# Groundwater of the future in the Roussillon flood plain: present-day situation and solutions for the 21st century

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**Abstract** In the Roussillon flood plain (France), as all around the Mediterranean Sea, water resources are not very important. However, for three decades, groundwater pumping has become very excessive. The consequences are clear: the levels of all aquifers are falling and the quality of water is getting worse. This is a serious problem because this water is renewed with an average period of about 5000 to 7000 years. In some wells of the plain, the signs are alarming with low aquifer levels and pollution by nitrates. Near the Mediterranean Sea, penetration by a salt wedge has been recorded. Better management of this resource is required. Several solutions can be put forward, such as the use of water coming from the karst reserves of the Corbieres Mountains, as well as the treatment of river water, stored by means of the existing dams. These solutions have a real cost: the price of sustainable management of the water.

**Key words** groundwater; overexploitation; Mediterranean regions; Roussillon flood plain; water pollution; sustainable development; demography

## INTRODUCTION

All around the Mediterranean Sea, freshwater is not abundant. However, in particular situations there is too much water: heavy downpours bring about river overflows and catastrophic floods. Freshwater is used for vital human needs, such as drinking water, and irrigation for agricultural activities. For centuries in this area, the utilization of water has been codified and regulated in order to be distributed, as equitably as possible, between all the different users. In other words, the question of water resources has been, for a long time, a major subject of concern for the Mediterranean population. Yet, upheavals are coming. Indeed, for 40 years the periphery of the Mediterranean Sea has been experiencing important changes concerning environment and population. Many studies show that the Mediterranean countries have had an important demographic increase. This phenomenon is going to increase during the next decades, but the availability of freshwater is not infinite in this Mediterranean region. In the future, it could be even worse if one takes into account the consequences of climatic warming due to global change. We can suppose that sooner or later a crisis situation will occur (Margat, 1992). This is a real cause of concern. According to the report on human development (PNUD, 2000), water demand in Mediterranean countries is about 2750 $m^3$ per capita per year. This value is still 2.6 times less than the world average consumption. Countries of the eastern and southern Mediterranean are more threatened by water shortages because of their more arid climates. The valuations for the future are pessimistic for the whole periphery of the Mediterranean Sea.

This research studies the current evolution of drinking water resources originating from groundwater in the Roussillon region, a coastal flood plain in the south of France. The following are studied in relation to the general problems concerning sustainable development and management of water resources:

– How deep are the water resources exploited in the Roussillon plain?
– What increase in water consumption can be envisaged?
– What are the actual threats to groundwater?

To answer these questions, it is necessary to consider environmental patterns, as well as land use and urban development related to demographic change during recent decades.

## STUDY AREA

Located in southern France, not far from the Spanish frontier, the flood plain of Roussillon is a coastal plain with an area of ~600 km$^2$. The climate is typically Mediterranean, marked by hot and dry summers. Average annual rainfall is 562 mm for the 1925–2002 period (Météo-France, 2002), but precipitation is very irregular during the year and exhibits a great inter-annual variability, so that exceptionally dry years occur (Serrat, 1999). This climate has consequences for catchment systems (Ludwig *et al*., 2004).

### Mountain range and hydrographic network

The Roussillon flood plain is bordered to the east by the Mediterranean Sea and to the north and to the south by mountains. It comprises a triangular area on the eastern margin of the Pyrenees with Corbières to the north, Aspres to the west and Albères to the south (Fig. 1).

The geomorphology and groundwater geology of the Roussillon plain are related to the genesis of the Pyrenees (Salvayre, 1983; Séguret *et al*., 1985) which are characterized by fractured granites and metamorphic rocks that encourage water infiltration (Arthaud & Pistres, 1993; Pistres, 1993). In the south, the Albères Mountains (elevation of about 1500 m) fall steeply to the Mediterranean, while in the west are the Aspres Mountains which reach an altitude of near 3000 m in the Canigou peak.

