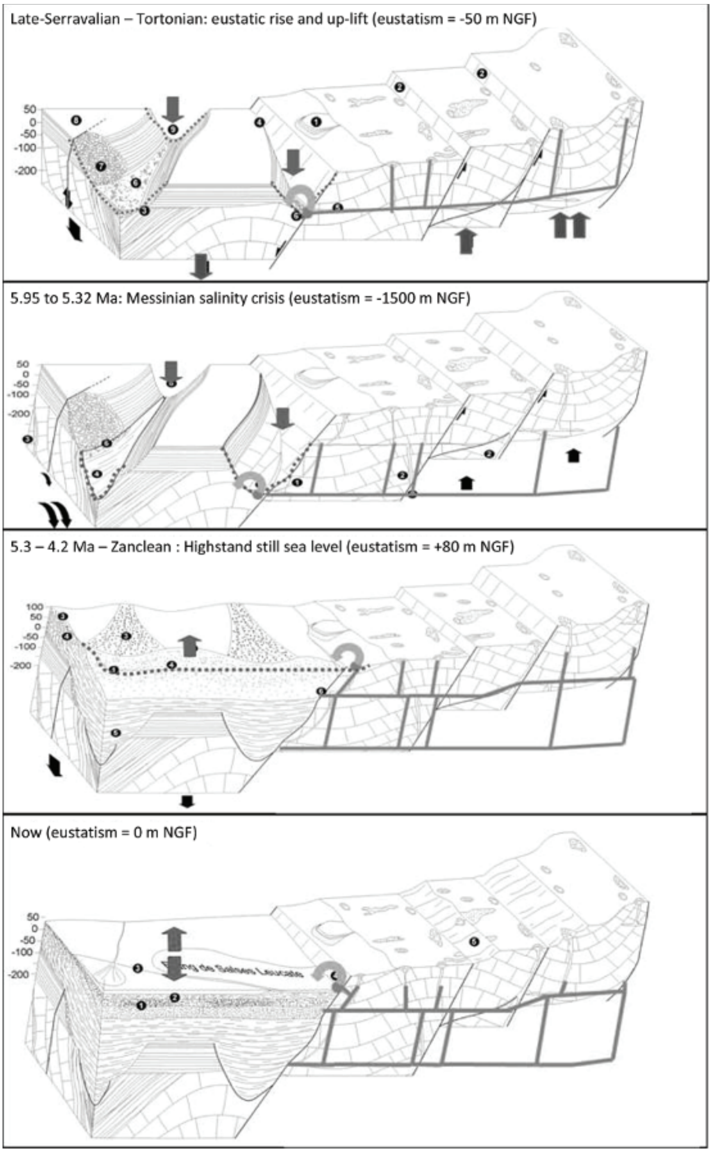


**Figure 1.8.** *Reconstructed diagram of the implementation of the karstic system in Fontestramar-Fontdame (Eastern Pyrenees, South of France)*

The land–sea continuum of carbonate platforms is characterized by the existence of freshwater outlets into the sea with undersea springs located along the coast (Figure 1.9) as well as by saltwater intrusions within fissured limestone massifs and karstic conduits. Undersea springs are situated between several meters and several hundred meters in depth. The amplitude and durability of the flow rate depend on the depth of open karstic conduits and the hydraulic water head within the limestone massif, influenced by precipitations on limestone outcrops in the continental domain.

Different types of coastal karstic systems develop according to the amplitude of variations in the sea level, favorable conditions for karstification and sedimentation (clay or basalt flows) following the rise in the sea level [FLE 12]. Undersea springs show a wide variety of functions: some are permanent such as Port Miou [ARF 06, CAV 06] in the Thau lake with the Vise spring [AQU 03, PIN 04] in France, the Mortola spring in Italy [FLE 07a], Moraig in Spain [FLE 08], Anavalos Kiveri in Greece [MIL 00], Banyas in Syria [BAK 07a] and Chekka (the shallowest) in Libya [BAK 07a, BAK 07b, KAR 67], whereas others are only seasonal. This is the case of the deep spring in Chekka (Libya) and several undersea springs in Croatia [BON 87, BON 95, MIJ 84], Toix in Spain for which there are flows during flooding, the rest of the time this conduit absorbs seawater [FLE 08].

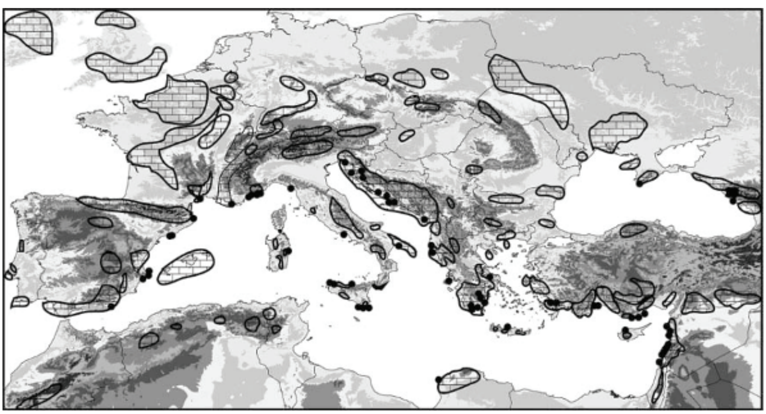

**Figure 1.9.** *Distribution map of karstic zones (represented by bricks) and coastal and submarine sources (black points) in the Mediterranean [FLE 05]*

During periods of rises in sea levels, the flow rates of some submarine springs may be several $m^3/s$, which is the case for the deep spring in Chekka and in Port-Miou [CAV 06]. During periods of low water levels, flow rates may be low, or even zero. When the spring dries up, seawater penetrates into conduits. Other springs have a flow rate that remains low and relatively constant at several dozen liters per second, which is the case for the spring of Mortola [FLE 07a].

