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Chapter 2. Groundwater in France: resources, use and management issues

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Abstract

This chapter describes the status of groundwater resources in France. French geology consists of a large variety of rock types, resulting in very different types of aquifers ranging from sedimentary basins, alluvial plains, limestone rocks, and crystalline rocks. Today, groundwater resources represent about 66% of France's domestic water supply, 31% of industrial water supply and 37% of total water use in agriculture. According to the European Water Framework Directive, about 33% of groundwater bodies were considered in good chemical status, and 10% were considered in a bad quantitative status in 2013. The main quality issues for groundwater are related to diffuse contamination by agricultural practices (i.e. fertilizers and pesticides). France has not yet faced the extreme cases of aquifer depletion experienced in many other countries. However, associated groundwater dependant ecosystems can be affected by groundwater abstraction. The long term challenges for groundwater management in France are related to the decrease of recharge due to climate change, sea level rise along the coast, and future change in groundwater use. The identified adaptation strategies are (i) new groundwater management policies, (ii) the development of managed aquifer recharge, and (iii) active groundwater management.

Keywords: aquifer, karst, water quality, climate change, abstraction, agriculture, adaptation strategy

1 Introduction

On a national scale, France has abundant water resources, thanks to high precipitation (900 mm/yr), extensive river systems flowing from numerous mountain ranges and large volumes of groundwater stored in aquifers. Every year, France receives 480 billion m³ (480,000 GL) of precipitation plus 11 billion m³ of surface water flowing in from neighbouring countries (including the River Rhine). From

this quantity of water, about 75% is lost by evaporation and transpiration through vegetation. Consequently, about 170 billion m³ is available for consumptive use which corresponds to about 2800 m³/inhabitant/yr¹ (AQUASTAT data from FAO).

An estimated 2000 billion m³ is contained within aquifers with about 108 billion m³ stored as surface water in lakes, dams and other reservoirs. However, water resources are not equally distributed throughout the country and availability can vary greatly according to the seasons. Mediterranean regions in the south have a dry and changing climate, while the southwest region is often affected by droughts. In this context, groundwater plays a crucial role in water supply especially for drinking water.

This chapter describes the diverse types of aquifers located on the French territory, how groundwater is used, groundwater management issues, and long-term challenges in a changing world.

2 Overview of the groundwater resources in France

French geology consists of a large variety of rock types (Figure 2. 1), resulting in very different types of aquifers ranging from sedimentary basins (depicted in orange to yellow), alluvial plains (light yellow), limestone rocks (blue and dark green) and crystalline rocks (red and brown). Three categories of aquifers are distinguished: (i) porous sedimentary aquifers located in alluvial valleys and large sedimentary basins where flow velocities are generally low, (ii) the heterogeneous aquifers with a fissure permeability constituted by limestone where flow velocities are generally high, and (iii) volcanic and crystalline rocks.

¹ The term 'water stress' is applied when annual water resources are below 1700 m³ per capita; the term 'water shortage' applies when the annual water resources drop below 1000 m³ per capita.



Figure 2. 1: Geological map of France.

2.1 Alluvial aquifers

These aquifers provide about 45% of France's groundwater use. They have a very important role in supplying the human needs of the country because they are located in alluvial plains where the most fertile agricultural lands and many cities are located (Figure 2. 2a). Because of their shallow depth, the aquifers provide high yields at low cost and play an important ecological role in supporting wetlands. In addition to the diffuse recharge from rainfall, the water balance of alluvial aquifers is highly dependent on groundwater flow from neighbouring aquifers and interaction with surface water (Figure 2. 2b). The drawdowns induced by pumping from

the alluvial aquifer often increase these inflows. This contributes to maintaining well yields but threatens groundwater quality due to the intrusion of poor quality surface water.

The largest abstractions are pumped from the Alsace alluvial aquifer ($\sim 500 \text{ Mm}^3/\text{yr}$), the Lyon plain ($\sim 300 \text{ Mm}^3/\text{yr}$) and Isere river valley ($\sim 180 \text{ Mm}^3/\text{yr}$).

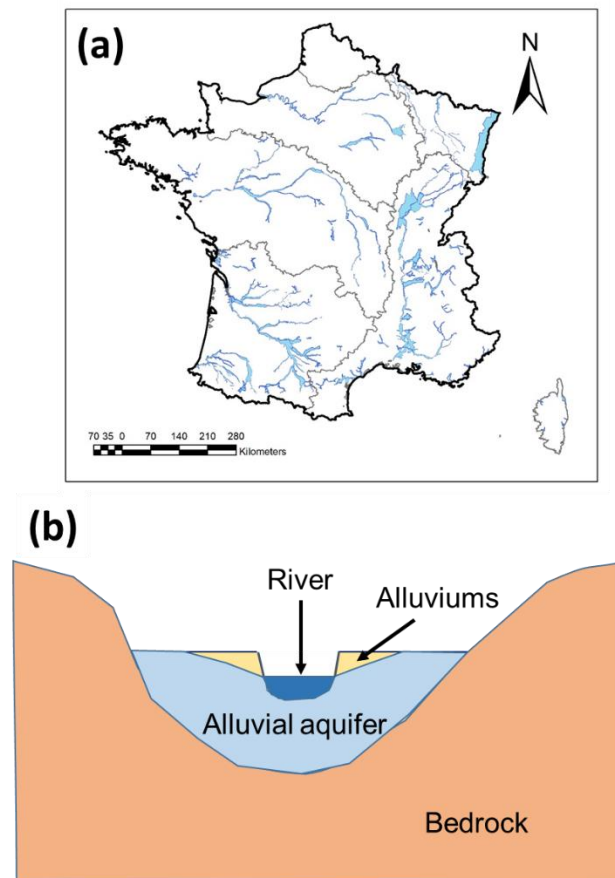


Figure 2. 2: (a) *Alluvial aquifers in France* (b) *Geological section of an alluvial plain.*

Example. The Alsace aquifer underlies the alluvial plain of the Rhine Graben (Figure 2. 3a). The French portion extends from the Vosges mountain range and Sundgau area to the Rhine River at Lauterbourg. The aquifer thickness ranges from a few meters to 200-250 m in the centre of the plain (Figure 2. 3a). Marls constitute

the bottom of the aquifer (Figure 2. 3b). The sandy gravel alluvium is highly permeable, especially in the vicinity of the Rhine River. The aquifer is recharged by (i) indirect recharge from rivers and canals partly fed by water diverted from Rhine itself, (ii) infiltration from rivers flowing out of the Vosgian range onto the plain and (iii) rainfall on the plain.

The Alsace aquifer has a surface area of about 3000 km², with the average stored volume of groundwater ranging from 30 to 50 billion m³ (AERM 2009).. The average yearly flow² is about 1.5 Mm³/yr (1.5 GL/yr), which corresponds to a renewal rate of 3% per year (AERM 2009).. The total abstraction rate is about 500 Mm³/yr. Most of the bores tap the aquifer at shallow depths (20 to 100 m) while some of them reach 150 m depth. The well yields range from 20-30 m³/h (5-10 L/s) on the margins, to 200-400 m³/h on the plain. Large diameter wells can supply up to 3000 m³/h.

