THE STATE OF THE FRENCH MEDITERRANEAN COASTAL AQUIFERS

N. Dörfliger
BRGM, Water department, 1039 rue de Pinville, F 34000 Montpellier, n.dorfliger@brgm.fr

ABSTRACT

The French Mediterranean coastal aquifers are essentially alluvial, deep sedimentary and karst. Whereas the alluvial aquifers are particularly sensitive to salt-water intrusion, contamination of the deep aquifers is generally due to vertical hydraulic connection with the shallow aquifers. As for the karst systems, which are quite well developed from Languedoc-Roussillon to Provence-Alpes-Côte d'Azur, their hydraulic pattern is generally complex; consequently the salt-water wedge is difficult to determine and can vary rapidly in both time and space. Although aquifer salinisation may be natural, i.e. in surface and karst aquifers (e.g. La Vise, Port Miou), it can also be due to human overexploitation. Fortunately no large areas of French Mediterranean coastal aquifer are so far concerned by salt-water intrusion. Water-management tools have been developed, as required by the Water Bill, in close cooperation with the water users and authorities.

INTRODUCTION

Geographic and socio-economic features

With about 600 km of coastline, the French Mediterranean is characterised by a contrasted topography ranging from the Languedoc coast with its vast continental platform and large brackish lagoons, to the mountainous and faulted Provence coast with its vertical limestone cliffs and the Calanques with narrow inlets and islands (figure 1). These last topographies are inherited from the Pyrenees-Provence orogeny. The Rhone delta, whose branches enclose the vast wetland zone of the Camargues, is at the junction of the two coastal topographies. The Corsica coasts are rocky and cliffed, similar to Provence, with inlets similar to Calanques; the exception is the Aleria plain on the east side of the island.

The French Mediterranean coast is under the jurisdiction of two administrative regions: Languedoc-Roussillon (LRO) with 2.3 million inhabitants (1999 census) and Provence-Alpes-Côte d'Azur (PACA) with 4.5 million inhabitants (1999 census). These two regions have seen the highest demographic growth in France between 1962 and now, with increasing activities being developed in towns such as Montpellier.

The major areas of economic activity along the French Mediterranean coast are (i) agriculture, (ii) tourism, and (iii) industry. For agriculture, vegetables and fruit are important in the plains of the lower Rhone, as well as in the Low Durance and the Roussillon in the west near the Spanish border. Vineyards and olive oil are also important both along the coast and inland.

Figure 1: Geographical map of the French Mediterranean coast.

The development of an irrigated agriculture has arisen under the impulse of two major regional development companies – the *Société du Canal de Provence and the Compagnie nationale d'aménagement de la région du Bas-Rhône et du Languedoc* – founded in the 1960s to foster economic development by utilising water resources and organising land-use. Also in the agricultural domain, mention must be made of important fishing activities with oyster beds and fish farms in the lagoons as at Thau and Salses-Leucate. In PACA, however, fishing activities occupy less than 1500 persons for about 1000 boats.

As regards tourism, the Mediterranean coast is the second most popular region of France, after Paris, because of its climate, cuisine, marine and freshwater activities, trekking, art & culture (including well known art festivals), etc. Thermal activities in the Languedoc Roussillon are also important, with spas such as Balaruc-les-Bains along the Thau lagoon to the east of Montpellier, which is the third most popular French spa and thus an important attribute for the local and regional economy.

The third area of economic activity is industry, including the scientific and technological park with the University of Excellence. LRO has attracted the pharmaceutical industry and medical executive management, as well as hardware companies. PACA provides more than 2/3 of the sea salt produced in France, and has seen a major development in the telecommunications industry (microelectronics, multimedia, hardware and software, etc.). It harbours a naval and armaments industry, as well as high technology for marine engineering (Comex), and is seeing a development of the petrochemical and agroalimentary industries.

General problems in coastal aquifers

General problems that affect coastal aquifers along the French Mediterranean coast are:

(i) Salt-water intrusion due to natural conditions and human interference, such as over-exploitation or vertical leakage from shallow to deep aquifers through old poor-quality boreholes.

(ii) An increasing demand for water resources due both to the growing demography and the development of resort activities such as golf courses, and to the summer tourist influx.

(iii) Competition for water uses from tourism, agriculture and industry, especially considering that the Mediterranean area is still under economic development.

(iv) The presence of large underexploited groundwater resources in the karst aquifers that are difficult to capture, especially when the major outlets are submarine.

GEOLOGICAL CONTEXT

Regional geology of coastal areas

The geology of the French Mediterranean coast is linked to the history of the passive margin of the Gulf of Lions, located at the crossroads of various geotectonic areas. This margin was initiated, according to Guennoc et al. (1994), during the Oligocene-Aquitanian extension, which evolved with the rotation and southeastward movement of the Corsican-Sardinian block, leading to oceanic opening in the Early Miocene (figure 2).

A vast domain, extending between the Massif Central and the overlapping Subalpine chains, is characterised by a large thickness of Meso-Cenozoic sediments. This domain, also known as the Southeastern Basin, is both the foreland of the Alpine and Pyrenean mountain belts, and the northern prolongation of the Provence Ocean that, from the Early Miocene, extended from Roussillon and Provence to Corsica and Sardinia (Dercourt, 1997).

The margin is surrounded by a highly tectonic domain in which three stages followed one another:

(i) Triassic and Jurassic extension that reactivated the northwestern end of the Hercynian fracture network as normal faults,

(ii) Structuring of the lower part of the Upper Cretaceous, affecting all the Pyrenean domain with an E-W major direction of deformation, and

(iii) Oligocene extension resulting in the extension of the graben towards the north of the Provence Ocean (Dercourt, 1997).

Within the Mediterranean Sea, the continental shelf is very wide in the Gulf of Lions and very narrow offshore of Provence and the Southern Alps. The slope is covered by two submarine deltas (Rhone and Var). The Corsica-Sardinian coastal morphology is similar to that in Provence, with a very steep margin and a narrow or non-existent shelf. Thick Pliocene and Quaternary deposits present along the margin are the prolongation of the terrestrial deposits hosting the aquifers.

Lithology of coastal aquifers

The coastal aquifers of the mainland are mainly porous, including alluvial aquifers such as in the Var, Rhone and Hérault valleys, deep sedimentary aquifers in places multi-layered (Pliocene and Quaternary), coastal-plain aquifers (from Sète to Lunel) and karst aquifers. In Corsica the coastal aquifers are

Figure 2: Main geotectonic areas of Southeast France (Guennoc et al., 1994).
Legend: 1: Recent volcanism; 2: Post-Hercynian series; 3: Hercynian basement; 4: Area of large salt domes; 5: Normal Oligo-Miocene faults; 6: Tertiary thrust faults; 7: Offshore exploration wells; 8: ECORS deep seismic profiles.

mainly alluvial (covering less than 3% of the total surface area, but providing more than 60% of the water supply), and sedimentary with the Miocene beds of the eastern plain and the Causse de Bonifacio. Corsica also contains some not very productive fractured hardrock aquifers.

CHARACTERISATION OF COASTAL AQUIFERS

Types of coastal aquifers

The LRO region includes a large variety of aquifers along the Mediterranean coast with, from west to east (figure 3), (i) alluvial aquifers of coastal rivers such as the Aude, Orb, Hérault, Vidourle and Rhone, (ii) deep aquifers such as the Pliocene-Quaternary multilayer Roussillon aquifer, the captive Astian sands aquifer between Béziers and Agde, and the buried Vistrenque aquifer, (iii) karst aquifers such as the Fontestramar-Fontdame karst system of Corbières, Clape Mountain, and the Thau karst system with the Gardiole and Aumelas massifs, and (iv) coastal-plain aquifers from Sète to Lunel.

In PACA, the coast includes both karst and alluvial aquifers. Although the karst aquifers are large, they are not well known and little exploited for drinking water or other purposes. They include the Estaque and Nerthe chain west of Marseilles (223 km^2) and the Beausset chain east of Marseilles (660 km^2). The extensive Ste-Beaume - Beausset-Agnis aquifer includes three major karst systems, i.e. the Calanques, the South Ste-Beaume - Port Miou, and the Beausset basin – Faron systems.

PACA also includes six alluvial aquifers in contact with the sea, the main one of which is the 545 km^2. Crau aquifer (Pliocene-Quaternary pebbles) with a particular recharge that comes mostly from external irrigation water (Durance river water). The other alluvial aquifers are located to the east of Toulon and are small (15 to 44 km^2).