Several coastal karstic systems are naturally impacted by saltwater intrusions either seasonally or permanently. In fact, few underwater springs discharge relatively freshwater throughout the year, which is the case for Mortola, Banyas and Anavalos Kiveri. In general, undersea springs discharge brackish water at least during periods of low water levels during the hydrological cycle with variations in salinity during rises in sea level (e.g. Port Miou and Moraig).

Three types of coastal karstic system may be distinguished, considering the degree of karstic development and hydrological functioning of the drainage system. The first type (type 1, Figure 1.10) is characterized by springs with a relatively low flow rate varying little during the hydrological cycle (e.g. La Mortola); the water is fresh throughout the year. The functioning is not really karstic, but instead similar to fractured aquifers. The conduits are small in dimension and not organized into a network. Significant losses of hydraulic water head near the springs create a sufficient hydraulic water head to prevent marine intrusion. These aquifers are low extension aquifers with limited reserves with regard to well-developed karstic systems resulting from several karstification phases. The second type (type 2, Figure 1.10) is a network of well-developed karstic conduits, often arranged along horizontal levels and connected to deep vertical conduits resulting from several karstification stages associated with successive decreases in the base level. The conduits are large with regard to the low current flow and cause a decrease in hydraulic water head at the outlet. The hydraulic water head within the aquifer is often too low to prevent saltwater intrusion in conduits, particularly during periods of low sea level. These aquifers drain large recharge zones and have large resources. Systems of karstic conduits are well developed below sea level and are open. The average flow rate of springs is high and is characterized by high seasonal variability; some submarine springs are not permanent. The salinity of water is usually low during rises in sea levels, but high during periods of low sea levels. This is the type of coastal aquifer most frequently observed in the Mediterranean (Moraig, Chekka, Port-Miou, Fontestramar [HEB 06], Almyros of Heraklion [ARF 04] and submarine springs of the Croatian coast). The third type (type 3, Figure 1.10) is associated with coastal karstic aquifers which have been affected by significant karstification according to several phases. They are characterized by submarine springs whose flow rate is large and variable and the water is fresh or very slightly salty during the hydrological cycle. The non-contamination by seawater is due to the obstruction of conduits by continental or marine sedimentary deposits due to karstification phases. Discharge occurs through covering layers. Losses of hydraulic water head are high within conduits, preventing permanent intrusion of seawater into the aquifer. The aquifer may be confined on land and may have a significant storage capacity of water at depth. The karstic aquifer in Banyas, Syria, is representative of type 3 [ALC 07, BAK 07], just like the spring of the Vise.

### 1.2.2. *The land–sea continuum: islands*

For large islands, the sea–land continuum characteristics do not differ from the continent–ocean continuum, with the exception of the absence of large river basins and therefore large sedimentary basins. For small islands with an area less than 3,000 km², the size of the saltwater–freshwater interface depends on hydrogeological and exploitation conditions. Saltwater intrusions may be local, not affecting the whole aquifer, which is the case for volcanic islands (e.g. Reunion, Canaries, Caribbean, Mayotte, Hawaii and Galapagos) or larger such as Majorca in the Mediterranean. This extreme situation corresponds to partial or complete and continuous intrusion beneath the island. Freshwater floats on saltwater. This situation exists in Malta, in ocean atolls and some Caribbean islets [CUS 02].