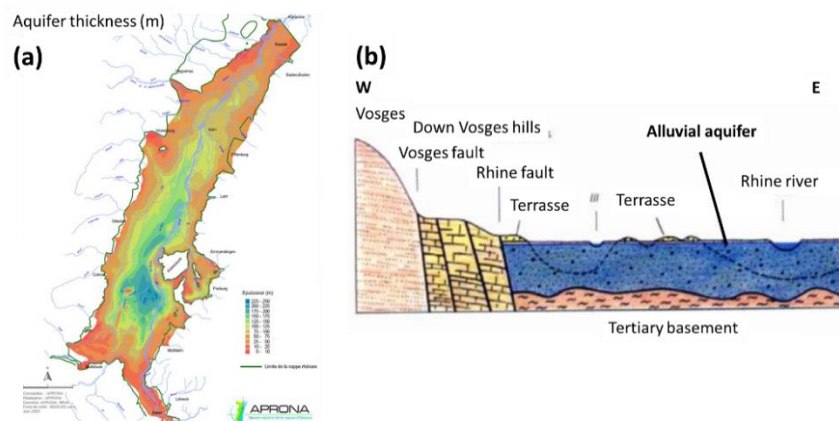


Figure 2. 3: (a) Map of Alsace aquifer thickness (modified after APRONA 2009) (b) Alsace aquifer cross-section.

2.2 Sedimentary basin aquifers

They are three main large sedimentary basins in France: the Paris, Aquitain and South-East basins (Figure 2. 4a). Aquifers in these basins can be classified into three types according to their structure and flow regimes:

- Large single-layer unconfined aquifers, mainly constituted by chalk and limestone rocks.

² Equal to natural recharge rate

- Multi-layered aquifers comprising heterogeneous Tertiary sediments located in the centre of Aquitaine (Figure 2. 4b) and Paris Basins that form a shallow unconfined aquifer and several deeper confined aquifers.
- Large deep confined aquifers mainly constituted by sands, sandstones (Albien aquifer in the Paris basin) or limestone (Carboniferous rocks in the North).. Initially artesian, these aquifers (Inferior Trias sandstones, in-framollasic aquifer in Aquitaine basin) are now highly developed and artesian conditions have mostly disappeared.

The Paris and Aquitaine Basins contain the most productive sedimentary aquifers which provide high yields from permeable layers. Chalk aquifers within the Paris Basin in northern France provide ~ 360 Mm³/yr, while multi-layered aquifers in the Aquitaine Basin supply ~ 350 to 450 Mm³/yr.

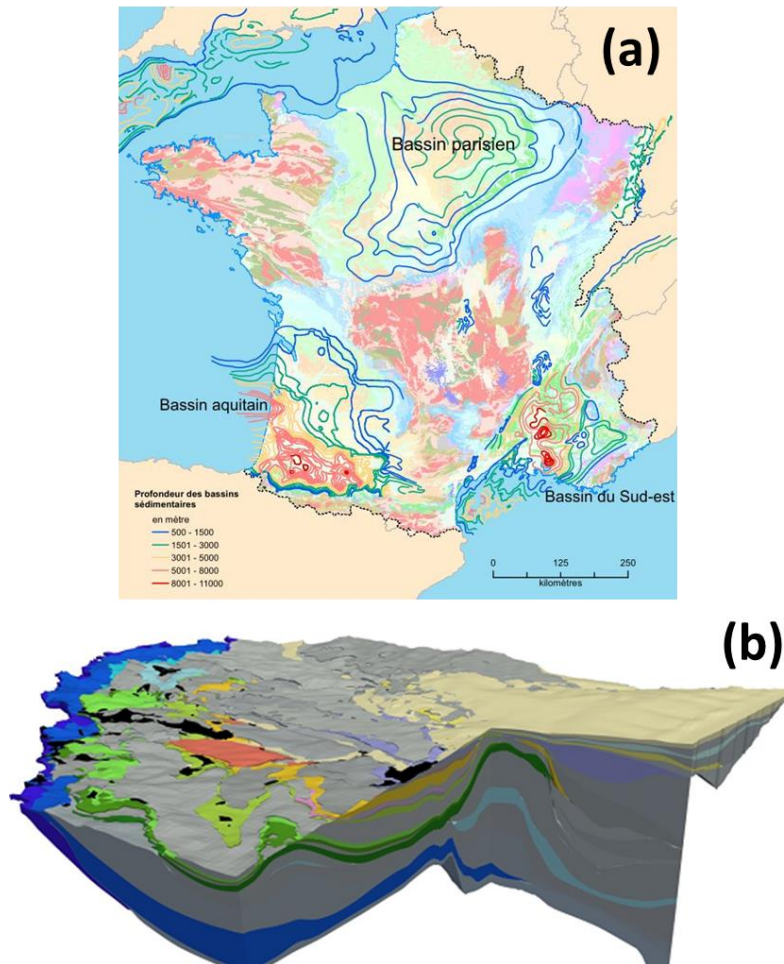


Figure 2. 4: (a) Location of the three main sedimentary basins (Paris, Aquitain and Southeast) (b) Geological cross-section of Aquitain sedimentary basin (© brgm, SIGES <http://sigesaqi.brgm.fr/Ou-est-ce-que-le-MONA.html>).

The Paris Basin is the largest sedimentary basin in France. The sequence extends from Permian and Triassic sediments at the base to Tertiary deposits at the surface and contains at least seven major aquifers (Figure 2. 5b), the deeper of which are brackish. The main aquifers are: the chalk aquifer from Upper Cretaceous (light green on Figure 2. 5a), the Albién green sands (~ 18 Mm³/yr, dark green), the Lower Jurassic limestone (light and medium blue) and the Vosges Lower Trias sandstones (~ 160 Mm³/yr, magenta on Figure 2. 5a). Large Tertiary aquifers (Beauce, Brie, yellow) lie at the surface of the basin.

The calcareous Beauce aquifer, located north of Orleans in the centre of France, is one of the largest aquifers in the country. The aquifer extends over an area of 9000 km² and contains an average storage volume of 20 billion m³. This area is one of the largest producers of cereals in Europe, with agricultural land covering more than 70% of the total area. About 3000 km² is irrigated, which represents an increase of 50% since 1988, mainly driven by the production of cash-crops in the summer (Lejars et al. 2012). Not surprisingly, groundwater abstraction has also increased. The sustainability of the Beauce aquifer has been achieved thanks to an agreement called 'Beauce Aquifer Charter' ('charte nappe de Beauce') which has limited the abstraction volumes for irrigation.

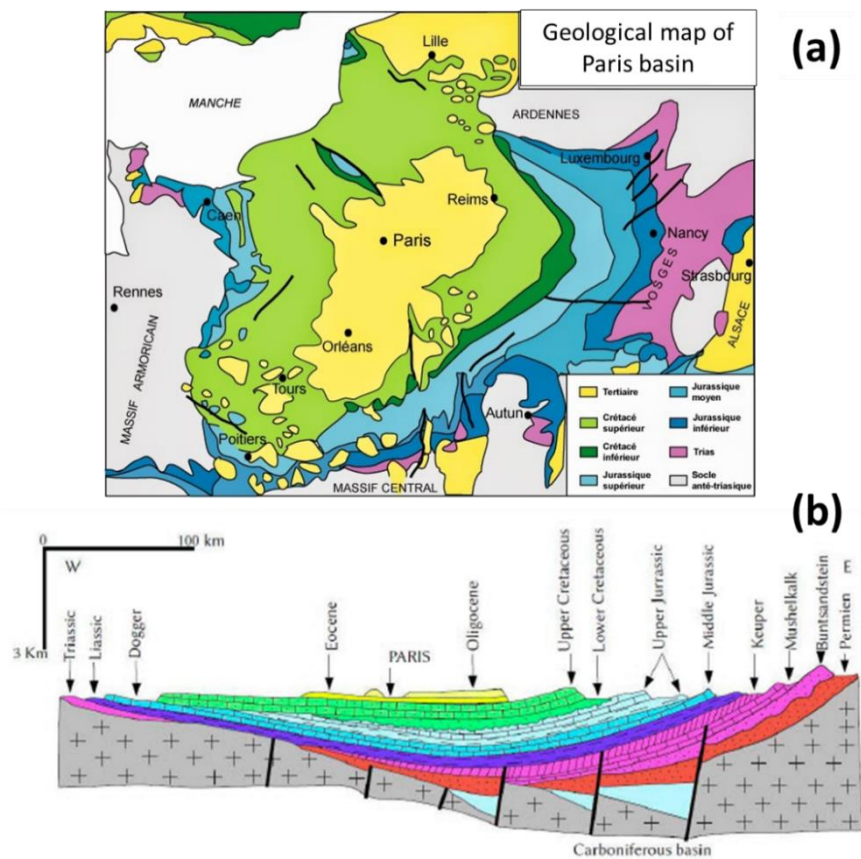


Figure 2. 5: (a) Geological map of the sedimentary Paris basin (modified after Brgm 1996) (b) Cross- section of the Paris basin (modified after brgm 1996).