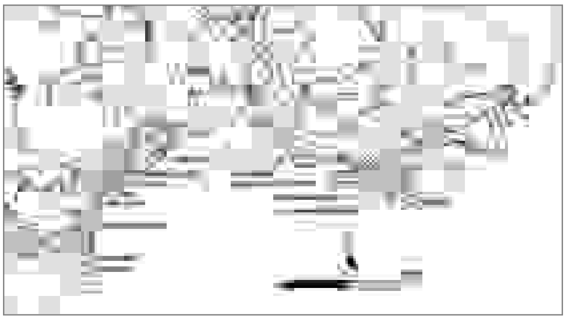


Figure 3: General map of main aquifers along the French Mediterranean coast.

Main parameters (permeability, porosity, thickness, etc)

Plio-Quaternary Roussillon aquifer

Pliocene layers: Salanque aquifer/deep Pliocene; The Messinian erosion surface is overlain by a marine succession that deepens seaward to reach a thickness of 640 m at the present coastline (Clauzon *et al.*, 1987). This succession essentially comprises mica clay and blue silts (Marine Pliocene clay) with lateral and vertical facies variations that include variably cemented sands and pebblestones (Marine Pliocene sand). The transition to continental facies corresponds to the prograding of the dejection cone on the submarine delta. The lower levels of the continental layers (Continental Pliocene) comprise horizontal sand and lignite clay with some interbedded lacustrine limestone. The initial thickness is estimated to have been 250 to 300 m (Clauzon *et al.*, 1987). The deep Pliocene aquifer is characterised by transmissivity values of 10^{-3} to $3x10^{-3}$ m^2/s (Chabart, 1996) and a storage coefficient of between 0.2 and $1x10^{-5}$. In the southwest of the Roussillon plain, the Pliocene aquifer is semicaptive with a storage coefficient value of about $5x10^{-2}$. The Pliocene Salanque aquifer is very productive with a transmissivity of 10^{-2} to $3x10^{-2}$ m^2/s (T = 10^{-4} m^2/s at the edge of the aquifer); this aquifer is captive with a storage coefficient between 2.2 and $6.4x10^{-5}$ (Chabart, 1996).

Quaternary layers: The Quaternary alluvial deposits are subdivided into two categories:

(i) old and recent banks or terraces with gravel and variably eroded pebbles (maximum thickness 3 m) for the old banks and up to 10 m of crystalline and limestone pebbles for the recent banks, and

(ii) Holocene layers corresponding to the maximum transgression of the Flandrian sea-level rise (Duvail et al., 2001).

The Quaternary alluvial aquifer lies along the main rivers and the coastline. Its thickness is varied:

- 10 m for the sectors located in the upper parts of the valleys (Agly, Têt and Tech)
- 20 to 30 m for the coastal fringe.
- Locally as much as 20 m in between.

The porosity of the Quaternary alluvial aquifer is about $7x10^{-2}$. This aquifer is confined at the coastal fringe, where its specific storage coefficient of 0.1 to $0.4x10^{-5}$ m^{-1}. The transmissivity values differ according to the sectors: thus current values in the Têt valley are $4\text{-}5x10^{-3}$ to $1\text{-}2x10^{-2}$ m^2/s with pumping rates from 50 to 100 and even 200 m^3/h. In the Tech valley on the coastal fringe, values are $5x10^{-3}$ to 10^{-2} m^2/s, and even higher locally, whereas at Salanque they are $5x10^{-3}$ to $2x10^{-2}$ m^2/s (Chabart, 1996).

The LRO karst system involves Middle and Upper Jurassic and Lower Aptian limestone, 800 m thick, and Middle Aptian layers, 100 m thick, for the Opoul Corbières karst aquifer whose major spring is the Fontestramar spring. Due to the heterogeneity of the karst environment, no representative data is available concerning the hydrodynamic properties. In addition, the Thau karst next to the Clape Massif is characterised by Jurassic limestone that constitutes the backbone of the area: up to 800 m of Callovian to Tithonian lime-stone is aquiferous. Local transmissivity values determined by pumping tests range from $0.5x10^{-4}$ to $3.5x10^{-2}$ m^2/s, and storage coefficients range from $8x10^{-4}$ to $3x10^{-2}$ (Marchal, 1986).

Deep aquifers

In the deep aquifers, such as the Astian aquifer be-tween Beziers and Agde, the hydrodynamic properties are relatively homogenous internally with transmissivity values ranging from $3x10^{-5}$ to $2x10^{-4}$ m^2/s in the northeast sector and from 10^{-3} to $6x10^{-3}$ m^2/s elsewhere (Laurent, 1993); the storage coefficient ranges from 10^{-4} to $6x10^{-4}$. Moreover, the efficient porosity in such sandy aquifers, whose thickness varies between 5 and 40 m, can reach values of 25% (Dubois, 1988).

Coastal plains – dunes

According to Heurteaux (1987), the coastal dunes of the Rhone delta are relics of an earlier extensive littoral sand bar; they are fairly modest formations of fine sand and are generally less than 5 m high. The freshwater stock in the dunes is never very large. The dunes form a specific protected environment and are not exploited as aquifers.

The CRAU aquifer

Ancient alluvial deposits of the Durance (gravel and pebbles with a sand matrix, locally cemented into pebblestone). These alluvial deposits are 5 to 10 m thick on the northern and eastern edges and in the central part of the aquifer; around the Entressen and Aulnes lagoons, their thickness is 0 to 5 m. Elsewhere, the thickness varies between 20 and 35 m, with a maximum along the axes: an east-west axis known as the Arles line, and a NNE-SSW axis known as the Miramas line. The permeability values are between $4x10^{-5}$ and $1.6x10^{-2}$ m/s, and the storage coefficient range is 1 to 8% (Bérard *et al.,* 1995).

Alluvial aquifers

The data presented here concern some representative alluvial aquifers of the Mediterranean coast in terms of thickness and hydrodynamic properties; i.e. the Var alluvial aquifer, and the Hérault valley. Data concerning the Roussillon Quaternary aquifer have been given in an earlier paragraph.

The transmissivity of the recent Hérault alluvial deposits ranges between $1.5x10^{-4}$ and $2x10^{-2}$ m^2/s, with the transmissivity values of the lower to upper banks being globally similar (Weng and Dörfliger, 2002). The permeability of this alluvial aquifer is generally in the range of 10^{-3} to $8x10^{-2}$ m/s. The thickness of the various banks and recent alluvial deposits varies between 5 and 10 m generally for the terraces, and up to 40 m for the recent alluvial sediments, which increase in thickness increases from north to south (Dubois, 1988).

PACA karst systems

Although karst systems are extensive in the PACA region and the major outlets are inventoried, the heterogeneity of the karst structures means that we have little data concerning their hydrodynamic properties. The karst systems develop in thick layers of limestone/dolomite, of which two examples are given below.

- The Port Miou karst system, in 400 m of Urgonian limestone, drains the network in the downstream part of the system; it is heterogeneous system about which little is known concerning its structure and the limits of its catchment area.
- The Paillon system whose sedimentary cover has a strong tectonic character. The Cretaceous beds are overlapped by Jurassic klippen, 400 to 500 m thick. The limestone compartments are fissured, with the groundwater flow being preferentially oriented along the syncline axis or major faults.

Resources / Pumping (rate, volume, etc)

In the LRO coastal area, almost 95% of the water supply is obtained from groundwater (40% from alluvial aquifers, 35% from karst systems and 20% from deep aquifers; Petit, 1996). Abstraction amounts to $150x10^6$ m^3/year (2000). Exploitation of the unique Roussillon Pliocene-Quaternary aquifer has increased considerably over the last 20 years and the mean annual groundwater abstraction from the total aquifer is evaluated at about 80 Mm^3, including 39 for drinking water and 4 for industry, plus 32 for agriculture that is supplied entirely by the Pliocene layers. The increased pumping is required in order to supply the increasing local population (Marchal et al., 2001).

With more than 600 boreholes, 4.6 Mm^3 are abstracted each year from the Astian aquifer, essentially for drinking water (75%). Pumping rates can exceed 100 m^3/h for artesian wells.

In PACA, the karst aquifer located in the western part of Marseilles (Estaque and Nerthe chains) supplies industry at a rate of $22x10^6$ m^3/year. Due to its vulnerability to contamination, especially in the industrial environment, this aquifer is not really used for drinking water supply. The second large karst aquifer is less exploited ($3.6x10^6$ m^3/year).