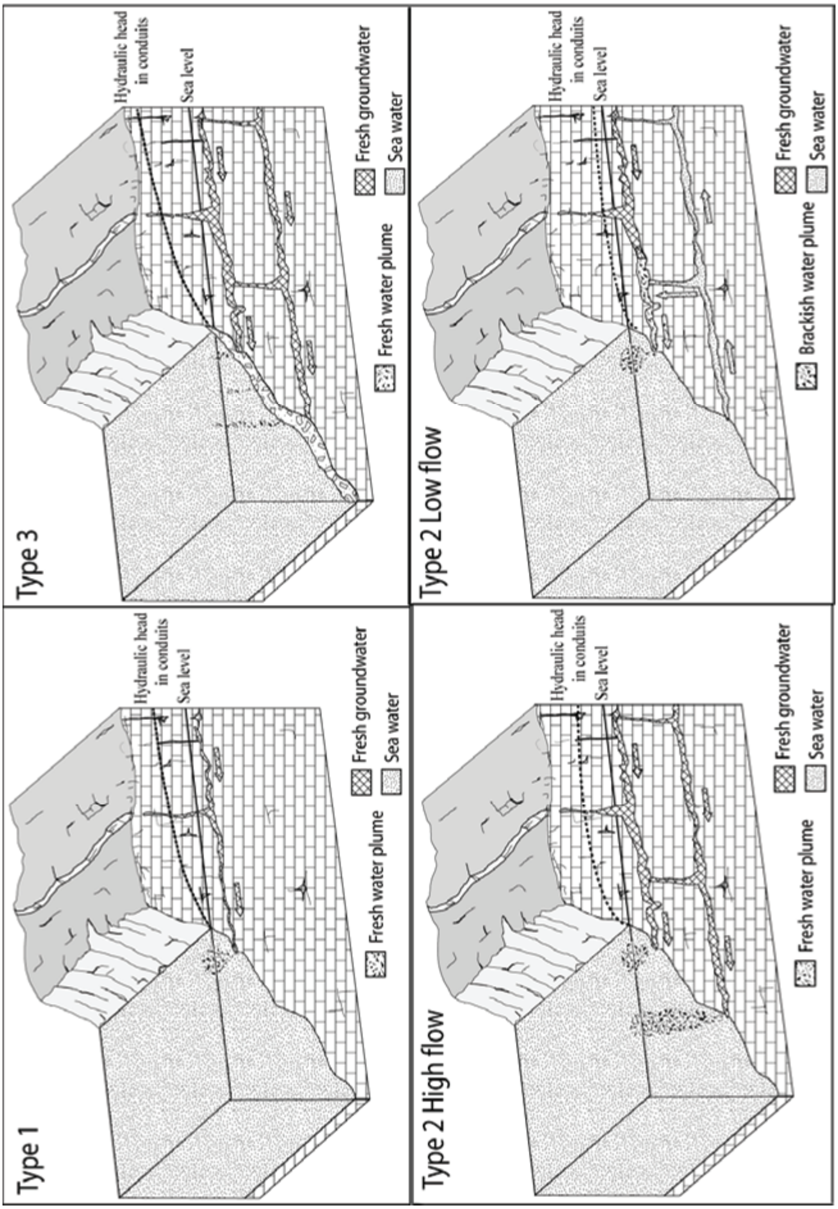


**Figure 1.10.** *Three types of functioning of coastal karstic systems with undersea sources, according to [FLE 12]*

For volcanic islands, the interface between the sea and land depends on the genesis and alteration of the volcanic layers present, and therefore on the type of volcanism, as well as the hydrogeological role of the main faults, according to their degree of connectivity. The more recent the volcanic layers, the more likely saltwater intrusion due to poor water storage in excessively transmissive layers [PRY 11]. On volcanic islands, two types of aquifer can be distinguished: a basal aquifer with or without a hydraulic connection to the sea and aquifers at high elevation, without any link to the sea, formed by water trapped in lava between dikes (perched aquifer) [LAU 06]. A conceptual model was developed for the Hawaiian Islands, and another for the Canary Islands (Figure 1.11) [GIN 00, JOI 05]. For the Canary Islands, the proposed conceptual model has, for some islands, low permeability at the center covered by more recent volcanic layers. The role of dikes within the volcano, from a hydrogeological point of view, varies according to the island [CUS 04, CUS 07, IZQ 11].

## 1.3. Problems with the management of water resources of coastal aquifers

The extraction of groundwater from coastal aquifers causes a decrease in the hydraulic water head of the aquifer, as well as in the bodies of freshwater and saltwater. This creates a groundwater level depression, a decreased discharge of freshwater in wet coastal zones and in the sea, on the one hand, and increased flux of saltwater in the aquifer, on the other hand. Isoconcentration curves are thereby modified and reach the pumping zone, and the mixing zone increases over time. In all cases, a larger volume of the aquifer is occupied by saltwater and brackish water. The water pumped according to the pumping configuration and hydrogeological proprieties may be fresh or rapidly become brackish or salty [CUS 02]. The lateral movement of saltwater is a slow process whereas upward vertical movements of water may be rapid (several hours to several days) in the absence of low hydraulic conductive layers. The presence of lithological layers of low hydraulic conductivity may influence seawater intrusion by delaying or reducing vertical flows of saltwater [MOT 92].