The area is drained by the Têt and Tech rivers whose directions are dictated by major faults. The Roussillon flood plain is a sedimentary basin deposited by these river sytems. This zone is limited in the north by the North Pyrenean Fault (NPF) (Arthaud & Laurent, 1995). The Agly watershed drains the Corbières mountains, which are formed in very thick and often karstified calcareous layers (1000–1500 m) of Jurassic and Cretaceous age. This northern break line of the plain plays a role in feeding the Roussillon groundwater.

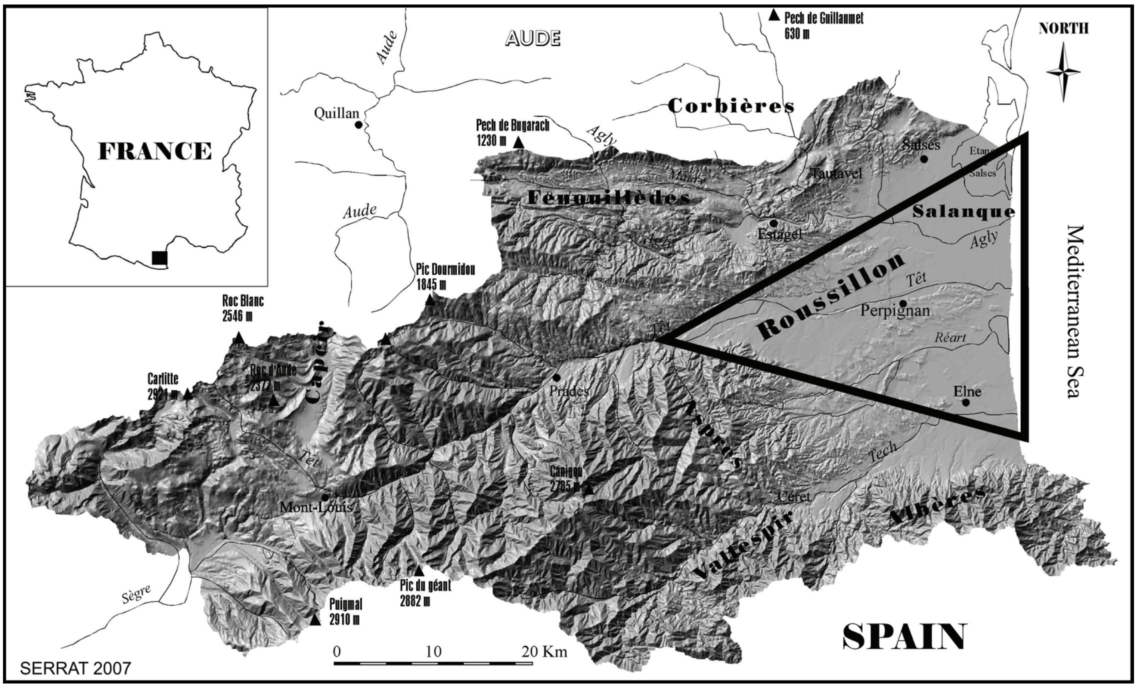



**Fig. 1** Roussillon flood plain and its mountain range borders.

These three coastal rivers (Tech, Têt, Agly) have a torrential regime (Serrat *et al.*, 2001), due mainly to their mountainous character and to the heavy Mediterranean downpours (Pardé, 1941; Soutadé, 1993), which has an influence on groundwater recharge and in a general way on the hydrological potential. A plan for managing the water resources of the study area was developed at the beginning of the 20th century and involved dam construction (Broc *et* al., 1992) that was completed for the Tet (Vinça dam) in 1975 and for the Agly in 1995.

## Groundwater and structural features

The Roussillon flood plain is a collapse basin (graben) filled with sedimentary layers (Bourcart, 1945; Monaco, 1973) with several aquifers at different levels as is common in many areas (Brown, 1996). This graben has been sinking since the Oligocene but in a discontinuous way. Subsidence has resulted from extensive geological structures in the oriental Pyrenean mountains (Serrat, 1996) and has led to a present contact between the granitic basement and the sedimentary series at a depth of ~2000 m, as observed in a test borehole drilled at Canet-en-Roussillon in 1958 (BRGM, 1988).

