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Mapping techniques and hydrogeological models to characterise seawater intrusion in French coastal aquifers and assess the potential impact of sea-level rise

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Contents

Coastal aquifers contain large quantities of groundwater essential for both human activities (drinking water, farming, industry and tourism) and for the environment (littoral wetlands, coastal marshes and lagoons fed by coastal groundwater). Along the 5 500 kilometres of coastline in continental France, 95 superficial and 17 deep coastal aquifers have been identified. In the islands (French overseas territories), aquifers are generally all coastal.

Partial intrusion of seawater into coastal aquifers is a natural phenomenon. The degree and range are variable and depend on the geologic features of the underground reservoirs. Intrusion may be amplified by pumping of freshwater and/or by a modification in the sea level, for example in response to climate change (Werner and Simmons, 2009). Natural seawater intrusion, whether coupled with an anthropogenic influence or not, risks contaminating the freshwater contained in the underground reservoirs.

This document presents, via examples, a number of tools that can be used to qualify seawater intrusion and the potential impact of a sea-level rise on salinity levels in coastal aquifers.

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Following a brief presentation of seawater intrusion, various methods to qualify the phenomenon are discussed and two in particular are reviewed in detail with illustrations. The first of the two required the development of indicators and is used to map the sensitivity of French coastal aquifers to seawater intrusion. The second method is a model used to determine the potential impact of global change on coastal aquifers. Examples from continental France and the overseas territories illustrate how it can be applied.

The saltwater wedge in coastal aquifers

Coastal aquifers may be found in an array of geological formations, e.g. sediment basins, alluvium, fractured basements, volcanic zones and karstified carbonated formations. They constitute the meeting zone of two types of groundwater:

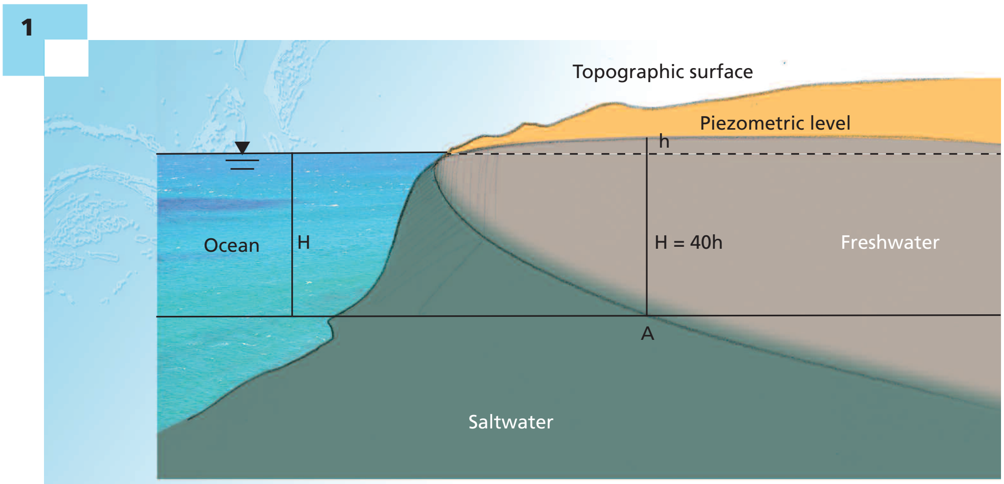
- freshwater provided by the infiltration of precipitation and the runoff of continental surface waters;
- seawater permeating porous aquifers along the coast or penetrating rivers via estuaries, thus increasing the salinity level of groundwater in hydraulic contact with surface waters (ocean, rivers).

Coastal aquifers are thus in contact with seawater that penetrates more or less the coastal geological formations. Freshwater being less dense, it "floats" on top of the saltwater (Figure 1).

Seawater intrusion occurs as a wedge that descends as it progresses inland. Called the saltwater wedge, it constitutes the interface between freshwater and saltwater. The interface evolves over time, depending on aquifer recharging due to precipitation, human use of aquifer water and the sea level.

The piezometric level is the altitude at which the groundwater is in equilibrium with the atmospheric pressure measured in a well. It rises farther inland due to aquifer recharge through precipitation, the topography and the physical properties of the soil. The piezometric level may be altered by pumping which creates a cone of depression around the well and causes the saltwater wedge to rise (Figure 2).