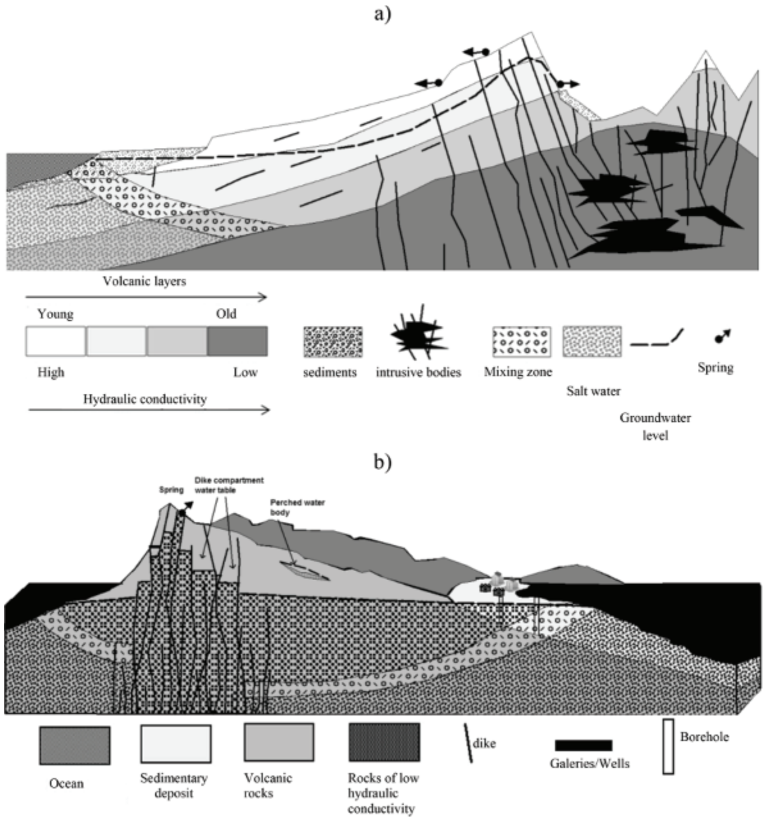


**Figure 1.11.** *a) Hydrogeological conceptual model with a distribution of the hydraulic conductivities by layer and the thick basal reaching the upper points, proposed by [JOI 05] according to [CUS 88] for the Fournaise volcano (Reunion). b) Hydrogeological conceptual model of the Hawaiian Islands according to [GIN 00]*

The problem of saltwater intrusion within coastal aquifers and their management is the subject of the following scientific studies: [BEA 99, CRO 95, CUS 85, CUS 97, CUS 02, CUS 10, GLO 59, HEN 64, VOS 87]. The geometry and extent of saltwater intrusion also depend on the degree of heterogeneity of the aquifer [DAG 98, HEL 05]. The essential concepts associated with coastal aquifers concern the saltwater–seawater interface and the origin of salinity of coastal aquifers.

In this context, freshwater flowing toward the sea comes into contact with the seawater. Due to the difference in density, freshwater (density ρs 1,000 g/L) flows on top of saltwater (density ρs = 1,025 g/L). An interface forms between the less dense freshwater flowing toward the sea and the underlying denser seawater. This is the saltwater intrusion or the mixing zone. This interface is not static, and especially when the aquifer is overexploited. Both media will therefore compete according to rules, which are in theory relatively simple but more complex in reality, and saltwater intrusion moves inland. Sometimes, the impact of the invasion of saltwater in a littoral aquifer may be irreversible.

Determining the shape and position of the contact zone between saltwater and freshwater has driven many studies for more than a century. The first studies on porous coastal aquifers were carried out at the end of the 19th Century [BAD 88, HER 01] based on the principle of hydrostatic equilibrium between two immiscible fluids of different densities, in two-dimensions (2D). In a porous aquifer at equilibrium, both media barely mix. In fact, the less dense freshwater lies on top of the saltwater with an inclined contact similar to a curved surface. The depth of the interface is determined by solving the flowing equation by taking into account the groundwater level whose reference is the mean local sea level and the density of freshwater and saltwater:

$$z = \frac{\rho_s}{\rho_s - \rho_f} \times h = a \times h \qquad [1.1]$$

where $z = z(x)$ is the depth of the saltwater–freshwater interface above sea level, $\rho_f$ is the density of freshwater, $\rho_s$ is the density of saltwater, $h = h(x)$ is the groundwater level of the aquifer above sea level and $a$ is the density ratio, generally understood as being equal to 40, but which may vary between 33 and 50 according to the density of saltwater. If this equation approximately identifies the position of saltwater intrusion, assumptions of the Ghyben–Herzberg principle show a certain number of limitations as follows:

– the fluids, freshwater and saltwater, are miscible;

– these fluids are subjected to hydrodynamic movements;

– groundwater flows are not taken into account;

– an aquifer is rarely homogeneous and unique.

Glover proposed a mathematical description for the intrusion phenomenon by considering the limitations mentioned above, to determine the position of saltwater intrusion in this configuration and, in particular, to calculate the distance from the coast to the interface freshwater–saltwater, in the sea (Figure 1.12). This formality depends on the permeability of the aquifer and the groundwater flow rate.

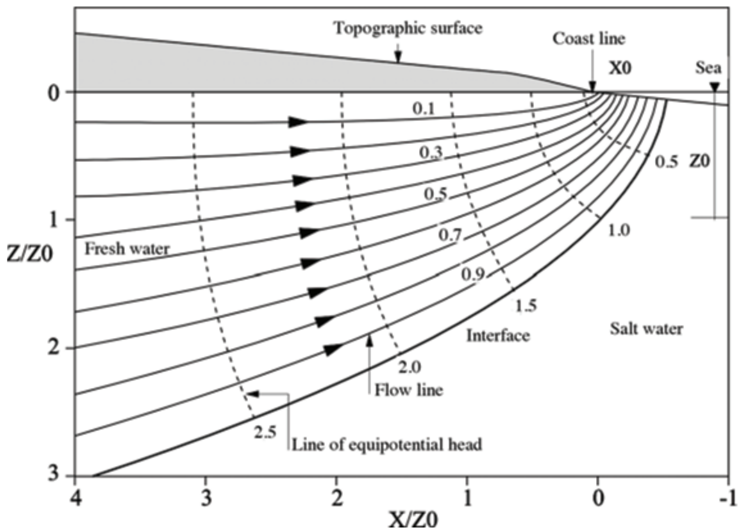


**Figure 1.12.** *Explanatory diagram of the Glover solution [CUS 02]*

The 2D Glover solution [COO 64] is valid for homogeneous coastal, isotropic and confined aquifers with a body of freshwater flowing over an interface for the permanent flow conditions of seawater. The water flows horizontally toward the sea. The total flow of freshwater $q_0$ is subdivided into 10 flow tubes. The hydraulic water head of freshwater is $H = \Phi\, z_0 / \alpha = \Phi\, q_0 / k$ with $\alpha = \gamma_f / (\gamma_s - \gamma_f)$, where $\gamma$ is the specific mass of freshwater (*f*) and saltwater (*s*), $x$ = distance to coast and $z$ = depth below the sea level.