This deep drilling undertaken by the National Oil Company has provided information on the sedimentary succession which has a fundamental influence on the groundwater. At the base of the geological section is the Paleozoïc basement (at 1785 m depth), which is overlain by ~70 m of siliceous deposits. The whole of the Mesozoic and Palaeogene are absent and Miocene deposits follow and comprise a thickness of ~1000 m of varying marine facies. The overlying layer consists of 600 m of Pliocene marine deposits that comprise mainly bluish plastic clays with the exception of sands

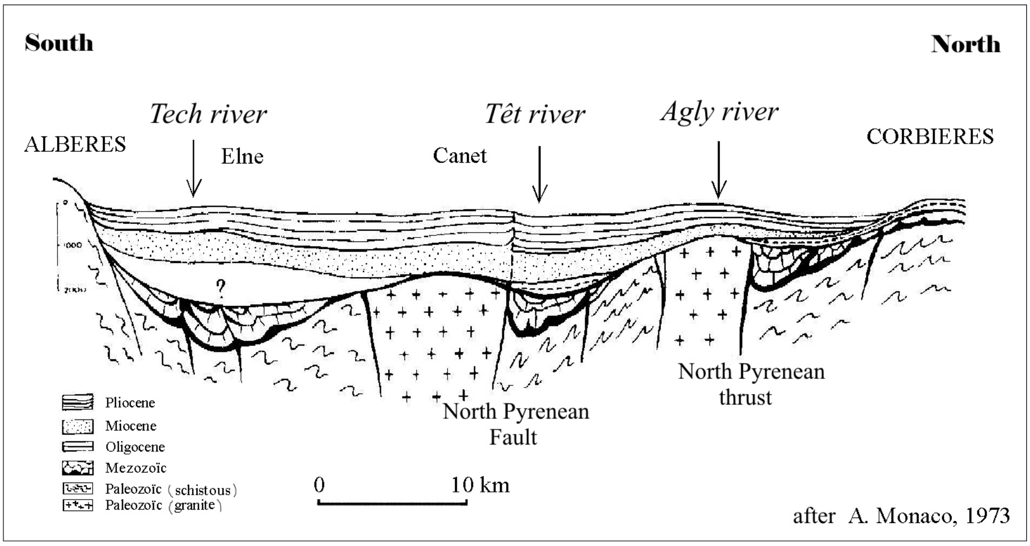



**Fig. 2** Cross-section through the Roussillon flood plain.

in the top 70 m of the series. This sandy facies constitutes the deepest exploited aquifer (–286 m to –212 m NGF) and has been designated as groundwater table number IV (Gadel & Got, 1967, 1968).

The overlying continental Pliocene deposits (groundwater table III) have an average thicknes of 200 m and are characterized by complex alternations between sandy and argillous series. Quaternary sediments of about 10 m thickness form the top of the sequence. To the north of the Roussillon flood plain (Salanque) the Quaternary sediments are thicker (~30 m) and water extracted from groundwater tables III and IV is generally used for agricultural irrigation.

From west to east, different facies are observed, and there is a progressive thickening of the sedimentary layers, especially those of Pliocene and Quaternary age. The sediments represent classic onlap deltaïc dynamics (Chamley, 1990; Collinson & Thompson, 1989) and the lateral facies change is typical of torrential conditions involving braided and overflow channels (Miall, 1996). There is marked particle size variation in the deposits associated with these channels with a range of sedimentary structures present at different spatial scales, and the structure of the different aquifers, especially groundwater table III (continental Pliocene), is closely related to the detailed nature of the sedimentary strata.

Furthermore, the graben has been affected by tectonic movements and WSW–ENE trending faults which have caused significant north–south variation in the thickness of the sediments (Fig. 2).

