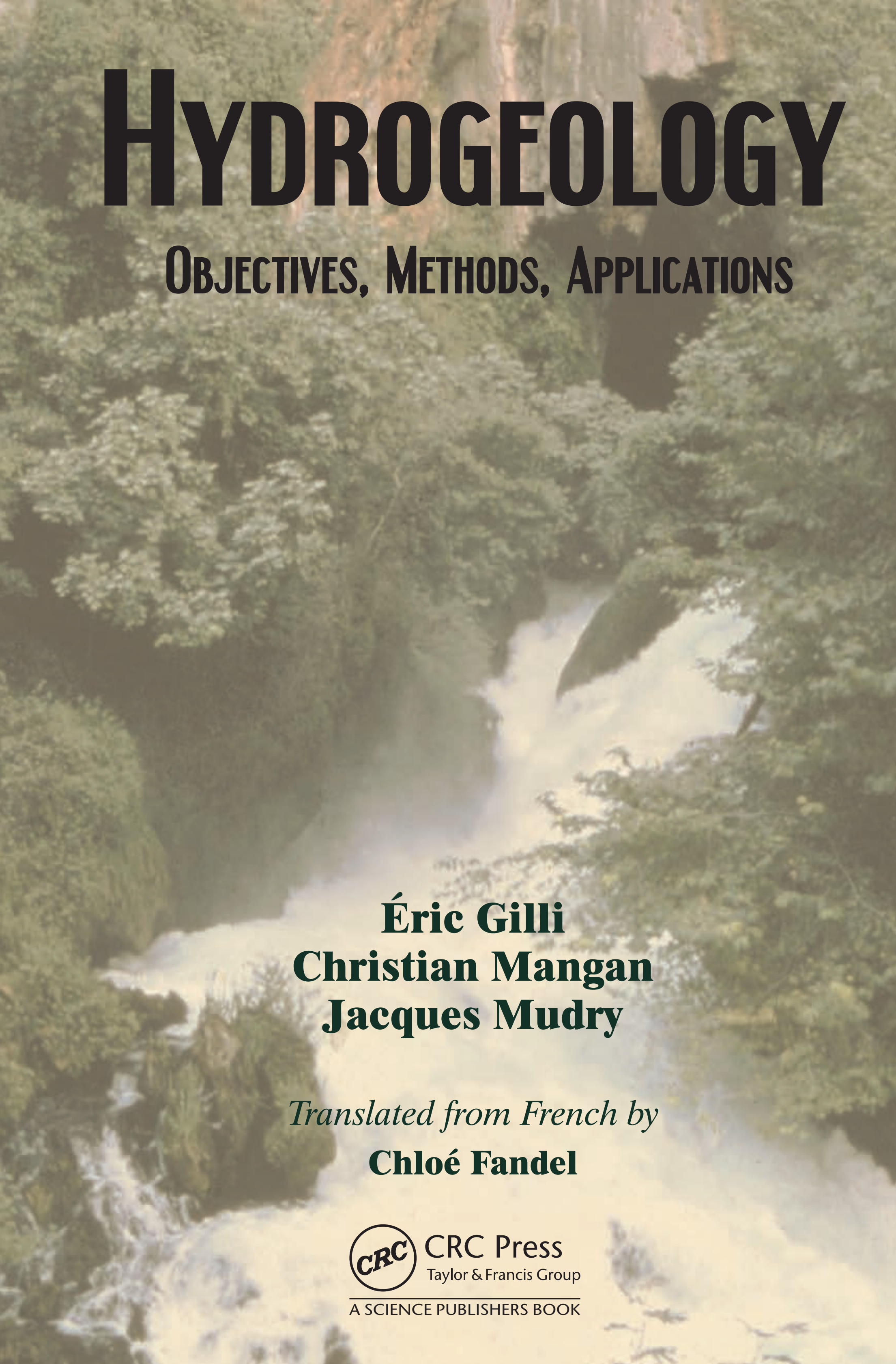

Hydrogeology

Objectives, Methods, Applications

Éric Gilli
Christian Mangan
Jacques Mudry

Translated from French by
Chloé Fandel

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HYDROGEOLOGY

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Foreword

The end of the 20th century was marked by increasing global awareness of the importance of preserving the environment. The 21st century now faces great challenges, one of which is providing drinking water to all inhabitants of the planet. Due to runaway population growth and pollution, pure water is becoming rarer and rarer. Water, source of life and of death, ally or enemy, is inextricably associated with the history of mankind. It is a vital resource that we must learn to manage and distribute. Many conflicts in the modern world are, upon closer examination, linked to water ownership. For the past few decades, we have been living through wars over black gold, but wars over blue gold are already taking place.

Hydrogeology is relevant to many aspects of society. And yet, even though there is no more commonplace action than opening a faucet or flushing a toilet, the provenance of that water often remains cloaked in mystery. Tortuous passageways, immense subterranean lakes, dowsing rods, pendulums, all populate our fellow citizens' tales. Pagnol[1] is not so distant when one sees local authorities prefer the dowser to the hydrogeologist when deciding on the future of their community; one then understands the enormity of the work yet to be done in shaking the obscurantism that persists over this field, which is nevertheless so important to us.

Writing a text on hydrogeology is a delicate endeavor, due to the universality of the material and the immense progress of the past 150 years. Therefore, we deemed the collaboration of a hydrogeologist, a geographer, and an engineer, a necessity in order to allow the interdisciplinary approach that modern science more and more requires. The authors wished to favor as large a vision as possible, and to illustrate each chapter with examples taken from France wherever possible. Each topic addressed therefore suffers from superficiality, but our hope is that the reader will be able to satisfy his or her initial curiosity and will then continue on to delve into more specialized texts.

[1]Marcel Pagnol (1895–1974), French author and movie director, known for the film *Manon des Sources*.

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Contents

B—TOOLS AND METHODS OF HYDROGEOLOGY

D—HYDROGEOLOGY IN CIVIL ENGINEERING