Given the diversity of coastal aquifers and the geological and hydrogeological configurations of the sea–land continuum, the actual identification of freshwater–saltwater interfaces is complex. It is necessary to refer to geological, quantitative hydrogeological and hydrochemical, or even geophysical descriptions, integrating observation networks (networks of groundwater observation boreholes with salinity measurements) to characterize the flows and salinity acquisition modes, and to propose management modalities.

The purpose of managing coastal aquifers is the sustainability of the groundwater resource, by considering other available water resources, assuring the supply of clean drinking water and respecting the environment. In comparison with the management of continental aquifers, the specificity relies on the consideration of the salinization hazards and the degradation of groundwater quality for aquifer development conditions. The main points to consider for the management of coastal aquifers are as follows:

– understanding the structure and functioning of aquifers;

– a monitoring or even a warning system, with the definition of threshold values for groundwater level and electrical conductivity for which it is necessary to modify the sampling for the given periods by adjusting to the water requirements or by using other water resources;

– the willingness of management authorities and management structure to implement management tools with users involvement [CUS 02]. 2D and 3D numerical models have been developed and they take into consideration the mass transport (salinity affected by density) [MOL 94, VOS 85]. The coordinated management of surface water and groundwater (e.g. the artificial recharge of groundwater to form a hydraulic barrier to limit saltwater intrusion) may be necessary for very sensitive aquifers. Numerical models help simulate scenarios of use and management for different hydroclimatic conditions.

### 1.3.1. *Coastal aquifers of sedimentary basins*

Coastal aquifers of sedimentary basins are exploited for different uses, which causes a significant risk of saltwater intrusion. The exploitation of these aquifers for different uses may cause a decrease in the groundwater level in the long term, as observed in the Roussillon basin (Figure 1.13) and a variation in the electrical conductivity of water and the concentration of chlorides (Figure 1.14). Even though empirical formulas help locate the position of a mixing zone between freshwater and seawater, the distribution of hydrodynamic proprieties within heterogeneous lithological layers makes it difficult to understand exactly how this interface functions. Intrusions occur not only in surface layers in the sandbar and in contact with lagoons, but also in deeper layers, according to the lithological nature in contact with the sea. The diffusion of brine within slightly permeable layers may occur.

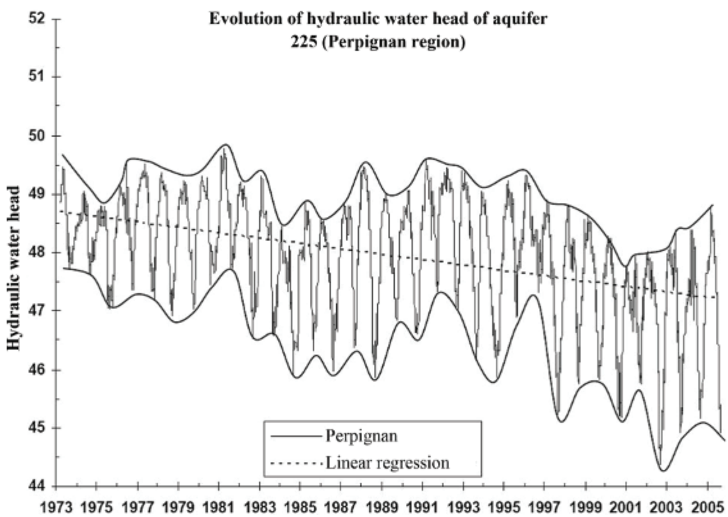


**Figure 1.13.** *Long term decreasing evolution in hydraulic water head of aquifer 225 (= Pliocene continental aquifer). The curve of the maxima and minima characterizes the increase in sampling range. Each high peak relates to winter and each low peak refers to summer, west-east [AUN 07]*

FIGURE 4.14 NOTES.– To the north of the Roussillon basin, the Salanque plain is most vulnerable to a decrease in water quality due to the presence of the Salses-Leucate lagoon, the high hydraulic conductivity of geological layers and the existence of numerous boreholes, some of which are defectuous. To the south of the

Roussillon basin, the quality of water only decreases in some sections close to the sea, with regard to the superficial aquifer.