The position of the freshwater/saltwater interface may be roughly determined using an analytical solution devised by Ghyben (1888) and Herzberg (1901) based on the ratio of the freshwater to saltwater densities. At all points in the aquifer, the interface is located below sea level, at a depth equal to 40 times the height of the piezometric level above sea level (Figure 1). More accurate estimates (Glover, 1959) take into account the flow of water to the ocean, resulting in the saltwater wedge being positioned at a slightly different level. In addition, for a given flow rate, the lower the permeability, the deeper the wedge. This factor is used to determine the sensitivity of aquifers to seawater intrusion.



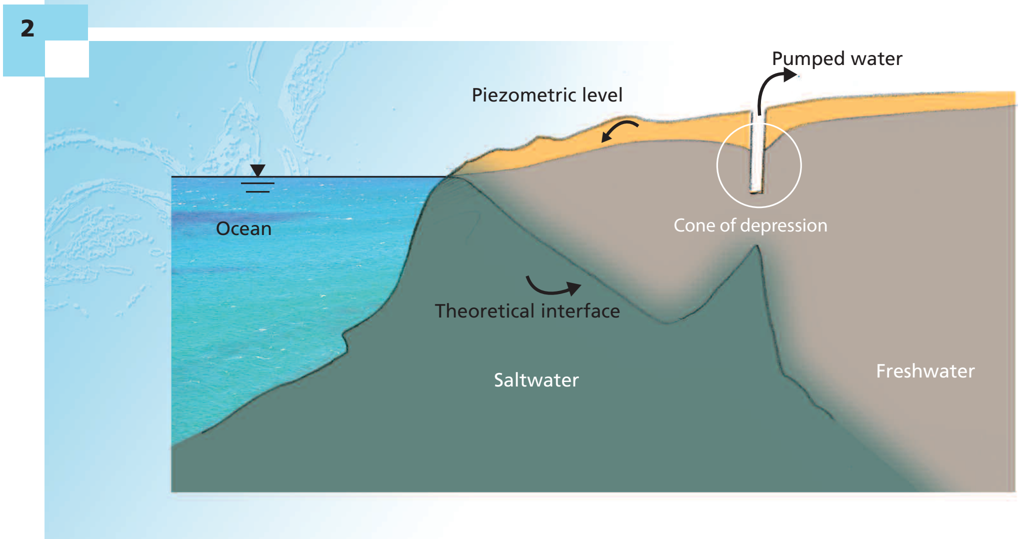


Figure 1. Cross-sectional view perpendicular to the coast, showing seawater intrusion as defined by Ghyben-Herzberg (drawn from Frissant et al., 2005). The saltwater wedge penetrates the porous aquifer such that at point A, the depth H below sea level is 40 times greater than h, the piezometric level.

Figure 2. Cross-sectional view perpendicular to the coast, showing the influence of pumping on seawater intrusion as defined by Ghyben-Herzberg (drawn from Frissant et al., 2005).

Tools available to characterise seawater intrusion

Seawater intrusion in coastal aquifers may be characterised using various hydrogeological tools. Four approaches, corresponding to different objectives, are presented here.

■ **Detecting salinity and monitoring its evolution.** Regular groundwater measurements of chloride levels (sodium chloride constitutes most of the salt in seawater) or of electrical conductivity (which depends on the quantity of dissolved salts in the water) is the first means to monitor an aquifer, both spatially and temporally.

A network of existing or dedicated wells can serve for such measurements in addition to monitoring the piezometric level. Salinity-monitoring options include continuous measurements of electrical conductivity at specific spots, periodic measurements on vertical profiles and continuous measurement of electrical conductivity on vertical profiles from recently created geophysical observatories.

Identifying the origin of the salinity. When salinity has been detected, geochemical and isotopic tools are available to determine the origin on the basis of samples drawn from wells. This method is useful in distinguishing between salinity from seawater and that caused by geological salt formations in the underground reservoir or contained in wastewater.

Determining vulnerability to seawater intrusion. When the data on aquifer salinity are limited, aquifer vulnerability may be estimated in a simplified manner by mapping the factors influencing seawater intrusion. This approach is discussed below.