Role and importance of coastal aquifers

As the coastal region is attractive for many activities (agriculture, tourism, industry, etc.), it is characterised by a generally higher population density than the rest of France. The coastal aquifers provide a major contribution to maintaining and developing activities. However, their exploitation is constrained due to the presence of the sea and the risk of salt-water wedges.

Groundwater resources in the Mediterranean coastal region are in high demand for conflicting uses:

(i) The pressures of human activities are higher, specifically in summer time when the local population is more than doubled.

(ii) The coastal region contains many fertile plains that favour agriculture, and commonly an irrigated agriculture.

(iii) The harbour economy has attracted heavy industry, which is a high consumer of water (e.g. Fos-sur-Mer, Martigues).

The coastal aquifers also play an important role in safeguarding the environment, specifically regarding the wetland areas that are in hydraulic connection with the aquifers and are dependent on their discharge.

Whereas the coastal alluvial-plain aquifers and deep sedimentary aquifers offer extensive resources that are relatively easy to access (relatively shallow water table in porous and flat terrain), the widespread karst aquifers along the French Mediterranean coast are underexploited. The karst systems represent important reservoirs for the future. Due to their complex structure and heterogeneity, as well as their vulnerability to contamination in general, these groundwater resources are used partially for a harvesting policy.

The coastal aquifers are important strategic resources for the future. They are, however, fragile in their environment and require the application of specific water-management techniques.

Applied study methods and techniques

Classical hydrogeological studies are applied to the coastal alluvial and sedimentary aquifers: i.e. geological surveys in order to determine the geometry of the aquifer, combined when necessary with geophysical investigations, a hydrogeological study (aquifer boundaries, piezometric monitoring, hydrodynamic properties, flow directions, water quality and ground-water modelling).

Recent progress in geological knowledge at the coast/continent interface may provide interesting consequences in terms of water management and salt-water intrusion control.

For the karst systems, due to their heterogeneity and hydrodynamic behaviour, it has been necessary to develop specific investigation methods. The step-by-step method formalised by Marsaud (1996) involves the following phases:

(i) identification: analysis of the reservoir geometry and of its functions in terms of transfer and transit,
(ii) demonstration: pumping tests in caves, springs or boreholes, and
(iii) assessment: developing water-management and protection plans for the karst system.

In addition, as mentioned also by Bakalowicz *et al.* (2003a) in this congress, coastal karst aquifers have been strongly influenced by the sea-level variations occurring during the Late Quaternary (Messinian crisis – 1500 m fall of sea level; Clauzon, 1990). Consequently, major outlets of coastal karst systems may be located under the sea. Innovative techniques have to be applied in order to characterise the physical and chemical time-series parameters of such submarine springs as well as their discharge (Bakalowicz et al. 2003b).

CURRENT STATE OF SEAWATER INTRUSION

Affected aquifers

In LRO, from west to east, the following major aquifers are affected by a seawater intrusion:

(i) Alluvial aquifers

- The coastal part of the Quaternary alluvial aquifers associated with the Agly, Têt and Tech valleys is no longer used for drinking water supplies due to the high salinity (Cl >300 mg/l).
- The Orb alluvial aquifer is an unconfined aquifer more or less in hydraulic relation with the river; exploitation may reach 100 m^3/h when the aquifer is recharged by the river. This aquifer is used to supply drinking water to Béziers, the salt-water wedge being located downstream of Sérignan.
- The Lez alluvial aquifer, between Montpellier and Palavas, was heavily exploited for drinking water supplies (St-Jean catchwork in Lattes). Too high a pumping rate increased the mineral content of the groundwater (600 to >1300 mg/l) to the extent that the catchwork has been deserted.
- The southern part of the Vistrenque aquifer is salt contaminated with Cl contents higher than 350 mg/l downstream of St-Laurent-d'Aigouze. However, this aquifer is exploited below the sand dunes for the Thalassotherapy centre at La Grande-Motte; the salt-water is filtered through fine sand. This groundwater is also used for the Sea Aquarium at Grau-du-Roi.

(ii) Deep aquifers

- The Roussillon multilayer Pliocene aquifer (Marchal and Chery, 1995; Chabart, 1996) contains excessive mineralization at northern Salses along the lagoon, and even more so along the coast at Barcarés. In September 1999 and 2000, the Cl content in these sectors ranged between 250 and 500 mg/l and even exceeded 500 mg/l (Marchal and Chery, 2001). The origin of the contamination is vertical leakage from the partially contaminated Quaternary aquifers to the Pliocene aquifers due to the existence of defective boreholes. New boreholes drilled next to the old ones show a strong decrease in the water's salt content. The Quaternary aquifer was contaminated either directly by marine intrusion or as a result of earlier overexploitation.

- In the confined sandy Astian aquifer (Valencia, 1970; Laurent, 1993) the Cl content reaches 60 mg/l for the lower values and 3.7 g/l along the Thau lagoon. Two contamination risks are associated with this aquifer: (i) salt-water intrusion due to interformational flow resulting from local overexploitation of the aquifer, and (ii) contamination from defective or deserted boreholes connecting the Astian aquifer with overlying contaminated surface aquifers close to the coast.

(iii) Karst aquifers

The water in the two coastal karst springs at Opoul Corbières is saline with an average salinity of 3 g/l; its chemical facies is chloride-sodic. Chemical and isotopic data confirm the seawater origin of the salinity, putting to rest the hypothesis of a Triassic origin of the contamination.

With the Thau karst system, one of its outlets is a submarine spring, with a temperature of 21 to 23 °C and a total mineralization of 2 to 3 g/l (Aquilina et al., 2002). The water is a compound of deep thermal water, fresh groundwater and seawater. In addition all the coastal springs located to the southeast of the Gardiole Mountain are brackish or salty: i.e. La Madeleine, Creux de Miège, Font Forte, Roubine de Vic and Ambressac (with mineralization at 0.3 to >2 g/l). Extraction from the Cauvy spring for drinking water is limited to 100 m^3/h, and even less during the low-stage periods, in order to avoid salt-water intrusion (Petit, 1996).

In PACA, the following major aquifers are affected by seawater intrusion:

(i) Alluvial aquifers

The small alluvial aquifers between Toulon and Nice have different behaviours regarding salt-water intrusion and the management means involved.

The Var aquifer, very elongate and perpendicular to the coast, has a salt-water intrusion wedge that is considered as stable in both time and space. Groundwater modeling shows that water abstraction could be increased without any salt-water intrusion into the actual catchwork.

The Gapeau aquifer supplies the town of Hyères from two well fields. The resource is considered as easily exploited and abundant, but increased abstraction between 1950 and 1970 resulted in a seawater intrusion. In 1969, an anti-salt dam was built on the Gapeau River, and water abstraction was limited to 20,000 m^3/day maximum; the deficit was set off by external water purchase. The Cl concentration increased from 30 mg/l (1989) to 800 mg/l (1991), following which the concentration remained static due to the im-portant reduction of the abstraction rate.

With the Argens aquifer we find quality problems where river-water is infiltrated in order to stabilise the seawater wedge. No data is available to judge of the efficiency of such technique (Petit, 1996).

(ii) Karst aquifers

Few data are available concerning the coastal karst aquifers and more specifically the salt-water intrusion. Due to the heterogeneity of the karst systems and to the existence of both submarine and coastal springs, we can be assured that salt-water intrusion definitely does exist, but its extent is not well known, as karst compartments may also exist. The karst structure re-mains difficult be determined.

The Port Miou and Bestouan springs, belonging to the same karst system, are freshwater springs influenced by salt-water intrusion. In the 1970's a joint venture (Frankarst) undertook some studies and con-structed dams in the gallery located upstream of the spring. After 1972 the water salinity in the Port Miou Gallery was three times less than at the first stage of dam building: from 1.7 to 6 g/l. (COST 621 Action, 2003, to be published).

Scope and type of intrusion

Salt-water intrusions in the coastal aquifers range from local to regional as well as from seasonal to general. Some alluvial aquifers are contaminated owing to their close connection with the sea and/or to their overexploitation. Abstraction from these aquifers has been either reduced or stopped, and resources from deep aquifers or non-coastal karst aquifers are or will be used to satisfy present and future water demands.

In the deep coastal aquifers, salt-water contamination is globally local. Its origin is due either to contamination from the upper aquifer through old leaky boreholes, or to the geologic layers and their hydrodynamic properties close to the coast.