2.3 Crystalline and volcanic rock aquifers

Crystalline rocks are mainly located in two large mountain ranges: the Armorican mountain range in the West and the Central mountain range in the centre of the country (Figure 2. 6a). The Vosges, Pyrenees and Alps mountains constitute other significant outcrops. The island of Corsica is also mainly comprised of fractured rocks.

The typical geological profile in weathered crystalline aquifers follows the lithological description by Dewandel et al. (2006) which from top to bottom, consists of (Figure 2. 6b): red soil from the first decimeters to the first meter, sandy regolith of a few meters thickness, saprolite from about 3 meters to 13 – 24 meters deep, granite or gneiss rocks. The upper part of the hard rock is highly weathered and fractured but the fracture frequency decreases rapidly with depth.

In low lying areas (Brittany), these aquifers are exploited through shallow boreholes 50-100 m deep, while in mountainous areas (Pyrenees, Alps, Central Massif), water is obtained from natural springs. Water abstraction rates are generally low, only a few m³/hour.

Volcanic rocks are mainly located in the Massif Central and overseas islands, such as La Réunion, Martinique, and Guadeloupe. The total amount of groundwater supplied by Massif Central volcanic rock aquifers is ~ 40 Mm³/yr. These aquifers provide low yields but they often represent the sole source of supply for small villages or agricultural farms.

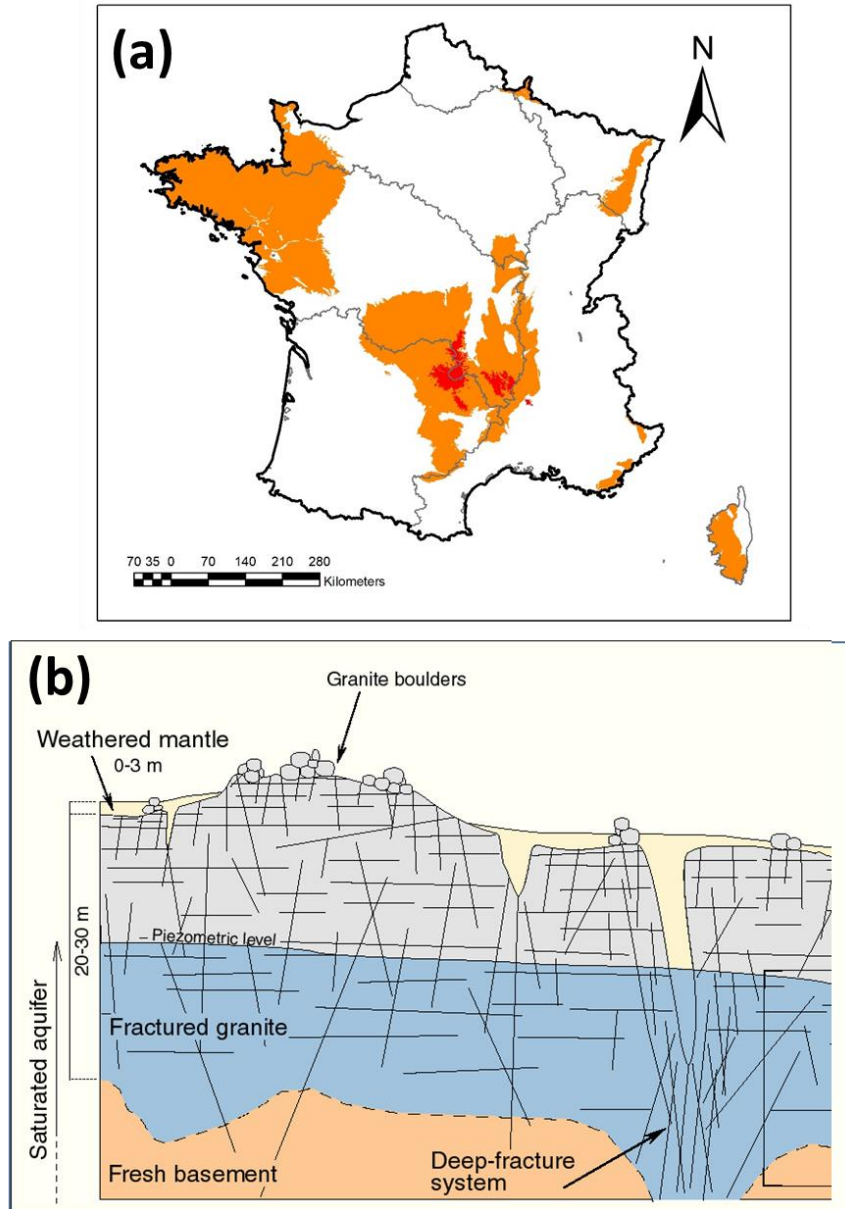


Figure 2. 6: (a) Map of crystalline rocks (red: granite, pink: gneiss, brown: schist, green: ophiolite, blue: basalts); (b) Hydrogeological cross section of a weathered crystalline aquifer (modified from Maréchal et al. 2004).

Example. In the Armorican Massif region (Figure 2. 7a), groundwater accounts for 25% of the drinking water supply from about 400 bores (Agence de l'eau Loire-Bretagne 2016). In all, 40 % of the groundwater supply comes from crystalline rock aquifers, while the remainder is obtained from alluvial, sedimentary and volcanic aquifers. Historically, groundwater extraction from the crystalline basement came from shallow wells (20–30 m deep) drilled into the upper part of the basement where regolith and shallow fractured rocks were sufficiently permeable (Roques et al. 2016). During the last few decades, deeper wells in the basement have been drilled to over 50 m deep to meet the increasing water demand, as well to avoid recurrent problems of surface water contamination. At the regional scale, the average bore-hole flow rate in the crystalline rocks is estimated to be around 9 m³/h (Mougin et al. 2008). In this region, high yields can be obtained from local fault zones (Figure 2. 7b).

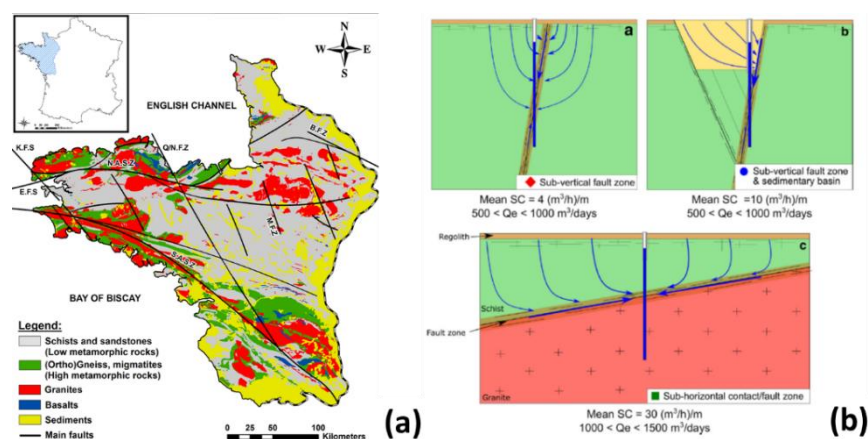


Figure 2. 7: (a) Simplified geological map of the main lithological units and main geological structures of the Armorican Massif. (modified from Les Landes et al. 2014). (b) Conceptual models of high-yield borewells due to fault zones Average specific capacity (SC; Q/s) and the range of exploitation flow rates (Q_e) are displayed for each model (modified from Roques & al. 2016).