## RECENT INCREASING WATER USE

It is obvious that the quantity of water used in a given region reflects population density and economic activity and may pose threats to water resources (Watson & Burnett, 1995). This southern region of France, that was a relatively unpopulated area of vine cultivation, has seen rapid economic, social and cultural change over the last three decades.

## Population growth

Littoral regions are attractive to people, especially along the Mediterranean coast. For the Roussillon area, this phenomenon has been amplified by national politics. Thus, on 18 June 1963, the French government created a mission for Tourist Adjustment in Languedoc-Roussillon. Locally, the main investments have given rise to development of tourism in Port-Leucate, Port-Barcarès and Saint-Cyprien. Housing for permanent residents has also developed, and a number of cities on the coast have seen a four-fold growth in population (Table 1).

These census data reveal an accelerating population increase during the last two decades, which has especially affected communes located to the east of Perpignan (i.e. Bompas, Pia, Claira). The town of Canet-en-Roussillon, for example, has seen a rise in resident population of 69% between 1982 and 1999 and a 3.9-fold increase since 1962 (Fig. 3).

**Table 1** Population census data since 1962 (INSEE data).

| Cities | GCP 1962 | GCP 1968 | GCP 1975 | GCP 1982 | GCP 1990 | GCP 1999 |
|---|---|---|---|---|---|---|
| Canet-en-Roussillon | 2648 | 3658 | 4356 | 6030 | 7575 | 10182 |
| Argelès-sur-mer | 3619 | 5022 | 5100 | 5723 | 7188 | 9069 |
| Saint-Cyprien | 1857 | 2592 | 3012 | 4405 | 6892 | 8573 |
| Saint-Laurent Salanque | 3296 | 3649 | 3571 | 4523 | 7186 | 7932 |
| Bompas | 1470 | 1693 | 1951 | 4670 | 6323 | 6944 |
| Pia | 1938 | 2147 | 2503 | 3226 | 4105 | 5120 |
| Le Barcarès | 776 | 1197 | 1347 | 2208 | 2422 | 3514 |
| Leucate | 1077 | 1233 | 1244 | 1968 | 2177 | 2732 |
| Claira | 1439 | 1446 | 1249 | 1415 | 2117 | 2625 |
| Torreilles | 1523 | 1591 | 1215 | 1492 | 1775 | 2072 |
| Saint-Hippolyte | 1133 | 1033 | 1044 | 1038 | 1616 | 1849 |
| Total inhabitants | 20776 | 25261 | 26592 | 36698 | 49376 | 60612 |

(GCP is the General Census of Population for France).

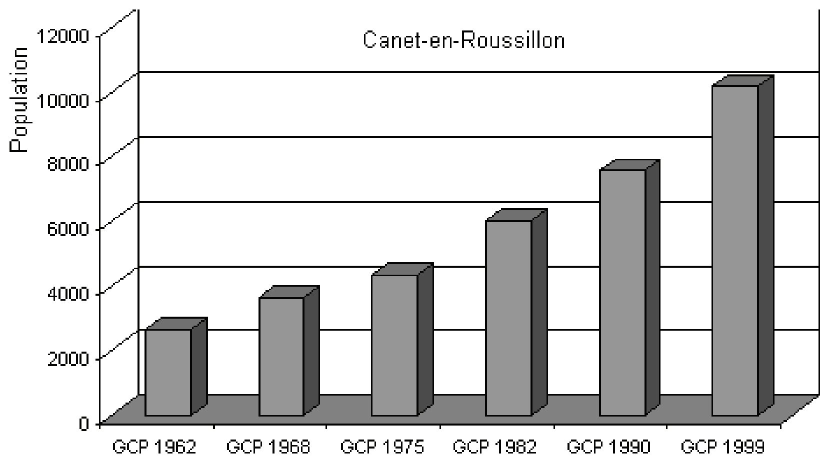



**Fig. 3** Census data for Canet-en-Roussillon since 1962.

For the towns as a whole in this area, the population has increased from 20 776 to 60 612 inhabitants since 1962 and this growth is set to continue.