Testing scenarios. Finally, hydrogeological modelling of a coastal aquifer can be used to understand seawater intrusion and test various scenarios. For example, scenarios may serve to explore the impact of changes in sea levels or changes in samples. However, sufficient knowledge on both the geometry and the physical parameters of the underground reservoir is required to create a model. Data collection requires geophysical studies or the drilling of boreholes with pumping and hydrochemical tests. Depending on the initial knowledge available and the issues at hand, this can be very costly in terms of time and money.

Using mapping techniques to assess the vulnerability of French coastal aquifers to seawater intrusion

To date, the impact of the saltwater wedge has been observed in certain French coastal aquifers, but on the whole, no major seawater intrusion has occurred.

The origin of the salinity in French coastal aquifers may be:

- natural, e.g. in the low-altitude Camargue, Nord-Pas-de-Calais and Picardie regions, in Brittany and on Noirmoutier Island, in the karst springs of the Calanques or the alluvial aquifers in the Languedoc-Roussillon region;
- anthropogenic due to freshwater pumping, e.g. in the Mediterranean alluvial aquifers (Provence-Alpes-Côte-d'Azur region), estuary zones in Upper Normandy or aquifer formations linked to the Marais Poitevin marshes.

To provide an idea of the sensitivity of aquifers to seawater intrusion along all coasts in France, the next pages show maps indicating various factors influencing seawater intrusion. Salinity measurements were mapped and combined with data on aquifer sensitivity to seawater intrusion (types of geological formations) and data on human abstractions.

Sensitivity of coastal aquifers to seawater intrusion

The sensitivity of coastal aquifers throughout continental France to natural seawater intrusion was estimated using data on the geological formations and notably their permeability (data drawn from BDLISA, the database on aquifer systems). Five sensitivity classes were established (see box).

The five classes of coastal-aquifer sensitivity to natural seawater intrusion used in the study

Low sensitivity. In this class, impermeable, non-aquifer formations, generally layers of clay, constitute a protective barrier for aquifers located below or toward the hydraulic upstream (inland).

Low to moderate sensitivity. Semi-permeable formations, made up in general of sediment having a more or less high clay content, limit water flows, but may comprise more permeable aquifers in some places. This is notably the case for multi-layered formations in deltas or sediment basins. This class includes basement formations, having low permeability levels and distinct aquifer sections, but that may also be semi-permeable in some places. These aquifers are generally sensitive to saltwater wedges. Multiple, superposed intrusions may occur, depending on the geometry of the multi-layered formation.

Moderate sensitivity. Formations with moderate to high permeability may correspond to sediment aquifers (non-karstified, fractured limestone, porous, highly permeable aquifers) or to basement aquifers (weathered and fractured layers) in the contact zone, with coastal springs.

Karst - variable sensitivity. Karstic aquifers in this class are characterised by major differences in the distribution of fractures and hollows. Conduits may exist along the coast and develop into entire systems. Due to variations in the average sea level with respect to the continent over geological time, conduits may exist several dozen metres below the current sea level. These conduits may result in openings, i.e. points that may operate as outlets and/or sinks, depending on the hydraulic load in the aquifer, itself dependant on aquifer recharge and pumping. The sensitivity of a coastal, karstic aquifer is variable, particularly if there are underwater springs at different levels, however this type of aquifer may also be in the "Proven high sensitivity" class. Specific zones comprising hollows and springs (e.g. the Port Miou spring in the Calanques near Marseille) may be ranked highly sensitive. Freshwater wells and pumping in karstic zones may cause unforeseeable results in terms of seawater intrusion, with no effects in some cases and significant intrusion in others. These zones require specific studies.

Proven high sensitivity. This class comprises zones made up predominantly of permeable alluvia with bodies of groundwater accompanying rivers. They are confronted with the combined intrusions of the saltwater wedge and saltwater penetrating rivers, which may result in small wedges in aquifers on either side of rivers. This class also includes aquifers where seawater intrusions already exist and where there is a major risk of the situation becoming worse due to pumping, according to regional studies.