2.4 Karst aquifers

Karst aquifers are widespread in France and supply 40 % of the nation's drinking water supply. Most of these aquifers occur in the southern part of the country (Figure 2. 8a). Their main advantage is the high permeability of the karst drainage network that can supply very large volumes of water (Figure 2. 8b). They are replenished very quickly through diffuse and localized recharge.

Close to the Mediterranean coast, the limestone massifs have been affected by the Messinian salinity crisis which occurred 6 million years ago when the closing of the Strait of Gibraltar cause a lowering of the Mediterranean Sea level. This eustatic and tectonic phenomenon and the associated lowering of the regional water levels, has increased the erosion and karstification potential of rivers and groundwater in the associated region, creating deep karst cavities and karst drainage networks. An example is the well-known Fontaine de Vaucluse karst spring which has been explored to a depth of 315 m. This deep development of karstification leads to high volumes of stored groundwater which can be pumped at high rates from a single pumping station under active management schemes like the Lez aquifer. As a result of this Messinian crisis, the deeper karst systems are now located under low permeability rock cover (for example, the Arc karst aquifer close to Marseille).

Apart from the Mediterranean coast, other productive karst aquifers include: La Rochefoucauld aquifer and la Touvre spring supplying Angoulême city (~ 13 Mm³/yr), la Chartreux spring supplying Cahors city (~ 3.5 Mm³/yr), and the Arcier spring in Jura mountains supplying Besançon city (~ 5 Mm³/yr).

Due to rapid groundwater flows in the karst conduits and direct infiltration of water in sinkholes, karst aquifers are highly vulnerable to surface pollution.

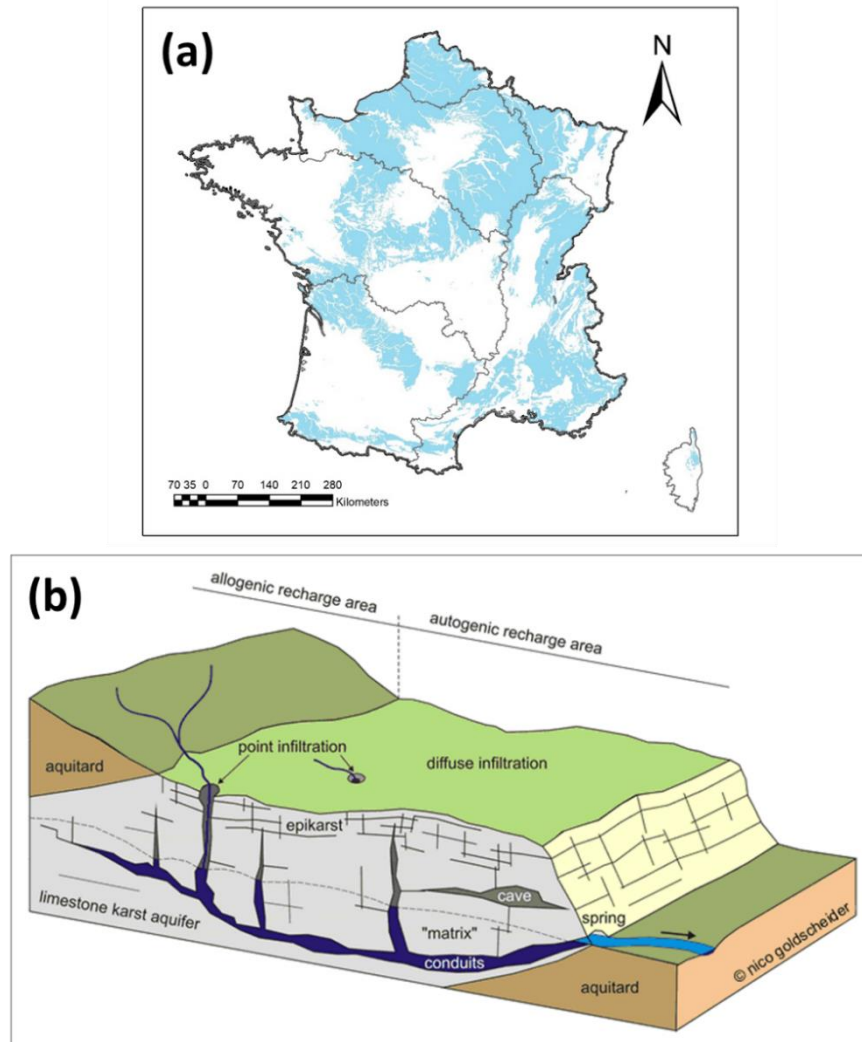


Figure 2. 8: (a) Map of karstic carbonate rocks (in blue), main karst springs and caves, and other aquifers (modified from Chen et al. 2017) (b) Karst aquifer simplified sketch (modified from Goldscheider and Drew 2007).

Example. The Lez spring system is one of the largest groundwater abstraction systems in the world, similar to the Fiegh karst system which supplies water for the city of Damascus. It is currently tapped by four pumping units located in four vertical boreholes that intercept the main karst conduit (Figure 2. 9). The mean pump-

ing abstraction rate of 34 Mm³/year is sufficient to supply drinking water for a permanent population of around 340 000 inhabitants in the city of Montpellier. Part of the pumped water is diverted into the Lez river in order to assure a minimum discharge rate of 200 L/s for environmental purposes.

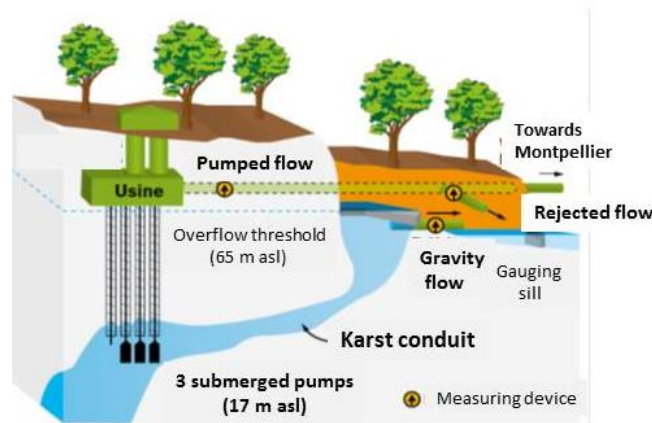


Figure 2. 9: The pumping system at the Lez karst spring © KFH Montpellier.

3 Groundwater usage

3.1 Historical development of groundwater use

France has a long history of groundwater use, with the first wells drilled in the 10th century in the Chalk confined aquifers of the Artois region in Northern France where the name “artesian well” originated (Barraqué et al., 2010). The increase in groundwater use in France was first associated with the development of drinking water supply systems and the industrial revolution in the 19th century, and was mainly localised in urban areas (e.g. Paris, Bordeaux). Today, groundwater represents about 66% of France’s domestic water supply, 31% of industrial water supply and 37% of total water use in agriculture (CGDD, 2017).