### Expected increasing need for water

For the region of Languedoc-Roussillon, INSEE (French National Institute of Statistical and Economic Studies) estimates an increase of about 34% (2.3 to 3.1 million) in the resident population by 2030, according to a medium growth scenario (Auzeby, 2001). For the Department of Pyrenees Orientales, the population is expected to grow from 392 803 to 510 000 inhabitants (GCP, 1999) although this number could be revised upwards.

In addition, during the summer period, there is an influx of tourists to these seaside towns. For the seaside towns as a whole, estimates made by different administrative authorities suggest a population of 1 million in the Department during August 2004.

The increasing tourist and resident population has already had repercussions for water resources, and particularly for the Pliocene aquifer, which is mainly used for drinking supplies. During recent years, the water volume pumped in the Pliocene aquifer was $43 \times 10^6$ $m^3$ $year^{-1}$ (Diren, 2006). An increase of ~30% (perhaps even 36% according to the Departmental Council) in the requirement for freshwater, is anticipated by 2020 on the assumption that all other conditions remain stable, including the per capita unit consumption at ~200 L/day, a stagnation in tourist inflow, and a stabilization of water losses due to leakage from the water distribution network.

## GROUNDWATER OVEREXPLOITATION AND ITS CONSEQUENCES

Thus, present pumping of water is already excessive as attested by the lowering of the groundwater table. The lowering in water table and alteration of water quality are the first worrying signs of this overexploitation, which unfortunately occur very frequently (Detay, 1997). The situation is made worse by a very slow renewal of the water in the Pliocene aquifer.

### Aquifer water characteristics and dynamics

Water in the Pliocene aquifer is very old and its renewal requires several millennia. Dating by $^{14}C$ of dissolved mineral carbon provides an age of 5900 years ±600 years at Saint-Hippolyte and 7500 years ±700 years at Canet-en-Roussillon (Salvayre & Olive, 1994), located near the coast. This slow renewal is due to the fact that the main recharge for the aquifer is coming from the upper Têt basin. Water in this aquifer progresses slowly to the east and the Mediterranean Sea at a rate of approximately 4 $m \cdot year^{-1}$ along a weak hydraulic slope of about 0.26‰. It is clear that this resource is not renewable over human timescales. The excessive pumping is going to jeopardise the current exploitation and especially the integrity of the groundwater.

## Consequences of groundwater overexploitation: lowering water table

Superficial Quaternary aquifers do not have the same functioning as deep groundwater; the renewal of water is generally far more rapid (some years), and there is a strong connection with alluvial groundwater. Nevertheless, it is the drop of the water table in the Pliocene aquifer that is exploited for drinking water, which is concerning and may be illustrated by the study of two boreholes over an observation period of more than 20 years. At Saint-Laurent de la Salanque the piezometric level has decreased by 3 m in 35 years in the Pliocene aquifer (Fig. 4). Furthermore, the abstraction for seaside towns (Port-Leucate, Port-Barcarès) has become inadequate and is threatened by penetration of the salt wedge, as is common in coastal areas (Andrews, 1981).

Similar observations have been made for the borehole at Sainte-Marie de la Mer where data have been recorded over a period 20 years (Fig. 5).