List of Figures

MAIN TEXT

EXERCISES

A

CONCEPTS IN HYDROGEOLOGY

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Chapter A1

Definition and History of Hydrogeology

1 THE SCIENCE OF GROUNDWATER

1.1 Etymology and definition

Hydrogeology (from the Greek *hydra*: water, *ge*: earth, and *logos*: discourse) can be defined as the science of groundwater. That said, water forms a single unit: precipitation, surface water, ice, and subterranean water are all parts of a continuous cycle. Hydrogeology therefore cannot be separated from surface hydrology, climatology, geology, and geography. Furthermore, as with all modern sciences, it calls on the countless domains included in physics, chemistry, and biology. As water becomes more and more valuable, hydrogeologists are also confronted with social and political problems. More, perhaps, than any other science, hydrogeology today requires an interdisciplinary approach. Defining it precisely is therefore a difficult exercise. Where does the subterranean world of the hydrogeologist begin and end? Is water contained in magma a part of it? Do hot springs at mid-ocean ridges fall under the domain of hydrogeology? Does one classify as subterranean a river crossing a cave/tunnel such as the Mas d'Azil (Ariège)? Is soil, where important physico-chemical reactions take place and where water can be extracted by plants, a subterranean domain? The reader will therefore understand that the simple definition "science of subterranean water" is intentionally vague, so to be all the more precise.

1.2 History

The human body cannot function without water for more than two days. The search for water was thus by necessity the first step humans took in studying their environment. Searching for a certain degree of quality is already seen among the great apes. Chimpanzees and baboons, when faced with muddy water, know to dig holes into riverbanks to obtain filtered water. This first step in hydrogeology, which goes back to pre-human times, allows us to presume that our ancestors were certainly concerned with ensuring a good drinking water supply for themselves. The frequent presence of springs near prehistoric settlements might be linked to this search for quality.

1.2.1 First relationships

Just as healers preceded medicine and alchemists preceded chemistry, the art of the water diviner, ever-present ancestor to the hydrogeologist, is lost in the beginnings of time (see chap. B6). The Bible describes Moses striking a rock to bring forth a spring; could this be a religious example of the diviner's dowsing rod?