Irrigation in France was first developed in the Mediterranean area from the diversion of river water from the Alps, Massif Central and the Pyrenees into collective irrigation schemes. The large post-war development projects of the 1950s and 1960s increased the scale of these diversions and popularised the use of surface water pumps and collective distribution infrastructure. Groundwater abstraction through collective or individual boreholes first occurred at a large scale in the Beauce region for maize production (see chapter 6) but quickly expanded in the western and northeastern regions of France. This trend towards the use of individual

boreholes and pumps is ongoing, coupled with a reduction in the use of the traditional collective systems (Loubier et al., 2013).

3.2 Trends in water use by sector

In 2013, the total water abstraction in France was about 38.5 billion m³, with the vast majority (70 %) sourced from surface water to serve as cooling water for electricity production (21.6 billion m³) and to supply navigation canals (5.5 billion m³) (AFB, 2017). Other uses (drinking water, agriculture, industry) comprise a total of almost 12 billion m³, of which about 50 % is supplied by groundwater. Table 2. 1 presents the contribution from surface water and groundwater for water use by the various sectors in 2013.

Table 2. 1: Water use in 2013 and trends over time (M m³).

	Drinking water	Agriculture	Industry	Total
Groundwater	3,700	1,035	930	5,665
Surface water	1,866	1,766	2,700	6,332
Total	5,566	2,801	3,630	11,997

About 66% of abstracted water for drinking water is from groundwater which is a strategic resource given its higher quality compared to surface water, and consequently has lower treatment costs. Groundwater represents about 36% of water abstracted for agriculture and 31% of abstraction for industrial use, which includes factories, commercial firms and various public buildings.

Overall, total water abstraction for drinking water has reduced by 15% between 2003 and 2013 as shown in Figure 2. 10. Industrial water abstraction has similarly reduced by 27% between 1998 and 2013. No significant evolution in overall water abstraction in agriculture can be seen since 2008 when monitoring and reporting became more consistent nation-wide.

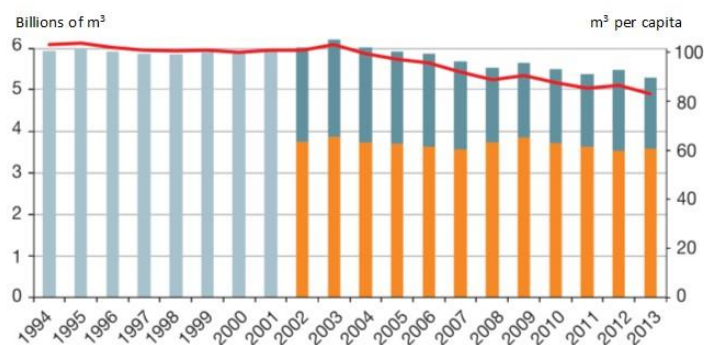


Figure 2. 10: Trend in water abstraction for drinking water supply. In light blue: total abstraction. In dark blue: surface water abstraction. In orange:

groundwater abstraction. Red line: abstraction water per capita. Source: modified from Banque nationale des prélèvements quantitatifs en eau, ONEMA-SOeS on 2013 data (CGDD, 2017).

Unlike domestic and industrial use which eventually recycles most of abstracted volume back to surface waters as wastewater, irrigation water applied by sprinkler or micro-irrigation is mostly consumed by evapotranspiration and as a result, agriculture is the largest net consumer of water e.g. 58% of water consumption in the Adour-Garonne basin (Ayphassorho et al., 2015).

3.3 Groundwater use in agriculture

Generally, irrigation in France is not essential for agricultural production as is the case in arid countries such as Australia; rather, it is used to 1) secure yields against climate risks such as drought, 2) increase average yields, and 3) improve product quality. The irrigation of crops consumes 80% of water used in agriculture in France, while the remaining 20% is used for livestock water supply and cleaning. Accurate figures on irrigation use are difficult to obtain because water meters are not installed on all individual water pumps yet, and the reporting of abstracted volumes is not systematic.

Most agricultural land equipped for irrigation is situated in the southwest, west, and northeast of France as well as in the overseas islands of Martinique and La Réunion. The main irrigated crops are maize and cereals, as well as potatoes, vegetable cropping and fruit production. Maize represented 41% of all irrigated land in 2010, down from 50% in 2000. This trend is partly related to the reduction in European subsidies for this crop (see chapter 24), as well as stricter restrictions on water use (see chapter 3) and higher prices for other cereal crops, in particular wheat.

The area of irrigated land has steadily increased from 500,000 ha in 1970, to a maximum of 1.57 million ha reached in 2000 (representing 6% of the total agricultural land). In 2010, the area of irrigated land had not changed significantly while the total area of used agricultural land had reduced by 900,000 ha (or 3.5% of the total area). Overall, irrigation appears to be maintained where it is regularly used, and may help to keep small agricultural holdings economically viable in a context of general consolidation of holdings and abandonment of agricultural land (Loubier et al., 2013).

The internal irrigation rate of agricultural holdings practicing irrigation in 2010 was 32%, a number that has slightly increased since 2000 and indicating that irrigation is becoming a more important part of some agricultural units. On average, irrigation is responsible for about 2,000 m³ of water abstracted per ha.

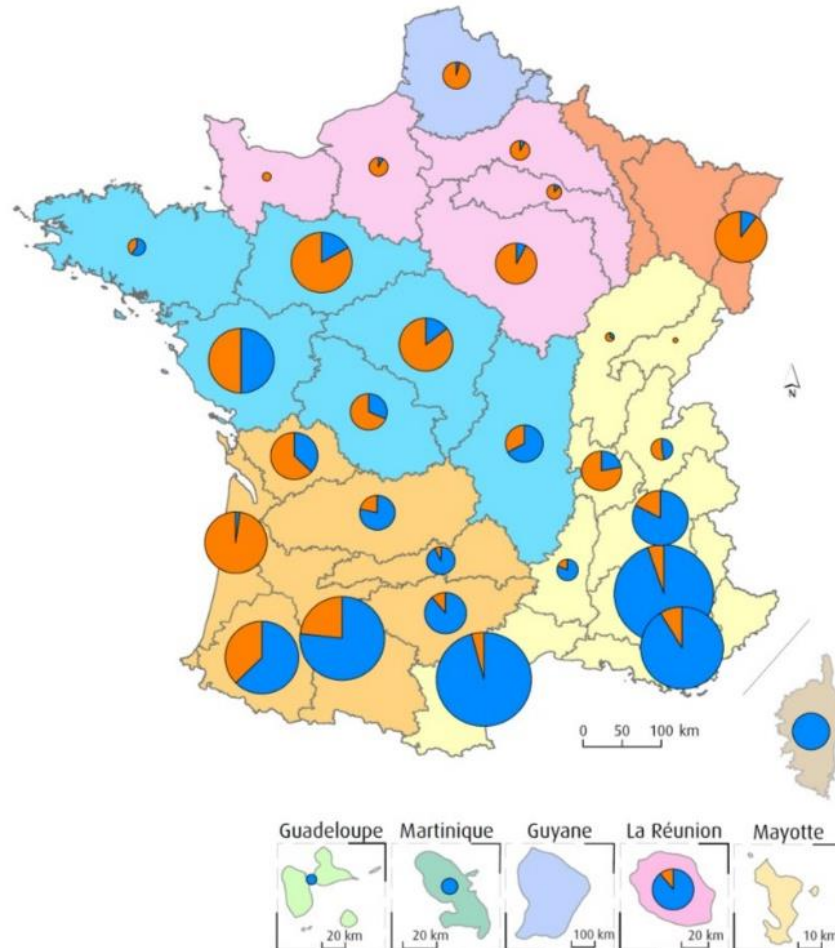


Figure 2. 11: Agricultural water abstraction by administrative district. In orange: abstraction from groundwater. In blue: Abstraction from surface water. The size of the circle represents the relative abstracted volume. Source: modified from Banque nationale des prélèvements quantitatifs en eau, ONEMA-SOeS on 2013 data (CGDD, 2017).