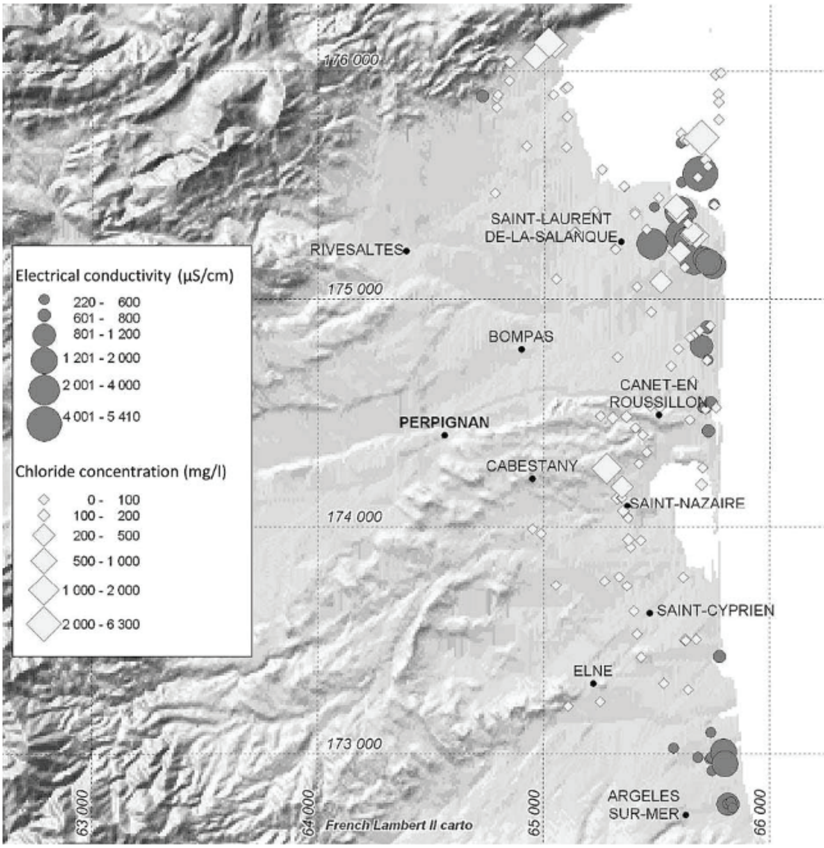


**Figure 1.14.** *Groundwater quality of coastal aquifers in the Roussillon basin. Electrical conductivity of the surface aquifer and chloride concentrations of confined aquifers [AUN 06]*

The location of saltwater intrusions within aquifers in continuity with the sea is studied using direct measurements (electrical conductivity or hydrochemical analysis of water samples) in groundwater observation boreholes or even indirect measurements, of a geophysical nature. At the regional level, the exploitation of airborne geophysical data helps demonstrate the spatialization of the saltwater intrusion [DOR 12]. Locally, hydrogeophysical data on boreholes in duplicate equipped with a Westbay (r) SWS system and multi-electrode system (SMD (c) Imageau) of copper separated by 0.7 to 1.5 m according to the borehole depth, thereby allow the continuous monitoring of the vertical distribution of the salinity of terrain. The electrical conductivity profiles of the pore fluid show the influences in precipitation on the filling as well as variations in hydraulic water head due to sampling. The system ® SWS samples different levels of aquifers intercepted by drilling to measure the pressure, temperature and electrical conductivity of water. The water samples are analyzed, particularly from an isotopic point of view to obtain additional information about the origin of salinity. The simultaneous use of different methods is a real innovation in integrated instrumentation. All of this data is used to establish a hydrogeological conceptual model of a sea–land cross section to model saltwater intrusion phenomena as well as management solutions (temporary decrease in sampling, artificial recharge by surface water or treated water to form a hydraulic barrier) [DOR 13a] (Figure 1.15).

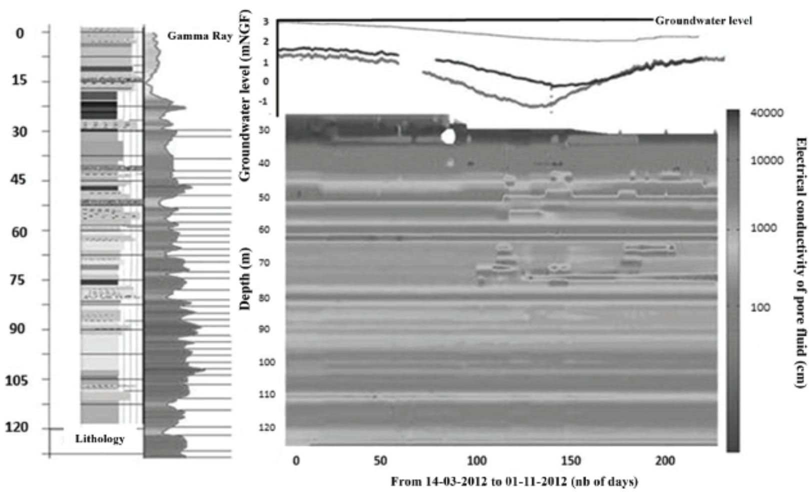


**Figure 1.15.** *Continuous recording of the electrical conductivity of a pore fluid on a groundwater observation borehole using a SMD device © Imageau [DOR 13a]*

From high-frequency boreholes, zones with varying salinities are identified both over time and vertically. For example, electrical conductivity of pore water at a depth of 30 m indicates, for the period of February–June 2012, an influence on the recharge and an increase in the hydraulic water head. A decrease in the freshwater zone is seen in the upper part (between 60 and 80 m) after the month of June, associated with a lower recharge and an increase in sampling. In the bottom part, the variability in electrical conductivity is low [DOR 13b].