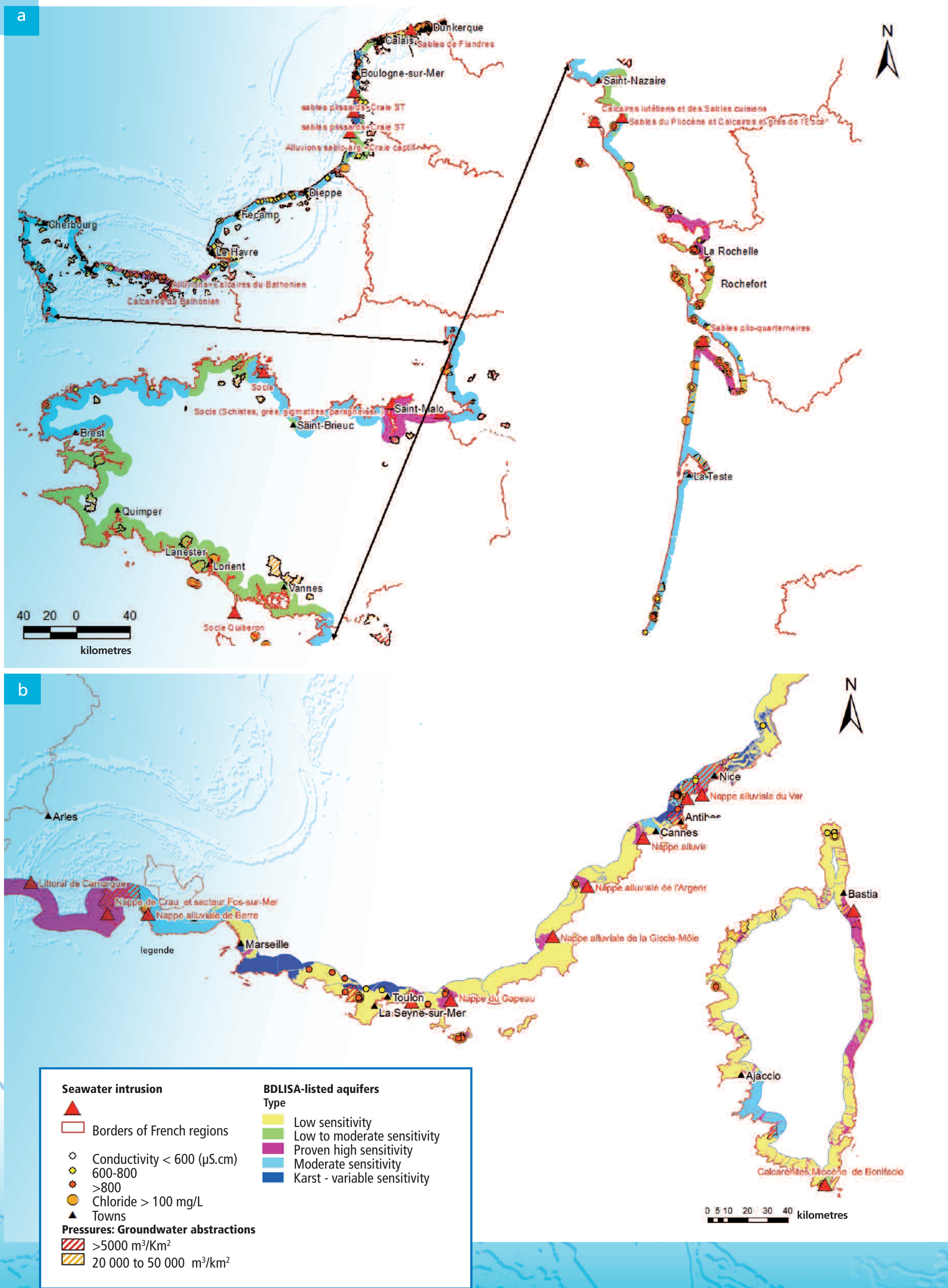
Data on human abstractions

Maps integrating the data on aquifer sensitivity and groundwater abstractions for drinking water, irrigation and industry have been drawn up. The abstraction data were drawn from the databases of the Water agencies (2009 data for the Loire-Bretagne basin, 2008 for the others, abstractions from deep aquifers were not included in this study).