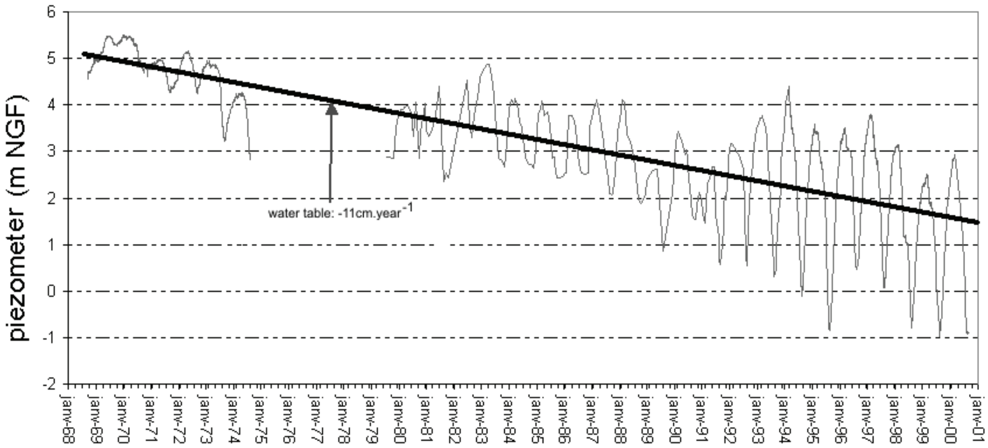



**Fig. 4** Fall of water table level in the Pliocene groundwater at Saint-Laurent de la Salanque.

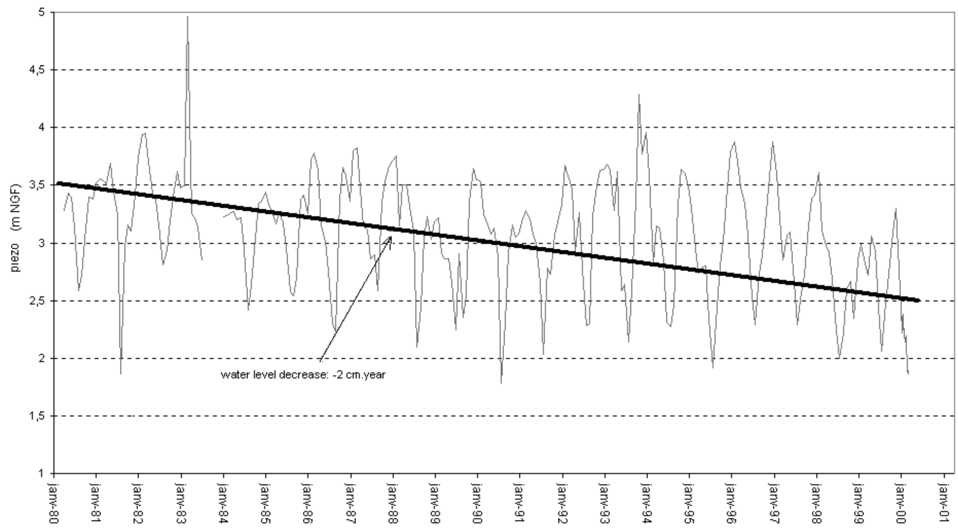



**Fig. 5** Lowering of piezometric level for Pliocene groundwater at Sainte-Marie.

There is further evidence of declining groundwater levels over longer periods. For example, 50 years ago, many artesian wells with positive pressure were observable in the villages of Roussillon, but today most of these have dried up.

## CONSEQUENCES FOR WATER GEOCHEMISTRY

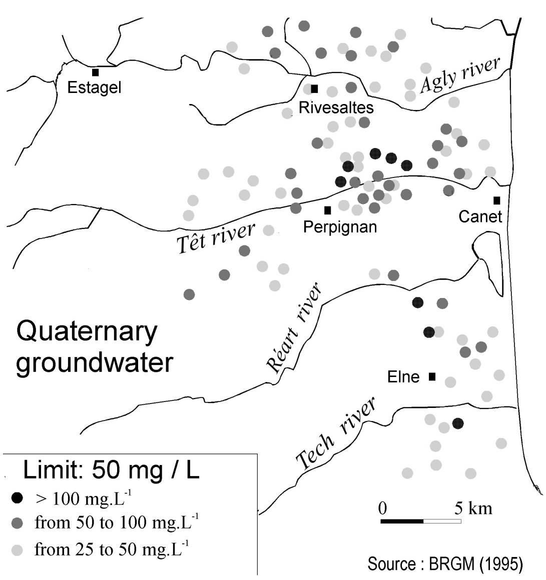
An alteration of water quality has been associated with the lowering piezometric levels and is dependent on two main vectors of pollution:

– the utilization of fertilizer and pesticides employed in agriculture,
– abandoned wells and boreholes left without any protection.