### 1.3.2. *Karstic coastal aquifers*

The management of karstic coastal aquifers is directly linked to the type of development. Groundwater may be exploited at continental coastal springs, boreholes intercepting favorable flow zones or even submarine springs. The heterogeneity of the medium makes it difficult to determine the exact location of the freshwater–saltwater interface, which will occur both in karstic conduits and fissured limestone blocks. Depending on the type of karstic coastal aquifer (see section 1.2.1.2), saltwater intrusion will be large and perennial. The purpose of monitoring networks of karstic coastal aquifers, with regard to their management, is to integrate monitoring points at sea in submarine springs that can function as an outlet or as an introductory point according to the hydrological and exploitation conditions on land, or even at sea.

Continuous submarine karstic springs have long intrigued populations. Since Antiquity, there have been attempts to channel submarine springs, but due to the complexity of the medium and the mixing between freshwater and seawater, this has not been very successful. Since the 1960s, research has been carried out on some submarine karstic springs in Europe, including France, Italy, Greece and Croatia. There has been a rise in interest over the past few years, due to the increasing demand for drinking water in coastal zones and due to shortages associated with the effects of climate change.

Quantifying the flow of submarine springs is still a crucial issue in order to define the value of water capturing; methods based on the chemical composition of water, particularly by measuring radon, are used to perform mass balances and deduce flow rates, but require a large amount of data. *In situ* measurements using a flowmeter installed in a pipe positioned and sealed to the right of the submarine spring, if the configuration allows it, provide information about flow rate and physicochemical parameters. However, these devices are fragile and vulnerable to winter storms (Figure 1.16). Finally, the development of an autonomous underwater vehicle (robot) equipped with probes facilitates repeated measurements to be taken in the space above submarine springs. These measurements must be interpreted using hydraulic models used in oceanography [DOR 06].

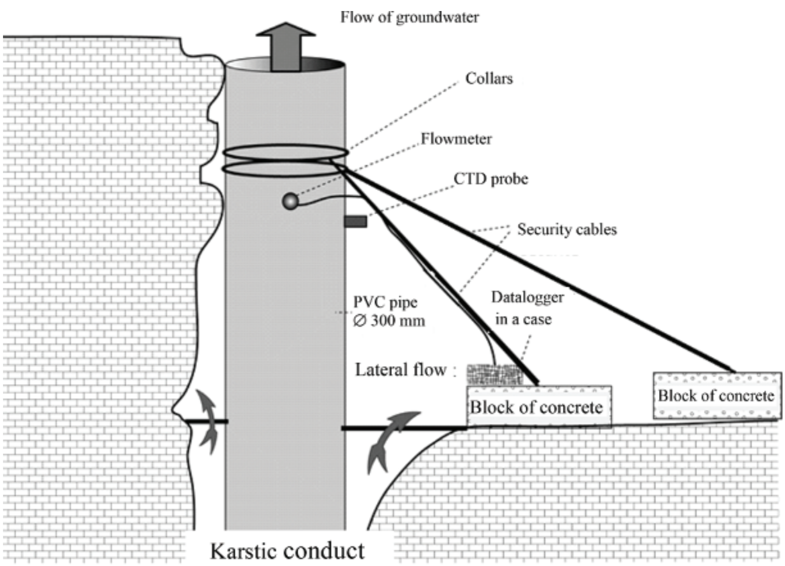


**Figure 1.16.** *Microcapture system of karstic undersea springs to record flow rate and electrical conductivity*

Recent studies, particularly in Libya (Chekka sources), have shown that the estimated flow rates of undersea springs were often overestimated (60 L/s at lowest water levels [BAK 12] compared with an assessment using a micro flowmeter and near-infrared image analysis given at 2 $m^3$/s [HAK 74, KAR 67]) and that the quality of groundwater, being of a brackish nature, did not favor their capture at sea. It is therefore preferable to look for favorable sections on land for drilling sites and equip undersea springs with devices to monitor the temperature and conductivity to support the management of karstic coastal aquifers [BAK 12].

Recording the pressure, temperature and electrical conductivity of water in one of the undersea springs at Chekka in Libya (source S2) shows the complexity of hydraulic relationships and exchanges between freshwater and saltwater, as well as the influence of a pump on land (Figure 1.17) [BAK 12]. During periods of high water levels, the hydraulic water head in the conduits is much greater than it is at sea, with freshwater being discharged into the sea. During periods of low water levels, the salinity of the undersea spring, with a relatively constant flow rate, increases progressively. Note that the salinity in spring S2 is influenced by variations in water head at sea with regard to tides, despite being of low amplitude (approximately 0.20 m) and also during storms. The level of seawater within the spring water varies between 50 and 80% throughout the tidal cycle. The variation in salinity is pronounced when hydrologic conditions change from low water to high water levels.