With the coastal karst aquifers, the salt-water intrusion is very often difficult to localise; it depends of the structure of the aquifer (distribution of the karst conduits and the connectivity to the annex system or less permeable surrounding rocks). In LRO, the coastal karst systems are also characterised by a thermal component of the water.

Seawater intrusion indicators

Localisation of the seawater wedges is very important in terms of coastal-aquifer management. Different methods exist for defining or indicating salt-water intrusions:

- Electrical survey for determining the geometry of the geologic structure and the salt-water wedge.
- Geophysical survey with electric, induced-resistivity and conductivity logging in order to monitor the evolution of the salt-water intrusion in time and space. In karst aquifers, where heterogeneity is common, the logging may be conducted between packers.
- Chemical analysis to provide indicators of water quality. The following ions, in particular, are analysed: Cl, Br, Na, K, Ca and Mg.
- Isotopic analysis for identifying the mechanisms of groundwater salinisation in coastal aquifers (water infiltrated through soils, salt-water intrusion, salt concentration due to evaporation). The major isotopes used for this purpose are:
  - ^{16}O, ^{18}O, ^{2}H and ^{1}H to determine the origin(s) of the water – marine, meteoric or mixed,
  - ^{3}H to determine the age of the potential recharge of the aquifer,
  - ^{18}O and ^{34}S to determine the origin of the sulphate – marine, old evaporites, sulphur oxidation of the aquifer matrix,
  - ^{14}C for determining the intrusion age and the transfer velocity within the aquifer.

MANAGEMENT

Framework

According to the French Water Bill (1992), water is part of the nation's patrimonial resource. The protection and the development of uses of the resource in respect of a natural equilibrium are of general interest. Everybody has the right to use water within the framework of rules and regulations. Consequently, the Water Bill requires the implementation of a model water-management programme by the Water Basin Agencies (of which there are six in France) (figure 4). The goal of such a programme is to promote sustainable social and economic development by equilibrating water-resource and aquatic-environment management. The programme includes 10 fundamental orientations: (1) the fight against pollution, (2) a guarantee of water quality for all uses, (3) a reaffirmation of the strategic importance and sensitiveness of groundwater, (4) better management before new investment, (5) a respect for natural environmental behaviour, (6) the renewal and preservation of aquatic environments, (7) the urgent renewal of particularly degraded environments, (8) a more efficient investment into risk management, (9) water management in term of territorial uses, and (10) reinforcing local water management.

There are no specific rules concerning coastal aquifers. However, the various management-scheme rules include management tools that can be applied to the coastal aquifers; e.g. dedicated water-management schemes for water management units (water catchment, aquifer), bay or lagoon contracts, and aquifer contracts.

The Water Basin Agencies have set up a specific Board in order to implement such water-management schemes (guiding programme and local or specific dedicated plans). The Board includes (i) State representatives, (ii) local and regional operators with government, public companies, local administrations and private actors, (iii) financial partners, and (iv) citizens representatives.

The programme is set up by the Local Water Commission, which is established by a government representative and comprises the following partners: municipal representatives (50%), user representatives (25%) and State representatives (25%).

Management tools

(i) Monitoring (water level and quality) network.

The monitoring network is generally set up for major aquifers such as the Astian or Roussillon aquifers where the networks were installed in 1990 and 1985, respectively. Water-level and TCD probes are installed in strategic piezometers, and manual piezometric and sampling campaigns are realised once a year during low-stage hydrological conditions.

(ii) Hydrogeological behaviour and modeling.

Hydrogeological studies were made in the alluvial and deep aquifers in order to determine their geometries and hydrodynamic parameters. The results of these studies were used to establish groundwater-management tools; i.e. groundwater models. Such models exist for the Roussillon (Chabart, 1996) and Astian (Laurent, 1993) aquifers, as well as for the PACAalluvial aquifers (i.e. the Gapeau and Var aquifers; Petit, 1996). These models enable predictive groundwater management and the selection of appropriate programmes for the aquifer management (e.g. drilling new boreholes, increasing or decreasing pumping rates, etc).

(iii) Water-management partnerships.

According to the Water Bill, the management structure must be set up in close partnership with local users. Such structures are now operational for the following water systems: the Salses-Leucate lagoon, the Thau lagoon, the Astian aquifer, the lower Var valley and the Gapeau valley.

Figure 4: Extract of the watercatchment basin Rhone Mediterranean Sea Corsica (RMC) with the under progress management structures.

(iv) Pumping reduction/redistribution techniques.

A programme for reducing and redistributing the pumping boreholes has been set up in order to reduce the salt-water intrusion. In the Astian aquifer, for example, a programme has been initiated to reduce pumping rates. Work is being carried out on the defective boreholes and a good practice guide is being established for drilling sensitive aquifers (Petit, 1996).

(v) Reuse of wastewater.

Reclamation experiences in coastal areas are integrated into policies dealing with water-resources management, health hazards related to the sanitary protection of beaches, shellfish production, and shoreline ecosystems preservation (Brissaud et al., 1991). An example is the Porquerolles experience: Porquerolles island (12 km^2), with 1000 permanent inhabitants and 10^4 visitors per day in summer, obviously has limited groundwater resources that are put under severe pressure. In order to control and limit the salt-water intrusion, wastewater reclamation is practised in order to avoid wastewater effluent disposal in a protected marine environment (Port-Cros National Park and Botanical Reserve) and to enable irrigation farming. The wastewater is treated in an activated sludge plant, with a lagooning system receiving the effluent of a tertiary treatment. The final water has a mean colloform content of 10^2/100 ml. Drip irrigation systems are being promoted over furrow irrigation (Cadillon *et al.* 1985, 1986). A lot of wastewater reclamation projects for both golf-course (Cavalière, Gruissan, Argelès sur Mer) and landscape (Port-Camargue) irrigation are being developed in Languedoc-Roussillon. Wastewater reuse appears to be an essential and important element in the integrated water management of Mediterranean water resources (Brisaud *et al.* 1991).

(vi) Combined use of surface and ground water, and artificial recharge.

Among the efforts made to limit salt-water intrusion in the Gapeau aquifer (PACA), which include setting up a dam on the river (against salt progression) and the reduction of water pumping rates, is the importation of external water to supplement the water supply.

In the Argens aquifer (PACA), surface water is used for artificial recharge in order to stabilise the salt-water wedge. However, no reported quantitative or qualitative data concerning the efficiency of this method is available (Petit, 1996).

(vii) Drought management.

During periods of drought, the management structures and the regional state representative authority publish regular information bulletins and impose restrictions on certain uses, such as irrigation, watering gardens and car washing. These National Hydrologic Bulletins are distributed to town halls and appropriate professional and citizen associations, as well as appearing on Web sites.

CASE STUDIES

The Messinian incision strongly influenced the geometry and setting of the base level, and thus the outlets of the karst aquifers (in particular) along the Mediterranean coast (i.e. the Roussillon aquifers, the Corbières karst systems, the Astian aquifer, the Thau karst system, etc.). Other alluvial aquifers in LRO and PACA (e.g. Gapeau, Agens and Var) are due to Quaternary paleogeography and climatic conditions.

Three case studies are presented: (i) the Plio-Quaternary Roussillon aquifer, (ii) the Astian deep aquifer, and (iii) the Thau karst system.

Plio-Quaternary multilayer Roussillon aquifer

(1) Aquifer characterisation

The Plio-Quaternary Roussillon aquifer, covering 850 km^2 between Albères to the south, Aspres to the west, Corbières to the northwest, and the Mediterranean Sea to the east, comprises essentially marllimestone that is locally highly karstified.

The Pliocene layers (clays and sand) are covered by Quaternary alluvial deposits in the Agly, Têt and Tech valleys, and along the coast between Leucate lagoon and Argelès-sur-Mer.

Geological background: during the Miocene, the sea gradually regressed following the Messinian salinity crisis (partial drying of the Mediterranean Sea; 6 Ma). A major phase of erosion induced depression of the fluvial networks and the deep canyons that have been identified in the Roussillon (Clauzon *et al.*, 1987; Clauzon, 1990) and termed the Messinian rias (Duvail *et al.*, 2001). In the Pliocene (5 Ma), the opening of the

Gibraltar Straits enabled a return of the sea, which penetrated the deep valleys and transformed the Roussillon basin into a ria. All the Pliocene layers were deposited within 1.2 Ma (i.e. 75 cm/1000 years; Clauzon et al., 1989). The Quaternary deposits were due to the interglacial transgression and regression phases. The last transgression (sea-level rise) resulted in some coastal constructions (e.g. dunes) and a lagoon area from Leucate to Argelès; today only the Salses-Leucate and Canet lagoons remain.