A few ancient texts describe water below ground. Homer's Styx, as visited by Ulysses a thousand years before our time, resembles a classic underground river. A cuneiform text, carved in 800 B.C. at the entrance to the Tigris Tunnel grotto (Lice, Turkey), tells of the Assyrian king Shulman Asharid III's visit to the underground segment, a few hundreds of meters long, of the Tigris river. A bronze plaque, discovered in the king's palace and currently at the British Museum in London, describes this excursion and shows the role of percolating water in the formation of a stalagmite (Hill & Forti, 1997).

1.2.2 Greek models

Scholars in Greek and Roman antiquity interpreted numerous hydrogeologic phenomena without coming to a satisfying conclusion (Ellenberger, 1988). The Mediterranean world was rich in major karst structures, with important springs used to supply cities with water. The ancient Greeks and Romans, faced with such complex systems, strayed from simple explanations, and, as a result, delayed the discovery of hydrogeology's fundamental principles. They also wished to define a universal mechanism relating various natural occurrences, ranging from volcanoes, to ocean currents, to major springs.

Despite the presence of known loss-resurgence systems, such as the Reka (Slovenia) and its resurgence at the Timavo spring, near Trieste (Italy), described by Strabo (1st century B.C.); surface water and groundwater were considered two distinct domains. Having observed that, despite the inflow of numerous rivers, sea level did not rise, ancient scholars imagined the existence of marine drains absorbing a continuous flow of water, a hypothesis perhaps supported by the example of the Kathavotres in Argostoli (Cephalonia, Greece), where seawater flowing into marine cavities powers millwheels (see chap. A9). Along these lines, Aristotle (4th century B.C.) thought that the Caspian Sea poured into the Black Sea via a deep drain. For Anaxagoras (5th century B.C.), this lost seawater flowed into enormous underground freshwater reservoirs. Plato (4th century B.C.) imagined instead that an enormous pit, Tartarus, took in all river discharges and then fed seas, lakes, rivers, and springs. But in order to accept a marine origin for fresh water features, one must find a desalinization process and a mechanism to bring water back up through the earth. Thales (5th century B.C.), perhaps after observing steam vents on volcanoes and the air currents within certain caves, proposed that a motor could be found in the push of the ground and in the subterranean winds. Lucretius (1st century B.C.) suggested that seawater was filtered through the soil in order to remove its salt.

Nevertheless, a few fundamental mechanisms had been understood. Aristotle (4th century B.C.) had foreseen the mechanism of evaporation. Vitruvius (1st century B.C.) had sketched out the water cycle in his observations that the water in valleys rose from low points, formed clouds, then rain, and infiltrated through cracks in the ground to reappear at the base of mountains. Herodotus (5th century B.C.), then Pliny (1st century) had grasped the relationship between sinkholes, areas of preferential infiltration, and springs.

And yet, Seneca (1st century), synthesizing his predecessors' thoughts in "Natural Questions," retained only the idea of an enormous underground freshwater reservoir fed by the transformation of air into water in underground cavities.

1.2.3 The Middle Ages and the Renaissance: the underground still

In the Middle Ages, Greek thought remained accepted only when it was compatible with the Bible, while the invention of the printing press allowed the widespread distribution of knowledge.

One of the first works devoted to subterranean water was Jacques Besson's "The art and science of finding water and springs hidden under ground," but the true father of hydrogeology was Bernard Palissy, author of "On Water and Springs" (1580). He demonstrated that the water in springs originates as rain seeping into fractures and openings below ground until it reaches impermeable horizons, above which it accumulates into underground reserves and circulates towards springs. His observations in caves in the Pyrenees led him to the conclusion that the plumes of steam exhaled by certain caves were also linked to infiltrated water.

And yet, his ideas did not take hold, and the generally accepted theory was that of the underground still (Figure 1), where water passed below ground through channels, was heated by a central fire and abandoned its salt, and then condensed in the mountains to feed underground lakes, which flowed out at the surface as springs.