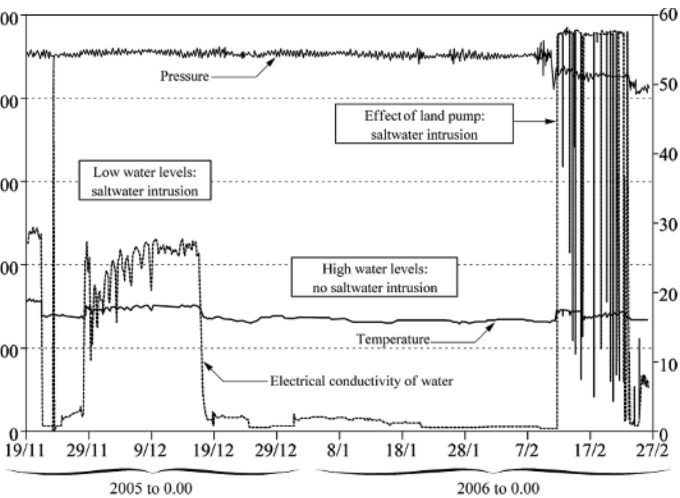


**Figure 1.17.** *Variations in hydraulic load, temperature and electrical conductivity of the underwater spring S2 at Chekka for varying hydrological conditions and under the effect of a continental water pumping [BAK 12]*

For the karstic system at Chekka, the flows usually occur in open conduits, with low water head losses. The discharge of the aquifer in the sea is sensitive to relative variations in hydraulic water head between the sea and the aquifer. As recharge to the aquifer is maintained by loss from rivers, the freshwater water head is sufficient to prevent saltwater intrusion into lower conduits. However, when the hydraulic water head in the aquifer becomes low, and especially in the conduits connected to undersea springs, saltwater may enter the aquifer (Figure 1.18) [BAK 12].

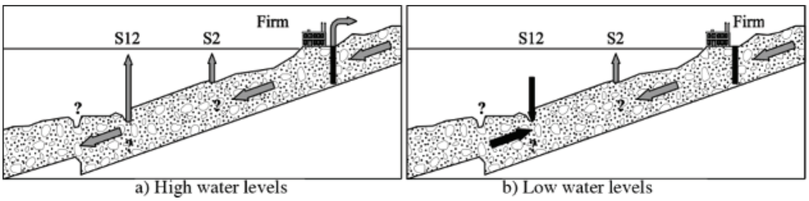


**Figure 1.18.** *Explanatory diagram of functioning of undersea springs at Chekka during periods of high water levels (left) and low water levels (right) with marine intrusion in S12 and discharge of brackish water in S2 [BAK 12]*

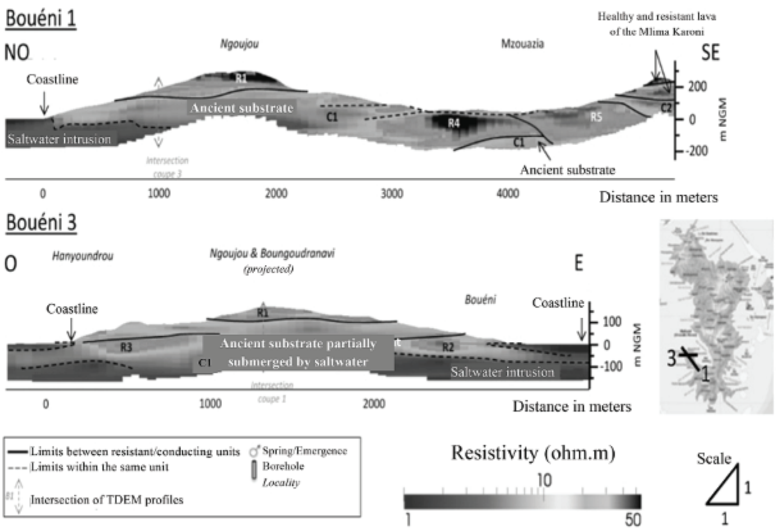


**Figure 1.19.** *TDEM profiles interpreted in the south west of Mayotte, Bouéni section ([JAU 12] in [DOR 13]) (see color section)*

### 1.3.3. *Coastal insular volcanic aquifers*

Given the limited knowledge of volcanic structures on different islands, due to the complexity of their internal structure, managing water resources and the sea–land continuum includes acquiring both hydrological and geophysical data. Electromagnetic airborne geophysical methods help obtain information about the structure of the volcanic edifice, the hydrogeological water resources' importance and saltwater intrusion zones [AUK 09]. For example, two sections of resistivity obtained by airborne geophysics in Mayotte demonstrate that saltwater intrusions may be rather extensive (Figure 1.19) ([JAU 12] in [DOR 13]).

## 1.4. Conclusion and perspectives

The portion of land between the continent and the sea is a complex and varied hydrogeological continuity depending on the geological conditions and groundwater development conditions. The geological and hydrogeological characterization of this continuum is essential to ensure the sustainable management of water resources. Also, geological approaches to sequential stratigraphy and reconfiguring of paleographic evolution, hydrogeological and geophysical approaches, geochemical and isotopic tools are important tools to determine the origin of salinity (saltwater intrusion, paleo-salinity, anthropogenic contamination, etc.) and to contribute to designing a conceptual model. Understanding the structure and functioning is essential to size up a monitoring and warning system as well as to develop numerical models useful for testing management scenarios and as a decision support tool.

Coastal aquifers are essential sources of freshwater for different uses in this space between the sea and land. Hydrological modifications in this space cause a modification in the freshwater–saltwater interface. Rising sea levels due to climate change may induce significant migrations due to the significance of variations in sea level and hydrogeological conditions of the mixing zone [WER 09].

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