In 2010, a sharp reduction in area equipped with collective irrigation systems was observed, while areas equipped with individual irrigation systems has continued to increase (Loubier et al., 2013). This trend is also occurring in the Mediterranean region where most irrigation is traditionally carried out through collective systems. At the time, a reduction of 50% in surface water irrigation is observed in these

regions. These trends indicate a move towards more water efficient systems, although it also poses local challenges due to a reduction in groundwater recharge via the losses from distribution canals and surface irrigation practices.

The development of irrigation has led to increasing societal conflicts across France, especially in the agriculturally productive regions in the west and south west of France which underwent a significant increase in irrigation for maize and cereal production in the 1980s and 1990s. Assuring minimum ecological flows is a significant challenge resulting from the cumulative pumping from rivers and extractions from individual boreholes in alluvial and sedimentary aquifers (Ayphassorho et al., 2015).

3.4 Groundwater and drinking water supplies

The drinking water supply network provides water to domestic users as well as all buildings equipped with sanitary infrastructure (e.g. schools, hospitals, hotels, sports, etc.), small businesses and industries. In 2013, the water abstraction per capita in France was 85 m³, a reduction of 20% compared to 2003 (Datalab, 2017).

The volume of water use is mainly dependent on the size of the residential population; however some groundwater basins experience large seasonal variations in population due to tourism. This can pose supply challenges in Mediterranean basins during the low flow season similar to those faced by irrigation. Drinking water supply is given the highest priority use during crisis. Water shortages have not yet caused restrictions on drinking water use in France, however restrictions on garden watering are regular.

The vast majority of the population (98%) have water delivered to their homes by public water suppliers, however since the 1990s, an increasing number of households in detached or semidetached housing units have drilled private supply bores due to various economic, political and ethical reasons (Rinaudo et al., 2015). Typically, households use alternative water supplies for gardening and other non-consumptive uses in order to reduce their water bills. According to Montginoul and Rinaudo (2011), the presence of domestic bores and shallow wells is reported in a majority of French counties in both southern and northern France, and is expected to significantly increase in the coming decade as a result of increased water scarcity, higher prices from public water suppliers, and the decreasing cost of alternative supply technologies. Furthermore, there is currently little regulation controlling drilling to provide private domestic supplies.

Overall the main challenge regarding groundwater abstraction for drinking water supply purposes relates to water quality and the risks posed by pollution, mainly from agricultural activities.

3.5 Strategic groundwater resources

Recent work has investigated the role that groundwater may play as insurance for drinking water supplies in case of extreme events or potential failures of supply systems in the future due large storms, flooding, earthquakes or large technological disasters such as nuclear war or accidents (Herivaux and Rinaudo, 2016). In the long term, drinking water supplies may be exposed to the impacts of climate change or from other progressive changes such as large scale pollution and increased operational costs. In the same way as typical insurance, the preservation of specific groundwater resources may result in increased costs in the short term but will provide long term guarantees which are of higher value than other types of resources.

According to Herivaux and Rinaudo (2016), three approaches have been implemented in France to secure drinking water supplies for such situations (see Figure 2. 12):

- Creation and maintenance of emergency boreholes ;
- Increasing the share of abstraction from confined aquifers that are naturally protected from human pressures;
- Preservation of groundwater resources that are currently not exploited (or are developed to a limited extent) for future use.

One such example is the Albien-Néocomien aquifer beneath Paris which has been identified in the river basin management plan as a strategic resource for an emergency drinking water supply. This large confined aquifer is up to 1000 m deep and can provide good quality water for several months in case of an emergency. In order to maintain its “insurance value”, public authorities have established regulatory controls on current abstraction to preserve sufficient volumes for cases of emergency. In addition, deeper pumping infrastructure was installed in order to secure supplies over a long period if necessary.



Figure 2. 12: Examples of groundwater resources reserved for their insurance role (Herivaux and Rinaudo, 2016).

4 Groundwater management issues

4.1 Quality issues

According to the European water framework directive, 67% of groundwater bodies in France are considered to be in a good chemical state in 2013 (Figure 2. 13a). Generally, the quality of groundwater is not adversely affected by water-rock interaction. Despite the existence of evaporites deposited during the Trias period, salinity contamination of aquifers has not occurred because these rocks are mostly isolated from aquifers by low permeability sediments.

The main quality issues for groundwater are related to diffuse contamination by agricultural practices (i.e. fertilizers and pesticides). High nitrate levels are observed in the crystalline aquifers of Brittany, due to effluent from intensive pork breeding and agriculture.

In karst aquifers, the issue is related to rapid flows during floods bringing turbidity and bacteria through the karst network to springs. It is necessary to properly map

the vulnerability to pollution of such aquifers and accordingly define appropriate land-use rules. Wastewater treatment plants and sewage networks must be well designed and maintained especially for such flood events.

In coastal areas, especially in overseas islands, sea water intrusion can be induced by high levels of pumping for drinking and irrigation purposes in densely populated regions. Chapters 12 and 19 describe two case studies where seawater intrusion was successfully managed. Monitoring of the geometry and fluctuations of the salt-water interface is necessary in order to properly manage water abstraction. In several cases, managed aquifer recharge is used to prevent saline intrusion. Compared to other countries (e.g Spain), seawater intrusion is well managed in France.

In alluvial aquifers, increasing pollution of rivers lead to the potential contamination of groundwater especially when pumping wells are located close to rivers. The potential filtration impact of riverbanks and aquifer is a rising scientific issue.

4.2 Quantity issues

Under the European water framework directive, water agencies analyse the state of groundwater aquifers. In 2013, 10% of groundwater bodies was considered in a bad quantitative state (Figure 2. 13b).

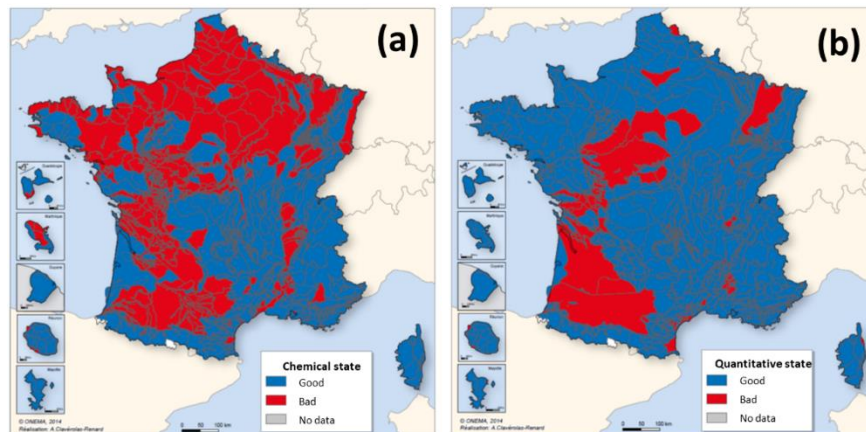


Figure 2. 13: Chemical (a) and quantitative (b) states of groundwater bodies in France in 2013, from Petit et Michon (2015).