The conceptual model for the Pliocene sedimentation is that of the Gilbert Delta (figure 5) (Clauzon *et al.* 1990)

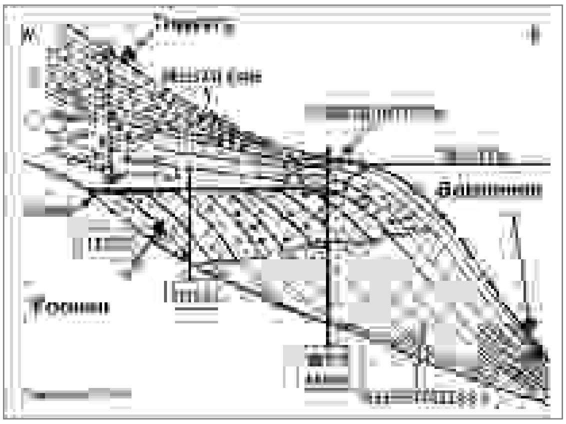


Figure 5: The "Gilbert Delta" model of sedimentation (Clauzon et al. *1990).*

Three aquifers can be distinguished: (1) the Quaternary alluvial aquifer, (2) the Pliocene Salanque aquifer and (3) the deep Pliocene aquifer. The first aquifer is in contact with the Mediterranean Sea. Scientific research conducted by Duvail *et al.* (2001) concerning the geology-geometry of the structure and the continent-offshore continuum in the Gulf of Lions may require a revision of this model and a new updating of the groundwater model.

According to the transmissivity determined by pumping tests and the interpolation taking into account lithology (homogeneous geologic zones), the mean permeabilities are respectively $3x10^{-4}$, $1.1x10^{-4}$ and $0.25x10^{-4}$ m/s for aquifers 1, 2 and 3 (Chabart, 1996). The mean storage coefficients are $7.35x10^{-2}$ for aquifer 1, and $5x10^{-2}$ for aquifers 2 and 3; the storage coefficients for the confined parts of these aquifers are $1.4x10^{-3}$, $2.6x10^{-3}$ and $4.9x10^{-3}$ for aquifers 1, 2 and 3, respectively.

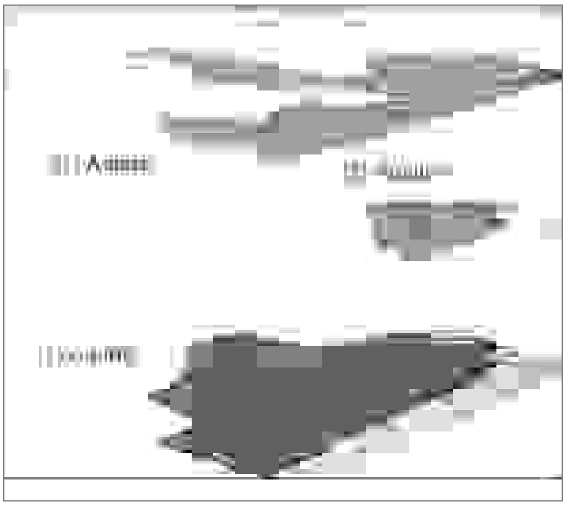
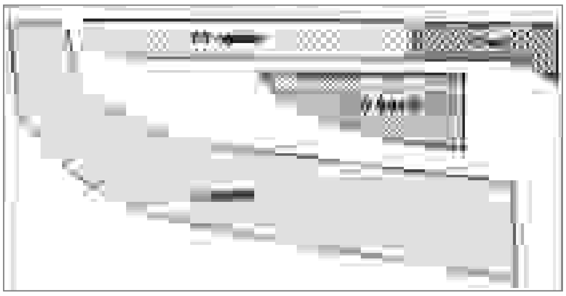


Figure 6: The Plio-Quaternary aquifer (multi-layers) in Roussillon (Chabart, 1996).



(2) Studies carried out

From 1990 to 1994, the BRGM developed a groundwater model in order to simulate the hydrodynamic behaviour of the Pliocene aquifer and to assess the impact of new abstraction boreholes.

Chabart (1996), in the framework of his PhD thesis and also in the framework of the MEDALUS project (Mediterranean Desertification And Land Use), worked on updating the groundwater modeling (figure 6). He determined water budgets in transient regime for both the high and low-water stages and established predictive precipitation and evapotranspiration scenarios for the Roussillon. The results of groundwater modeling were analysed in terms of water-management issues.

A detailed geology study of the Roussillon has been in progress since 2000 (Duvail et al. 2001). New knowledge concerning the offshore-continent continuum may provide important data that could have consequences on the groundwater flow patterns (modification of the boundary limits).

BRGM has been publishing reports concerning the marine contamination of the Pliocene Roussillon aquifer since the 1980s. Piezometric time series and water resistivity from 1982, as well as chloride content, well logging and chemical/isotopic analyses, have been interpreted by Marchal and Chery (1995). The last report concerns the monitoring of the Plio-Quaternary Roussillon aquifer (Marchal and Chery, 2001). Annual campaigns (resistivity and chloride content) were carried out from 1982 to 1997, at the end of the summer period, on between 100 and 120 boreholes situated at less than 4-5 km from the lagoons and the coast. The monitoring network includes 23 measurement points for water head and temperature, with five of these also recording conductivity. Data are teletransmitted.

(3) Control and evolution of the aquifer

From the piezometers that have returned more than 10 years of records, it would appear that the general water level of the Pliocene aquifer is decreasing at a variable rate of less than 10 cm per year. There are nevertheless two singular points. The first is in Barcarés where the recorded water level for 2000 was very close to the interannual mean; in addition, no significant change has been noted since 1990 (local stability of water abstraction). The second is in Torreilles where we note an increasing water head (0.60 cm in 10 years; Marchal and Chery, 2001).

Where the evolution of the Cl^- content is concerned, high concentrations are always recorded in the Bacarès area and between Canet-en-Roussillon and St-Nazaire. The excessively high values of the mineralization (>500 mg/l) are located close to the Salses-Leucate lagoon and specifically in the commune of Barcarés. In general, the water quality of the Pliocene layers does not seem to deteriorate with time. Moreover there is a spatial heterogeneity of Cl content, even in the sectors with high concentrations such as Barcarés. This heterogeneity can be explained by the presence of old leaky boreholes that provide a connection between the surface layers and Pliocene layers (Marchal et al. 2001) (figure 7). In addition, local geological conditions may favour a hydraulic connection between the Quaternary upper layers (where Cl could be >1 g/l) and the Pliocene aquifers. Moreover, increasing abstraction in the Pliocene Salanque aquifer (aquifer Nº 3) may also contribute to accelerating the vertical downward leakage, particularly during the summer period (Marchal *et al.* 1995).

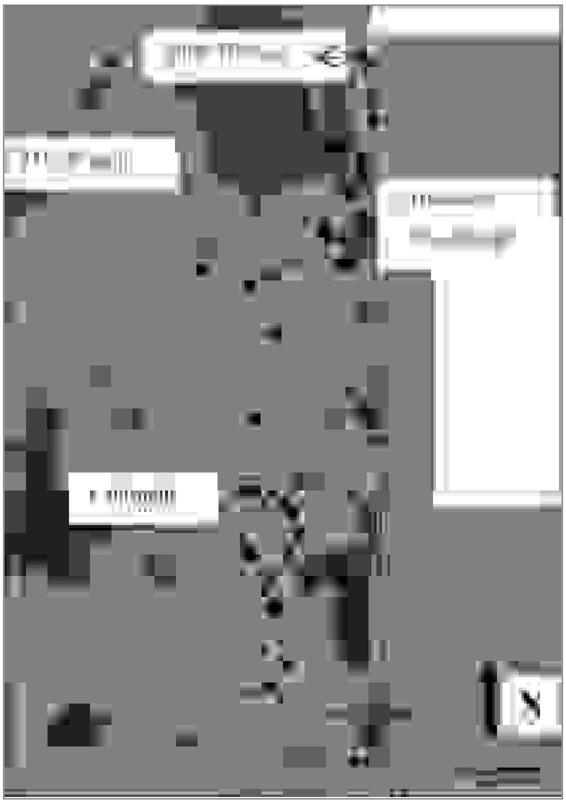


Figure 7: Chloride content in mg/l – September 1999 – Roussillon Pliocene aquifer (Marchal, 2001).