Map integrating sensitivity and human abstractions

Figure 3 shows the map of groundwater vulnerability to seawater intrusion over a five-kilometre wide coastal zone. The map indicates both the geology of the underground reservoirs and the abstraction levels. It highlights the most vulnerable zones along French coasts that include Eastern Corsica, large sections of Languedoc-Roussillon, the northern coast of Poitou-Charentes, the north-eastern coast of Brittany and the Calvados coast. Note that the Mediterranean zones are the most heavily impacted by anthropogenic pressures which may enhance the risk of seawater intrusion.

3



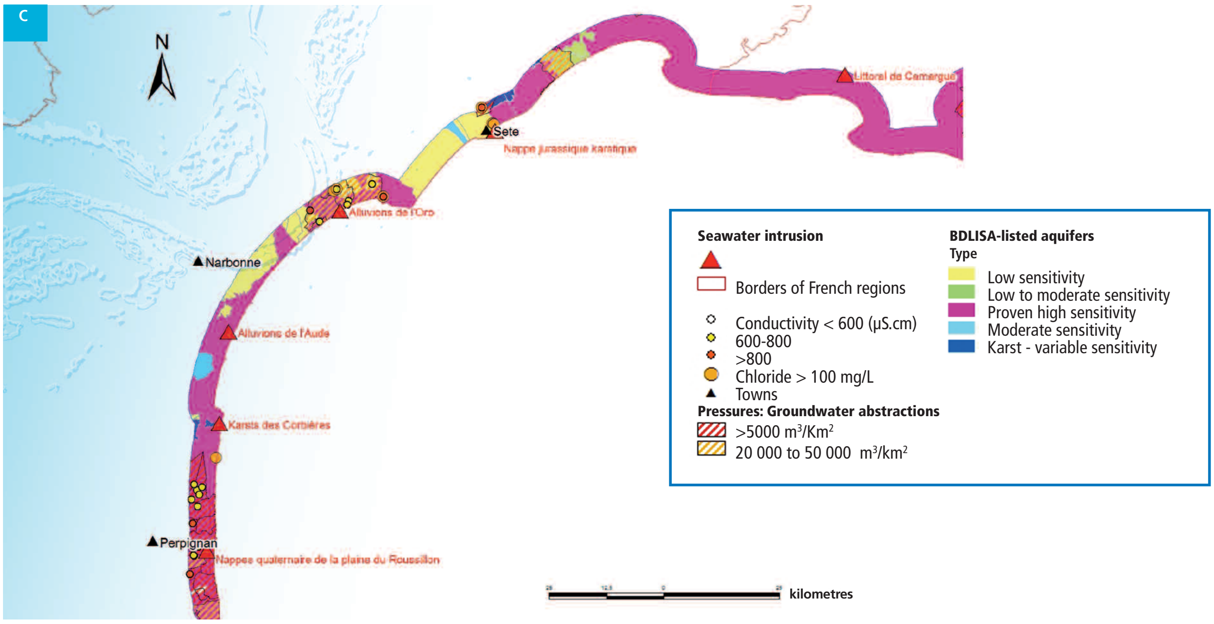


Figure 3. Map of groundwater vulnerability to seawater intrusion over a five-kilometre wide coastal zone.

Using models to assess the consequences of global change on coastal aquifers

The term "global change" covers all modifications in biosphere dynamics caused directly or indirectly by human activities. The influence of global change on seawater intrusion in coastal aquifers is linked first to increased demand for water due to population growth (for both drinking water and farming), secondly to sea-level rise (see box) and more generally to the impact of climate change on the water cycle.

Climate change and sea-level rise

The secular sea-level rise is caused by various factors listed here in order of importance, i.e. thermal expansion, melting of glaciers and ice sheets, and melting of the ice caps (Arctic and Greenland). The rise is not uniform on the global scale. The variations depend on differences in temperature and salinity.

Depending on the author, the foreseeable increase in the sea level by 2100 ranges from 0.2 metres (GIEC, 2007) and 5 metres (Hansen, 2007), however a value greater than 2 metres is not plausible given the physics involved (Pfeffer, 2008). The most recent estimates are fairly consistent, ranging from 0.8 to 1.8 metres. In light of the significant uncertainties inherent in the various methods, 0.6 to 1.0 metre are a plausible range for an increase in the sea level for use in impact studies on coastal aquifers. Note that in the overseas territories, sea-level rise may be greater during tropical storms and the recurrence interval for 1-metre rises is only ten years. For these reasons, maximum values of 2 metres should also be considered in analysing the consequences of a sea-level rise.