There is a wide range in present exploitation rates³ of aquifers (Margat 2006):

- The most exploited aquifers are not necessarily those with the highest bore yields. For example, large unconfined aquifers with high recharge rates and large storage volumes (e.g. karst aquifers), are often underutilised;
- Exploitation rates reaching 100% are rare: in most cases, the extraction has increased the infiltration from rivers which counter balances the losses due to abstraction.
- In most of the aquifers, the abstraction volume is less than a tenth of the natural groundwater flow

Watertable lowering is observed in a few aquifers where water flows are unbalanced (i.e. the pumping rate being higher than the replenishment of the aquifer through natural recharge). In these cases, studies have been launched by water agencies in order to define a volumetric limit (“volumes prélevables”) of groundwater that can be take out from the aquifers (see chapter 11). Declines in groundwater levels can induce several adverse impacts.

In alluvial aquifers (or other shallow aquifers connected to surface water), the watertable decline induced by pumping can temporarily reduce groundwater flow to the surface water. This will reduce the baseflow of the river during dry periods, threatening aquatic life and decreasing water quality. This occurs for example for the Tarn, Dordogne and Lot Rivers in south-western France, as well as several rivers in the Beauce region, and in north of France (see chapter 6). In regulated rivers, a minimum discharge rate in the river can be maintained by water released from reservoirs managed by electricity companies. In some cases, watertable decline could reverse the natural exchange flow between the aquifer and surface water leading to a deterioration of groundwater quality. Research is on-going in karst aquifers where flow exchanges between surface and ground water are very complex. Most of the time, in unconfined aquifers, the induced increased recharge counterbalances the pumping and water table remains stable (Figure 2. 14a).

The lowering of the watertable can also threaten wetlands. Maintaining a watertable that stands at or near the land surface for a long enough period each year to support aquatic plants is a challenging issue for some wetlands. For example, the historically well-known Marais Poitevin marsh has a high risks of adverse impacts during droughts due to groundwater pumping for maize irrigation (see chapter 18).

In a few confined aquifers, the absence of direct or indirect recharge induces long-term water table depletion (Fig 14b). In such multi-layered aquifers, the verti-

³ Exploitation rate is the ratio between abstraction flow and natural groundwater flow

cal hydraulic exchanges are dependent on the hydraulic gradient between the aquifers. The natural upward flow from a deep confined aquifer to a shallow unconfined aquifer can be reversed by water level declines induced in the deep aquifer by high pumping rates (Figure 2. 14). In that case, possibly poorer quality water from the shallow aquifer can contaminate water in the deep aquifer. It is therefore important to properly manage pumping in both aquifers in order to avoid such contamination (see chapter 12).

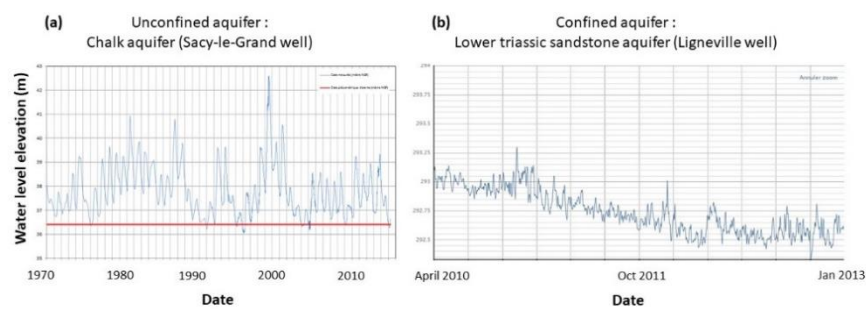


Figure 2. 14: (a) Watertable fluctuation in an unconfined aquifer (b) Water pressure fluctuations in a confined aquifer.

In summary, France does not face the problems of aquifer depletion which are experienced in many other countries. However, the associated groundwater dependent ecosystems are more likely to be affected by the abstraction of groundwater.

4.3 Long term challenges

4.3.1 Climate change and recharge

The Explore 2070 project⁴ has developed and assessed strategies to adapt to climate change impacts on hydrological systems and coastal environments in mainland and overseas France up to 2070, based on different climatic, demographic and socio-economic scenarios.

Rises in temperature (and consequently evapotranspiration) combined with decreasing rainfall, will lead to a decrease of effective precipitation in the future. The application of seven climate models using the median GHG emission scenario

⁴ <http://www.brgm.eu/project/explore-2070-rising-to-climate-change-challenge>

(A1B, 4th GIEC report) enabled an estimate of the change in natural recharge rates (Figure 2. 15). With predicted recharge variations of +10 to -30% in the optimistic scenarios, and -20 to -55% in the pessimistic scenarios, a decline of similar proportions in groundwater levels would be expected, and therefore groundwater resources are likely to decline significantly overall by 2070. Two areas which are likely to be more severely affected are :

- the Loire basin with a 25 to 30% recharge decline across half of the catchment area,
- the south-west of France with a 30 to 50% decline in recharge.

All of the scenarios also show a decline in average river flow by 2065, which varies from a 10 to 40% reduction in the northern half of the country, and a 30 to 50% reduction in the southern half, with local extremes of up to 70%. Despite this relative decline in river flow, some models show that very high surface water levels are nevertheless possible during the winter in some catchments (e.g. the Somme and Rhine Rivers), confirming the likelihood of lengthy periods of flooding.

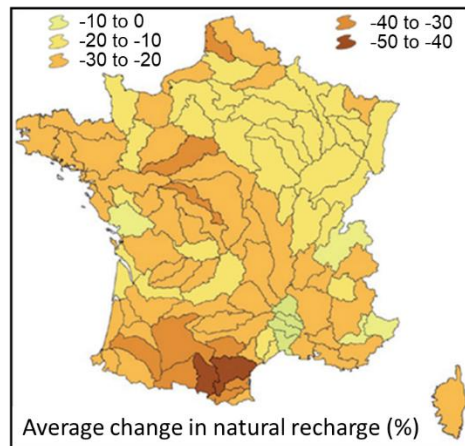


Figure 2. 15: Impact of climate change on natural recharge rates of aquifers from now to 2045-2065 period (from MEDD 2015).

4.3.2 Climate change and sea level rise

Sea level rise is expected to have several impacts (Figure 2. 16):

- An increased risk of sea water intrusion and variable inland migration of salt water, especially in karst aquifers

- A rise of the salt/fresh water interface in estuaries and the infiltration of salt water into unconfined aquifers: this phenomenon could be accentuated by the decline of river flow rates due to climate change or increases in groundwater abstraction
- The submersion/inundation of lowlands by seawater and infiltration of salt water into unconfined aquifers.

The risk of inundation is especially high along the Mediterranean coastline where significant areas are likely to be flooded due to the very low elevation.

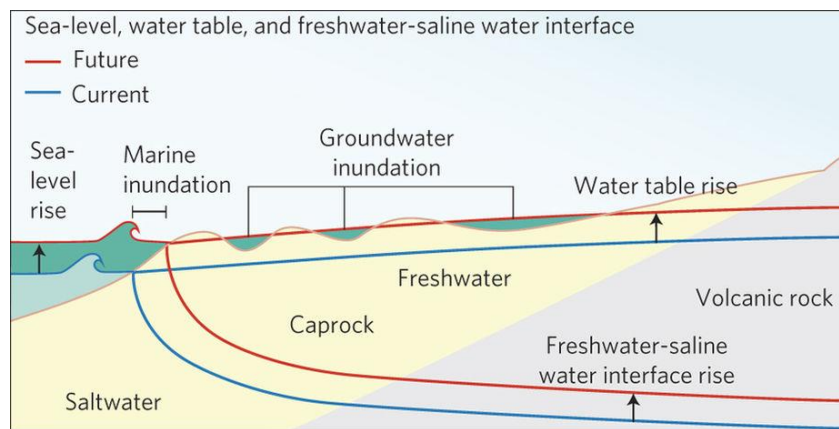


Figure 2. 16: Impacts of sea level rise, from Rotzoll and Fletcher 2013

4.4 Future changes in groundwater use

The main scenario for change is an overall decrease in groundwater abstraction of 20% by 2070 (Table 2. 2). Drinking water abstraction is expected to decrease by 15% due to decreases in individual consumption rates and network losses, and industrial consumption will decrease by 53% due to recycling efforts and production changes. Agricultural demand is expected to remain stable. The regional distribution of groundwater abstraction changes is illustrated in Figure 2. 17.