The general chemical facies of the Pliocene aquifer is calcium-bicarbonate. Where there is a marine contribution, certified in particular by isotopic analysis, the groundwater facies is chloride-sodium, which is specifically the case for the boreholes located in the Quaternary alluvial aquifer.

The sulphates of the Plio-Quaternary aquifer are generally of meteoric origin, although a few boreholes show a marine contribution of sulphates in their salinity. However, isotopic analyses appear to show that the actual seawater contribution to the upper layers of the Pliocene is less than 10% (Marchal *et al.* 1995).

Deep Astian aquifer

(1) Aquifer characterisation

The sandy Astian aquifer extends over 450 km^2 bounded to the east by the Gardiole massif with Upper Jurassic limestone, to the west by the Lower Cretaceous limestone and the surrounding Béziers Oligo-Miocene layers, and to the north by the Astian sand facies that crop out in Corneillahn, Thézan, Nézignan, Florensac and Mèze. To the south the aquifer is limited by the Thau lagoon. The geometry of the floor and roof of the aquifer is relatively homogenous. The thickness of the sand layer (Sandy Marine Pliocene) averages about 20 m (Laurent, 1993). According to a recent study (Fuchey and Le Strat, 2001) concerning the geological modeling of the Plio-Quaternary deposits in the lower part of the Hérault valley, the thickness of this aquifer layer ranges from 10 to 30 m. (figure 8).

As with the Roussillon aquifer, the Gilbert Delta sediment model, proposed by Clauzon (1990), explains the Pliocene deposits. The Pliocene sandy marine layers correspond to the foresets of the Gilbert Delta (figure 5).

Even though the offshore seismic profiles run by the *Compagnie Générale de Géophysique* between 1960 and 1990 along the actual coast (Agde – Montpellier), were reinterpreted (Hannot, 2001), the submarine aquifer outlet is difficult to define. The Messinian incision surface is evident as salt layers corresponding to the associated salinity crisis. The Pliocene formations can be distinguished, but without it being possible to determine the different facies (Clayey Marine Pliocene, Sandy Marine Pliocene, Continental Pliocene).

The hydrodynamic properties of the aquifer are (Laurent, 1993):

Figure 8: Geographical location of the Astian aquifer and isopach curves of the Sandy Marine Pliocene (Fuchey and Le Strat, 2001).

- Transmissivities between $3x10^{-5}$ and $2x10^{-4}$ m^2/s in the northwest and northeast sectors, and between 10^{-3} and $6x10^{-3}$ along the coast.
- Storage coefficient between 10^{-4} and $6x10^{-4}$.

(2) Studies carried out

The principal study concerning the Astian aquifer is the elaboration of decision-making tools on the aquifer (groundwater numerical modeling, water needs assessment sector by sector) carried out by Laurent in 1993 for his PhD thesis. The management procedures were developed jointly with actions aiming at a better information and awareness of the various actors concerned, thus leading to an aquifer contract in 1994. It was an experimental pilot operation anticipating the new Water Bill (1992) and taking into consideration the impending danger of a salt-water wedge penetrating the confined aquifer in the Astian sands.

An update of the groundwater model was realised in 2001 by a private engineering company on behalf of the Regional Environment Authority. Further geological studies carried out by Fuchey and Le Strat (2001) and Hannot (2001) also include the sector of this aquifer.

(3) Control and evolution of the aquifer

The chloride concentrations range from 60 mg/l for the lower values within the larger part of the sector, to 3675 mg/l along the Thau lagoon. The 250 mg/l chloride isoline (maximum concentration admitted by the WHO) delimits three areas: Cap d'Agde, along the coast between Agde and Sète, and along the northern edge of the Thau lagoon.

The south-southwest sector of the aquifer, corresponding to the vast majority of the aquifer, is characterised by a mean Cl concentration of 70 mg/l; no evolution in the concentration has been observed since 1960. A second sector has been identified along a NE-SW axis from Agde to Meze (northern edge of the Thau Lagoon); this sector showed a progressive positive Cl concentration trend from 1960 to 1985. (figures 9 and 10).

A water budget was established, in addition to analyses of the water needs and uses. This led to a global diagnosis that took into account the economic constraints, the physical properties of the environment and the socio-economic aspects. One of the major conclusions was that the aquifer is locally overexploited (i.e. along the coast), and that the risk of a salt-water intrusion was present. Following the establishment of a management structure (SMEGA) in 1990, which integrates local partners in the groundwater management of this aquifer, constructive action programmes have been put forward concerning reductions of water abstraction, deteriorated boreholes, a good practices guide for well drilling, users' information, water saving and aquifer monitoring.

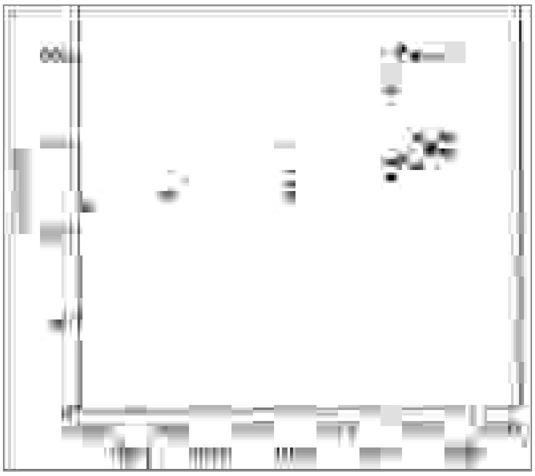


Figure 9: Evolution of chloride concentration between 1960 and 1992 in the southeast sector (Laurent, 1993).

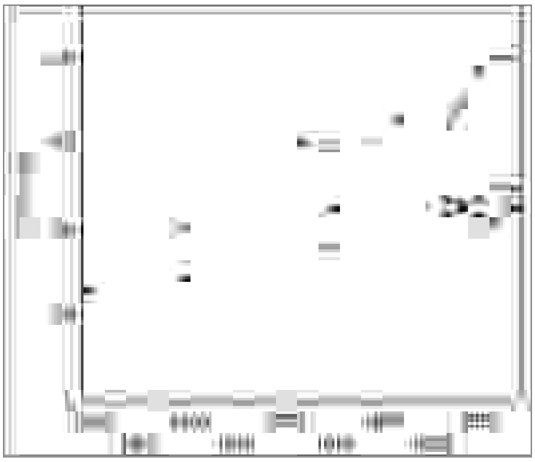


Figure 10: Evolution of chloride concentration between 1960 and 1992 in the northeast sector (Laurent, 1993).

Thau karst system

(1) Aquifer characterisation

The Thau karst aquifer system was selected as one of the case studies of the COST 621 Action. Major data have been extracted from the description of the test site that will be published in the COST 621 Action report.

The Thau karst aquifer lies to the west of Montpellier in an area that was strongly affected by the uplift of the Pyrenean Mountains and the opening of the Gulf of Lions (Choukroune, 1976; Guennoc et al. 1994; Séranne et al. 1995; Séranne, 1999), resulting in a complex structure.

Thick Jurassic limestone layers are exposed in two massifs – Gardiole Mountain and the Causse d'Aumelas – separated by the Montbazin-Gigean graben in which the Jurassic limestone is directly overlain by 200 m of Miocene deposits. The aquifer system lies within the Jurassic (Malm and Dogger) limestone of these two massifs and comprises two principal aquifers: one in Late Jurassic limestone and the other in Bathonian dolomitic limestone, separated by marly deposits (Callovian-Oxfordian).

Several karst springs are located within the limestone layers of Gardiole Mountain and the Montpellier western fold. The water catchment area of this unique Thau karst system was determined using geological and hydrogeological approaches such as lithology, structure, dye tracing tests and groundwater flow axes. The catchment area of around 200 km^2 is oriented north south (figure 11).

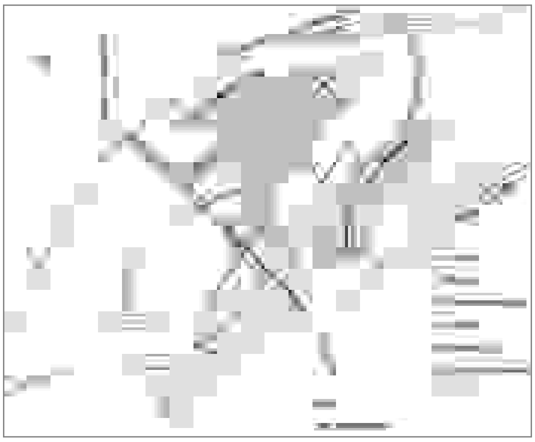


Figure 11: Structural framework and water catchment delineation (Ladouche et al., 2001).