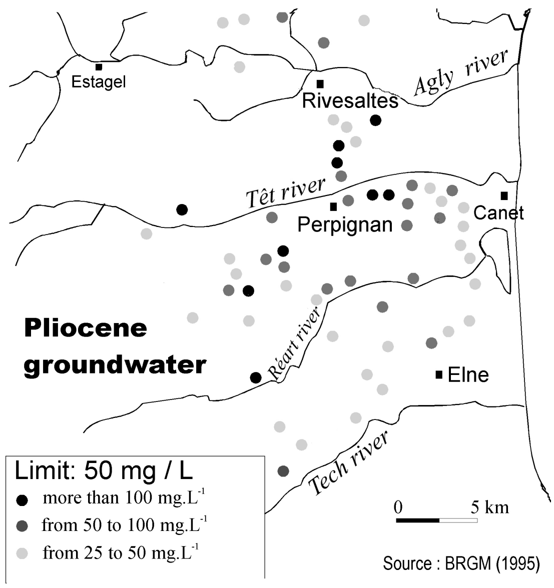
Pollution due to fertilizer affects groundwater in the Quaternary and Pliocene aquifers. The Upper Quaternary groundwater is polluted, especially along river courses, where there is a concentration of agricultural activities (Fig. 6(a)).

Both the continental and marine Pliocene aquifers used for the consumption of drinking water by many towns in the Roussillon flood plain are contaminated by nitrates (Fig. 6(b)) and levels are often above the permitted norms (50 mg $L^{-1}$), especially around Perpignan. A recent study showed a slight improvement of the situation in 2005, but the contamination still persists. This pollution is very worrying because the renewal of this groundwater is nearly zero.

Another source of pollution is caused by the bad design and state of, or the abandonment of boreholes, which encourages the pollution of groundwater by surface water penetration (Bear, 1979). In the Roussillon plain, several thousands of boreholes exist and many unproductive boreholes have been abandoned. Using modern technology, it would be possible to cap or fill abandoned boreholes, but this has not been done. Furthermore, some boreholes have connected polluted and unpolluted aquifers and caused the spread of contamination.




(a) Quaternary groundwater pollution




(b) Pliocene groundwater pollution

**Fig. 6** Water pollution by nitrates: (a) Quaternary groundwater, (b) Pliocene groundwater.

## CONCLUSION

When regular pumping from rivers is impossible or does not yield sufficient supplies, as is the case of Mediterranean rivers, groundwater is exploited and subjected to "*an increasingly unsustainable pressure*" (PNUE, 2002). In France, groundwater supplies 16.5% of the total consumption, including 57% of the supply to drinking water systems (Zektser & Everett, 2004). In the area of the Roussillon flood plain, aquifers are largely dependent on geological structures. Over the last three decades there has been over-exploitation of groundwater in this area with multiple adverse consequences for the Mediterranean coastal zone including threats of salinization, falling water tables and consequent reduced productivity and increased costs of groundwater pumping, greater risk of pollution and an increased threat of ground subsidence.

Some of these serious consequences could be irreversibe, and greater regulation of groundwater exploitation in Roussillon, as well as planning of alternative water resources, appears to be urgent. The utilization of existing artificial reservoirs on the Têt and Agly rivers, which have a capacity of $52 \times 10^6$ $m^3$, would allow a regular water supply for users and would limit pumping in a significant manner. This solution of surface water utilization will require additional water treatment facilities and has a financial cost. However, this will be necessary if European Union water policy objectives of obtaining by 2015, best drinking water quality, including groundwater and coastal water in Europe, and also preserving the quantity and quality of water resources are to be met.

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