Table 2. 2: Predicted changes in groundwater abstraction ($M m^3$)

Year	Drinking water	Irrigation	Industry	Total
2006	3631	1276	1436	6344
2070	3100	1271	679	5050
Change (%)	-14.6	-0.4	-52.7	-20.3

The climate change induced changes in groundwater abstraction are expected to lead to a small decrease of rates of water level declines generally but in coastal areas, an increased decline in water levels and increased risk of saline intrusion is predicted due to population increases and increased water demand (Figure 2. 17).

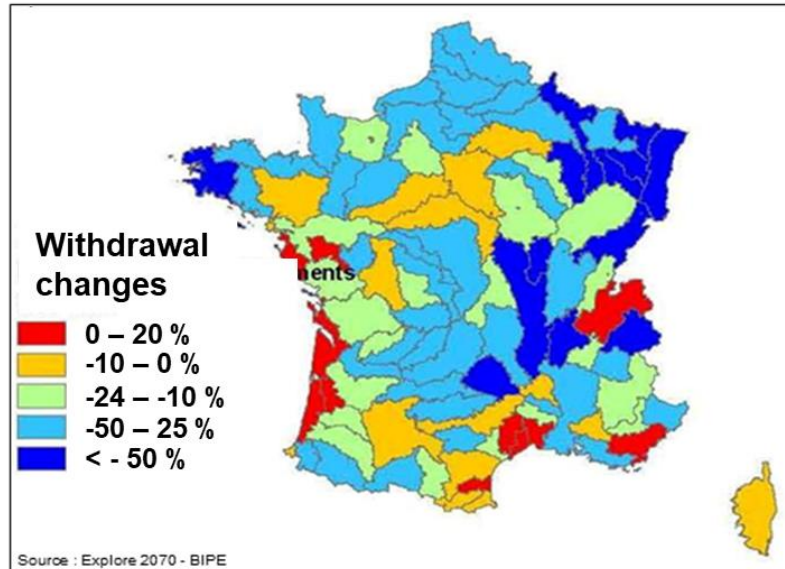


Figure 2. 17: Expected changes in groundwater abstraction (from 2006 to 2070)

4.5 Emerging adaptation strategies

4.5.1 New groundwater management strategies and policies.

An increasing number of basins are expected to be confronted with a mounting imbalance between available resources and demand for those resources. The management model using volumetric limits which is currently deployed in a limited number of groundwater basins will need to be implemented in many others. Allocation policies will also need to be more flexible (see chapters 22 and 23).

4.5.2 Managed Aquifer Recharge

“Good quantitative status” of groundwater is achieved when the volume of water withdrawn is less than the renewal capacity of the aquifer, and when the connected surface ecosystem health (e.g. wetland, river) is maintained. With continual population growth combined with climate change, the management of groundwater resources in France is mostly focused on more efficient water use. But it is likely that these actions shall not be sufficient to cope with water shortages in some areas, and

Managed Aquifer Recharge (MAR) could be a novel and efficient way to maintain and improve groundwater quality and quantity.

In Europe, France has the third highest number of MAR sites after Germany and Netherlands. Surface water spreading via infiltration basins and induced bank filtration are the most numerous MAR systems (Casanova et al 2015). Most of these are located in alluvial plains or sedimentary aquifers, but they contribute only 3% of drinking water supplies. Currently, the MAR technique is used to maintain water levels in pumped aquifers but also for improving groundwater quality: i.e. to stop saline intrusion in coastal aquifers (example of Hyeres Aquarenova project), or to improve the quality of water pumped in alluvial plains close to a polluted river using a double pumping/injection system.

In the future, the MAR technique could constitute an alternative solution to deal with decreases in natural recharge rates under climate change. The cost of recharge (including the maintenance of infiltration systems) and the recovery efficiency (the volume of infiltrated water that can be recovered for any use) are still the main issues for implementing such management solutions.

4.5.3 Active groundwater management

Karst aquifers serve as major underground water reservoirs that supply the ever-increasing water demand arising from the population boom in the coastal region and main cities especially in the Mediterranean Basin. Through “active groundwater management” (Collin 1994), water resources in these systems can be optimally utilized by overcoming the negative effects of high variations in spring flow variations. In the dry season, this requires pumping at a rate that is higher than the replenishable flow so as to tap aquifer water reserves, which in turn will be replenished during the following rainy season. This also reduces the intensity of floods at the onset of the rainy season. Karst aquifer systems in France are often located upstream of a coastal stream catchment which has been urbanized and is subject to Mediterranean-type flash floods. The latter cause flooding and property damage, which in turn may have considerable economic impacts, or lead to loss of human life, as occurred in Nîmes in 1988.

Conservation of coastal river ecosystems is also a key issue, especially during low flow periods when some of the pumped groundwater is diverted to the river to help maintain the streamflow and consequently the stream’s ecological balance. Multipurpose management of such aquifers is an integrated way to address these seemingly conflicting issues: supplementing drinking water supply demand, reduction of flooding hazards, and conservation of aquatic environments.

In the Lez karst aquifer under active management, described above (Figure 2. 9), a model has been used to simulate several scenarios of pumping under present and future (2045-2065) climate (Ladouche et al. 2013). It is useful to determine the sustainable pumping rate allowing to respect the authorized drawdown and pumps elevation. However, even when considering the present water pumping rate being

continued into the future, the aquifer would be totally recharged and the groundwater level recovered to the overflow level each year (Figure 2. 18).

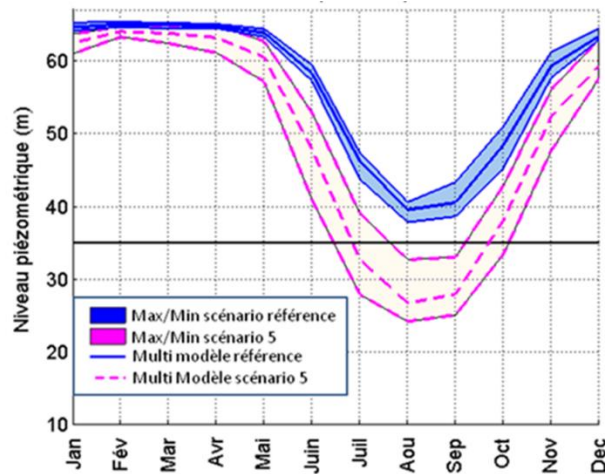


Figure 2. 18: Modelling results at the Lez karst system spring - Comparison of present water levels under present abstraction rate (33 Mm³/yr) with future water levels under climate change and increased abstraction rate (44 Mm³/yr) – horizontal black line corresponds to the authorized minimum water level, modified from Maréchal et al. (2014).

5 Conclusions

Although France is blessed with abundant surface water and groundwater resources and appear favourably in international terms, the high water demand and the widespread emission of pollutants, together with the predicted impacts of climate change, put significant pressure on the long term sustainability of groundwater reserves. The existing regulatory and policy instruments provides a comprehensive framework for managing groundwater. However, improved implementation and further political awareness of the long term value of protecting groundwater resources is necessary. Given the high spatial heterogeneity of situations across the country, future implementation will also need to be flexible to enable delivery of national strategies in a targeted manner appropriate to diverse situations.

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