The karst aquifer can be considered as a karst coastal system since one of the outlets is the La Vise submarine spring that lies -30 m below sea level. Major springs are located along a major fault (Issanka and La Vise springs), or close to it (Cauvy and Ambressac springs), and along the southeast edge of Gardiole Mountain. The spring water is characterised by a strong thermal component. The thermal water, with a temperature of 26 to 50 °C and an electrical conduc-tivity of 2630 to 21300 µS/cm, is pumped for the Balaruc-les-Bains thermal spa. Note that the electrical conductivity of the springs is only 500 to 1700 µS/cm.

(2) Studies carried out

Due to a water-quality problem that occurred in the spa wells during 1993, numerous studies (economic, geological, hydrogeochemical and hydrogeological) were carried out between 1996 and 2001. The latest studies included the following steps:

- Definition of the reservoir geometry and its limits based on a detailed geological study.
- Hydrogeological characterisation of the total limestone aquifer of the Montpellier western fold and at the level of the Thau karst system.
- Characterisation of the systems in terms of transit and transfer from interpreting water-level, conductivity and temperature time series in various springs and spa wells, as well as from hydrochemical and isotopic data (two sampling campaigns).
- A tentative explanation of the 1993 phenomenon.
- A general synthesis with suggestions for installing a monitoring network and a warning system in such complex hydrogeological frameworks.

(3) Control and evolution of the aquifer

Seventy water points (springs and boreholes) were monitored monthly over two years, with water head and conductivity/temperature being logged in 12 of them (3 coastal springs, 3 thermal wells and 6 piezometers). Most of the points were equipped with a multiline data logger system. The submarine La Vise spring was specifically instrumented; one of the outlets located at the bottom of the cone (-30 m below sea level) was microcaptured with a PVC pipe; partial water head and lagoon levels were then recorded simultaneously using the same 2-hour step time.

The parameter time series recorded at the La Vise spring are shown in figure 12.

The aquifer water head shows a seasonal behaviour, with a strong decrease in springtime and a rapid increase in autumn; it is an annually recurrent phenomenon. Although the pressure head does not seem to be related to rainfall events (Pinault et al. submitted in 2002), a correlation can be demonstrated through statistical data treatment using the effective rainfall as input. Except during technical problems with the in-strumentation, a time variability (01/01/1997 – 01/11/1999) of the water conductivity can be correlated to rainfall events.

The discharge of the La Vise spring was determined using stationary temperature and salinity data on various profiles according a grid in the vicinity of the spring and then carrying out a modeling (Bakalowicz et al. 2003b). The thermal flux was modeled in a first step in order to determine the spring discharge. Two finite-element models were developed and coupled in order to simulate the temperature field and determine the discharge for a set of experimental data collected in March 1999. The temperature field in relation to the velocity field was calculated for several boundary conditions. The two boundary conditions were discharge rate, with a range between 50 and 1000 l/s, and the spring temperature, assumed to be constant at 20 °C. According to the experimental data, the discharge of the La Vise spring for this hydrological condition is closer to 50-100 l/s than to 1000 l/s.

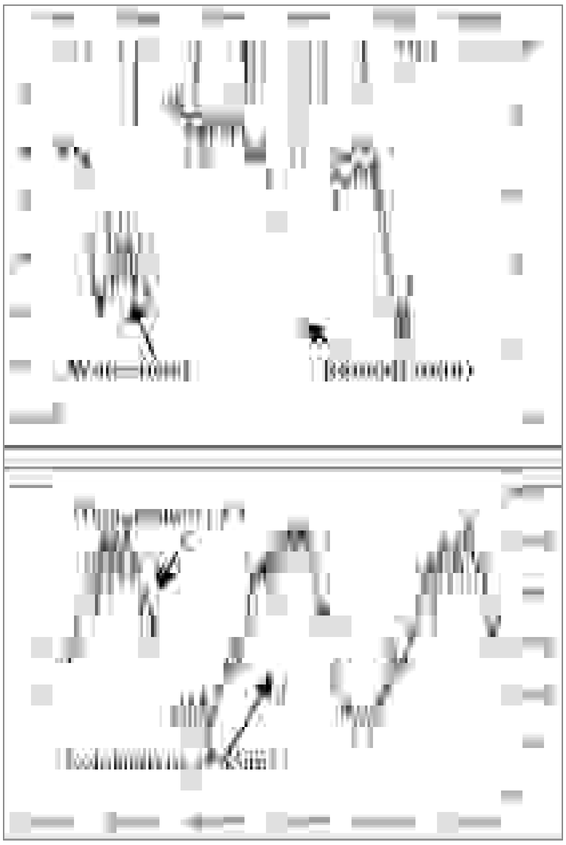


Figure 12: Time-series of pressure head, temperature and conductivity of the La Vise spring (Ladouche et al., 2001).

(4) Hydrochemical characterisation

Some 20 points were sampled during two campaigns – one in summer 1996 (low-water stage) and one during winter 2000 (high-water stage) – in order to characterise and determine the origin of the water and estimate the ratio of various reservoirs (surface water, karst aquifer and thermal water).

The analysis allowed us to demonstrate that the karst water of Gardiole Mountain has a different chemical signature from that of the Aumelas Massif; this is due to the absence of dolomite in Gardiole Mountain. It also showed that the water of the Issanka spring is linked to the Aumelas Massif, which is consistent with artificial-tracer test results and piezometric data. The isotopic data show that the relative salinity of springs located in the coastal area of Gardiole Mountain is due to hydrothermal participation.

The thermal waters of the Balaruc sector have high temperature (as much as 50 °C) and a high salt content (up to 5.7 g/l of chlorine). The use of geothermometers (Si, K/Mg and Na/K) allowed us to estimate the tem-perature of a thermal reservoir located between 1200 and 2200 m depth at between 50 and 80 °C.

The thermal salinity results from the mixing of karst water older than 40 years and old seawater. The maximum ratio of seawater in the thermal wells is 30-40%.

The salinity component of the La Vise spring water is essentially due to the contribution of deep thermal water. The geochemical signature of the La Vise spring can be explained as the result of mixing between thermal water and karst water principally from Gardiole Mountain.

(5) Conceptual hydrogeological model – reconstruction of the 1993 phenomenon

The Thau karst system is made up of the major part of the Aumelas Massif, the southwest part of Gardiole Mountain and the Balaruc-les-Bains peninsula. The groundwater flows from north to south toward the base level marked by the Thau lagoon. Hydraulic continuity is revealed specifically by the thermal wells. The groundwater flows are organised conceptually ac-cording two systems; a local system corresponding to the karst, and a regional system that is deeper and influenced by the thermal reservoir. The discharge of both systems is via springs.

A time series reconstruction for the previous years was done through convolution of transfer functions determined from signal analysis on experimental data and rainwater events. This was carried out for the following points: the Ambressac and Cauvy springs, two thermal wells, and the Tennis and P4 wells on the peninsula. It was not possible to reconstruct the output signal for the La Vise spring, as it was rather difficult to determine a significant transfer function for the water-head variations with respect to rainfall. The simulation was calibrated for the Tennis well for which 1990-2000 data were available.

With the simulated waterhead time series for the F4 thermal well, we note that the water head at the end of summer 1993 was similar to that measured in December 1998. The contribution of thermal water during these periods was minimal. The simulation results for the other points show that water levels were low in September 1993, but globally higher than the level observed in 1998 (the most deficient year of the observation period).

An example of the data simulation is given in figure 13 for the Cauvy spring.

As the hydrological conditions were no more serious in September 1993 than in 1998, the modifications of the thermal water (wells) and the problem of salinity in the Cauvy spring would be due to a modification of the hydraulic equilibrium of the system. Hydrological conditions were certainly an element in favour of this disturbance, but not the major responsible element.

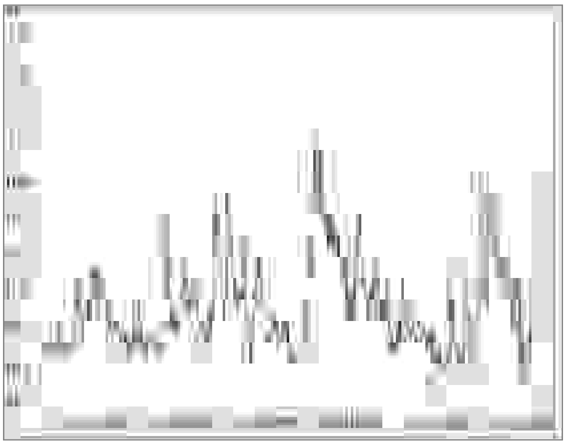


Figure 13: Simulation of piezometric levels for the Cauvy spring through convolution. The shorter line (1999 to 2000) in grey is the experimental data, and the black line represents the simulated time-serie (Ladouche et al, 2001).