Evolution of population growth in coastal zones

Based on INSEE (French national statistical institute) data, estimated trends in population growth can be used to predict population densities in coastal towns in 2040 (Dörfliger, 2011b). Towns for which the population is projected to double by 2040 are located primarily on the south-western Mediterranean coast (Languedoc-Roussillon), in the Bordeaux region and in Southern Brittany. Water abstractions for these populations may increase the risk of seawater intrusion.

Impact of climate change on coastal aquifers

Climate change may affect coastal aquifers by modifying the sea level as well as the spatial and temporal distribution of effective precipitation (rainfall available to recharge groundwater). The potential impacts on groundwater resources in coastal aquifers consist of:

- a modification in seawater intrusions and changes (to variable degrees) in the freshwater-saltwater interface following an increase in the sea level;
- flooding of low areas by the sea and seawater infiltration of unconfined aquifers. In the five-kilometre zone along French coasts, approximately 600 square kilometres of land lying at an altitude of less than one metre are vulnerable to sea-level rise. These areas are located primarily along the Mediterranean, in the Vendée region and along the Gironde estuary (Dörfliger, 2011b);
- a modification in aquifer recharging due to spatial and temporal variability in precipitation and evapotranspiration, as well as in freshwater volumes and its distribution in aquifers;
- a modification in aquifer-discharge zones, which may impact wetland ecosystems.

Using hydrogeological modelling to characterise seawater intrusion due to sea-level rise caused by climate change

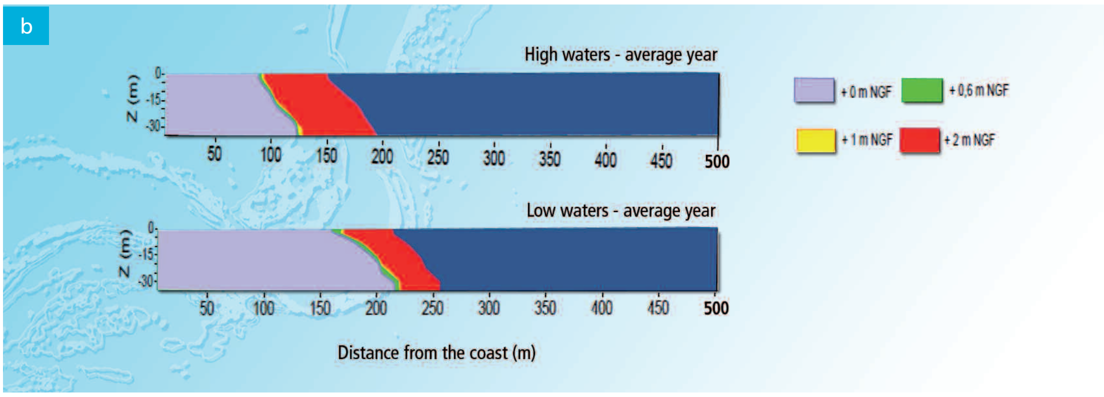
Digital models were used to test the effects of a sea-level rise on seawater intrusion in the Gironde estuary, the Dogger aquifer in the Marais Poitevin region and on Grande-Terre Island in Guadeloupe (Dörfliger, 2011a; Dörfliger, 2011b).

- For the Gironde estuary, the models revealed only a slight impact of a sea-level rise on salinity levels. The abstractions remain the major factor influencing the saltwater wedge.
- In the Marais Poitevin region, a sea-level rise could produce an effect several kilometres inland. For a rise of 0.6 to 1 metre, the shift in the saltwater wedge is minor (less than 20 metres), however, it is much greater for a rise of 2 metres under current operating conditions (Figure 4).
- The simulations on the aquifer of Grande-Terre Island in Guadeloupe show that salinity increases slightly throughout the island, from the coast inwards. According to the models and a simplified technique mapping vulnerability (Figure 5), the most sensitive sectors are those where the piezometric level is less than 2 metres above sea level and its slope is slight. The two sectors identified by these techniques are the northern plateaus and the eastern section of the eastern plateaus.