In 1993, removal of the bell covering the major outlet of the La Vise spring (a system that is under pressure) induced a change in hydraulic head. As the system is characterised by a good hydraulic continuity at this level and is under low hydrological conditions, we see that a small modification of the water equilibrium can have an important effect; i.e. seawater intrusion would have been possible under the effect of disequilibrium.

(6) Water management perspectives

From the results of our study, it was clear that guidelines needed to be established for monitoring the karst system and thermal reservoir in order to be able to manage any further problems. As the hydrogeological system is complex in terms of geology and tectonism, and because of the lack of information concerning the hydraulic properties of the thermal reservoir, the suggested water-management elements do not fall within the standard type of management model or decision-support system. The suggested water-management approach is to install a monitoring network with warning messages according critical values of temperature, conductivity and water level.

REFERENCES

Aquilina L., Ladouche B., Dörfliger N., Seidel J-L., Dupuy C. & Le Strat P. 2002. Origin, evolution and residence-time of saline thermal fluids (Balaruc springs, S-France): implications for large-scale fluid transfer in the continental crust. Chemical Geology 192: 1-21.

Bakalowicz M., Fleury P., Dörfliger N. & Seidel J-L. 2003a. Coastal karst aquifers in Mediterranean regions. 1. An interesting ground water resource in complex aquifers.

Bakalowicz M., Fleury P., Jouvencel B., Promé J-J., Becker P., Carlin Th., Dörfliger N., Seidel J-L. & Sergent Ph. 2003b. Coastal karst aquifers in Mediterranean regions. 2. A methodology for exploring, exploiting and monitoring submarine springs. Proceedings of TIAC'03, Alicante.

Bérard P., Daum J-R. & Martin J-C. 1995. "MARTCRAU": Actualisation du modèle de la nappe de la Crau. BRGM Report R 38199, 18p.

Brisseaud F., Rodier C., Lasala M. & Salgot M. 1991. Waste-water reuse: a sanitation and management strategy for the Mediterranean coastal areas. Toxicological and Environmental Chemistry, Vols. 31-32: 549-557.

Cadillon M., Cova R., Jeudi de Grissace B. & Tremea L. 1985. La gestion des ressources en eau sur l'île de Porquerolles. Problématique et perspectives d'optimisation. Programme d'Action Prioritaire – Projet Développement des Ressources en Eau des Iles et Zones Côtières Isolées. PAP 3/ME/0503-83.05.

Cadillon M., Malaval A., Rippert A. & Tremea L. 1986. Valorisation des eaux usées par l'irrigation en forêt méditerranéenne. L'expérience de Cogolin (Var). Forêt Méditerranéenne 8(2): 151.

Chabart M. 1996. La recharge de l'aquifère multicouche du Roussillon et les conséquences d'un éventuel changement climatique sur la gestion de la ressource en eau (Pyrénées-Orientales). Orléans: BRGM, BRGM Document 257.

Choukroune P. 1976. Structure et évolution tectonique de la zone nord-pyrénéenne. Mémoire de la société géologique de France, 55, 127/ 1-116.

Clauzon G. 1990. Restitution de l'évolution géodynamique néogène du bassin du Roussillon et de l'unité adjacente des Corbières d'après les données écostratigraphiuqes et paléogréographiques. Paléobiologie continentale, Montpellier, XVII: 125-155.

Clauzon G., Martinelle J., Aguilar J-P. & Suc J-P. 1987. Roussillon – Penedès – Baix Llobregat, Livret guide des excursions. Interim Colloquium RCMNS, groupe de travail en écostratigraphie. Montpellier, Barcelona, 21-25 Sept. 1987. 78 p.

Clauzon G., Berger G-M; Aloïsi J-C., Got H., Monaco A., Maretin-Buscail R., Gadel F., Augris C., Marachal J-P., Michaux J. & Suc J-P. 1989. Notice explicative, Carte géol. France (1/50 000), feuille Perpignan (1091) BRGM(ed), Orlé-ans: 40 p.

Clauzon G., Suc J-P., Aguilar J-P., Ambert P., Cappetta H., Cravatte J., Drivaliari A., Domeneh R., Dubar M., Leroy S., Martinell J., Michaux J., Roiron P., Rubinon J-L., Savoye B. & Vernet J-L. 1990. Pliocene geodynamic and climatic evolutions in the French Mediterranean region. In: "Iberian Neogen Basins", Paleontologia i Evolucio, Sabadell, meme. 2: 131-186.

Dercourt J. 1997. Géologie et géodynamique de la France Outre-mer et européenne. Paris: DUNOD.

Dubois V. 1988. Caractérisation d'une nappe en milieu alluvial à partir des chroniques piézométriques mensuelles. Applica-tion aux relations nappe-rivière (nappe de l'Hérault). Doctoral thesis, Université des Sciences et Techniques du Languedoc. 232 p.

Duvail C., Le Strat P. & Bourgine B. 2001. Atlas géologique des formations plio-quaternaires de la plaine du Roussillon (Pyrénées Orientales). BRGM Report RP-51197-FR: 44 p.

Fuchey Y.& Le Strat P. 2001. Modélisation géologique des dépôts plio-quaternaires de la basse vallée de l'Hérault. BRGM Report RP-50770-FR: 79 p.

Guennoc, P., Debeglia N., Gorini Ch., Le Marrec A. & Mauffret A. 1994. Anatomy of a young passive margin (Gulf of Lions – South France): contribution of geophysical data. Bull. Centres Rech. Explor.-Prod. Elf Aquitaine, 18(1): 33-57.

Hannot F 2001. Etude de la nappe astienne. Détermination de la géométrie de l'aquifère pour la partie marine. BRGM Report.

Heurteaux P. 1987 La dynamique des eaux souterraines des dunes de Camargue. Ecologia Mediterranea Tome XIII (31):75-97.

Ladouche B., Dörfliger N. & Bakalowicz M. 2001. Etude du pourtour est de l'étang de Thau, Phase II, Caractérisation hydrochimique des réserversoirs souterrains karstiques et hydrothermaux, Volume 3, BRGM Report RP-50788-FR: 64 p.

Laurent A. 1993 La gestion en bien commun des eaux souterraines: la nappe des sables astiens de VALRAS-AGDE (Hérault), une opération pilote en Languedoc Roussillon. Thesis, Université Montpellier II.

Marchal J-P. & Chery L. 1995. Contamination marine de l'aquifère plio-quaternaire du Roussillon (Pyrénées Orientales). BRGM Report R 38604: 83 p.

Marchal J-P. & Chery L. 2001. Surveillance de l'aquifère plio-quaternaire du Roussillon (66). Observations réalisées en 1999 et 2000. BRGM Report RP-50349-FR. 265 p.

Marsaud B. 1996. Structure et fonctionnement de la zone noyée des karsts à partir des résultats expérimentaux. Documents du BRGM 268, Orléans: BRGM (ed): 301 p.

Petit V. 1996 Les aquifères littoraux en France métropolitaine. BRGM Report R 39298. 120 p.

Pinault J-L., Dörfliger N., Ladouche B. & Bakalowicz M. 2002. Characterisation of a coastal karstic aquifer functioning using an inverse modeling approach. Thau karstic aquifer, Southern France. Submitted to Water Resour. Res.

Séranne M. 1999. The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview. In: Durand B., Jolivet L., Horvath F. & Séranne M. (eds) The Mediterranean Basins: Tertiary Extension within the Alpine Orogen. Geological Society of London, Special Publication 156: 15-36.

Séranne M., Bénédicto A., Labaum P., Truffert C. & Pascal G. 1995. Structural style and evolution of the Gulf of Lion Oligo-Miocene rifting: role of the Pyrenean orogeny. Marine and Petroleum Geology 12: 809-820.

Valencia G. 1970. Etude hydrogéologique de la nappe astienne de Valras-Agde. Doctoral thesis, Laboratoire de Géologie, USTL Montpellier.

Weng Ph. & Dörfliger N. 2002. Projet PACTES, Module: contribution des eaux souterraines aux crues et inondations, site de l'Hérault, BRGM Report RP-51718-FR: 75 p.