4

Figure 4. Progression of the saltwater wedge for different scenarios of sea-level rises, along a transect in the Marais Poitevin region (the leading edge of the wedge is defined as a chloride concentration of 100 mg.L-1).

The saltwater wedge along transect AB on Map 4a is shown in Figure 4b under high-water (top) and low-water (bottom) conditions for four sea levels (+0, +0.6, +1 and +2 metres A.S.L., above sea level). The diagrams show the saltwater wedge according to the altitude (z) and the distance from the coast. The results were produced by the regional hydrogeological model covering the grey area on Map 4a.



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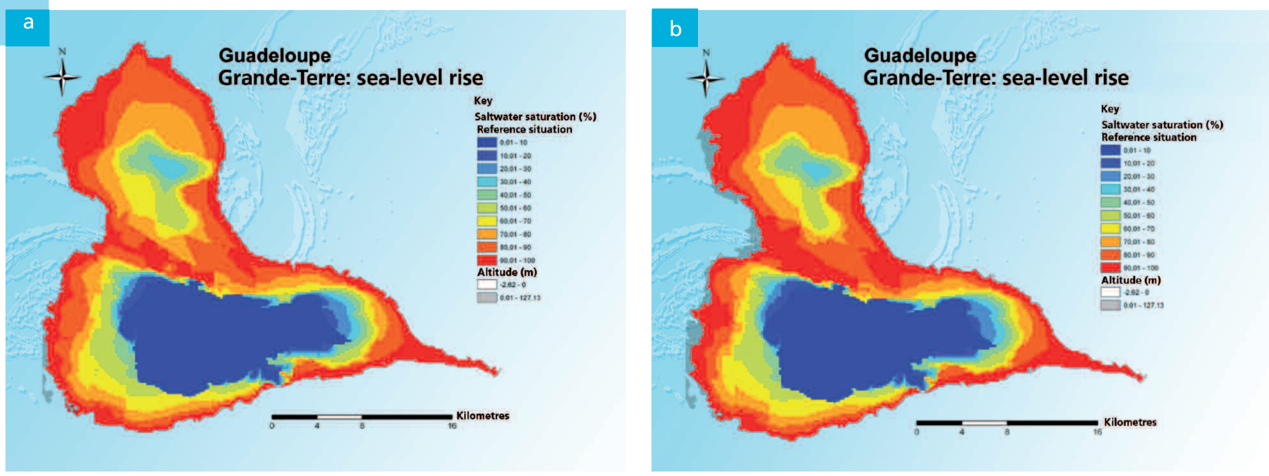

Figure 5. Saltwater saturation of the aquifer in Guadeloupe, NGG levels (standard Guadeloupe sea level). Figure 5a shows the current (reference) situation, Figure 5b shows the simulation for a 1-metre rise in the sea level above NGG.

Conclusion

Several types of tools are available to characterise seawater intrusion in coastal aquifers, including measurement networks, mapping of functional indicators and hydrogeological modelling.

These tools are presented here via a number of examples in continental France and the overseas territories. The results show that to date, seawater intrusion in French coastal aquifers is limited, however, certain regions are more vulnerable than others. In the future, however, the sea-level rise in conjunction with modifications in precipitation and evapotranspiration regimes, plus increased demographic pressures in the form of larger abstractions of groundwater could result in greater seawater intrusion in coastal aquifers.

Given current and future use of groundwater from coastal aquifers considered sensitive to a sea-level rise and to demographic pressures, management of water resources is indispensable to ensure sustainable use by the different consumers.

Management of coastal aquifers requires a monitoring network and the establishment of piezometric warning levels. If those levels are reached, abstractions must be limited over a given time period by reducing consumption or by calling on other water resources. The monitoring network for groundwater levels must be linked with a warning network signalling increases in groundwater salinity reaching threshold levels in aquifers. The salinity-warning network requires the continuous measurement of electrical conductivity, either generally or at specific points in wells. Coordinated management of surface and groundwater (e.g. artificial recharging of groundwater to create a hydraulic barrier to seawater intrusion) may be required for sensitive aquifers covering important needs. A management tool is thus necessary. It must include a digital model capable of simulating the position of the saltwater wedge under different scenarios (aquifer recharging due to precipitation, infiltration of surface water, abstractions, sea level, etc.).

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For more information

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