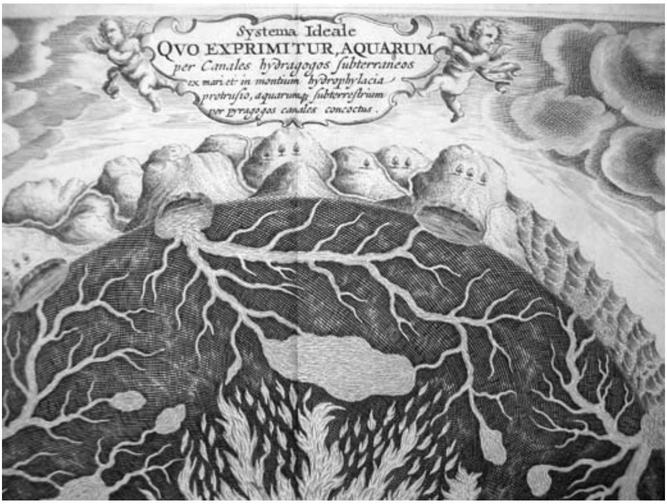


Figure 1 The underground still: 17th century engraving.

1.2.4 The 17th century: the water cycle

Modern geology is being born in the West. A few major works dealing with subterranean water can be found: "*Mundus subterraneus*" (Athanasius Kircher, 1665), "*Principia Philosophiae*" (Descartes, 1664), "*Prodromus*" (Stenon, 1669); but they restate the concept of the underground still. It is in 1674 that Pierre Perrault's "On the Origin of Springs" reveals the importance of evaporation and infiltration. Perrault proved that the upper Seine's discharge corresponded to only a sixth of the amount of water entering the river's watershed. A large percentage of the water had therefore disappeared. Mariotte (1620–1684) came to the same conclusion, and during the same period, Halley (1656–1742) quantified evaporation. The motor bringing water from ocean to mountains and the mechanism for desalinization were thus discovered at the same time. The modern conception of the water cycle was, then, born in the 17th century, after more than two thousand years of debate amongst the greatest scientists on the planet.

1.2.5 The birth of hydrogeology

The basic concepts of infiltration having been already laid down, the mechanisms governing water once it reached the surface of the soil were refined and clarified by La Métherie (1791).

In 1856, Darcy, an engineer of the Ponts et Chaussées (Bridges and Roads administration) in charge of the city of Dijon's water supply, defined the mathematical law which, linking the permeability of a medium and the hydraulic gradient, governs the flow of groundwater (see chap. A6.2). That law's formulation marked the beginning of modern hydrogeology. The great problems in the field at the end of the 19th century were mainly tied to well-digging and to the exploitation of alluvial aquifers. Studies on those topics were therefore numerous. They were primarily concerned with the relationship between geology and groundwater, the definition of hydraulic laws below ground, and the study of water chemistry.

During this same time period, in Camprieu (Gard), Edouard Alfred Martel laid the foundations of speleology, while following the underground path of the Ruisseau du Bonheur to the Bramabiau spring. But such activity, deemed too athletic, was generally looked down upon by university scholars, and it was only around 1960 that the creation of the Moulis laboratory by Philippe Renault and Félix Trombe led to the birth, in France, of karst hydrogeology, a branch of hydrogeology to which an important section of this text will be devoted.

The 20th century saw the height of often-pharaonic projects, such as giant dams on the planet's great rivers, which modified the hydrogeology of entire regions, or the Great Man-Made River (Libya, see chap. E3). These great construction projects were sometimes stricken by tragedy, such as the catastrophe at Malpasset (see chap. D4), which served as an example of hydrogeology's critical role in civil engineering.

The end of the 20th century was marked by the appearance of numerical modelling. Thanks to technological progress, a computer using Darcy's Law and its derivatives, and collecting data acquired with ever-more-sophisticated instruments, can simulate aquifer functioning and serve as and aid to aquifer management. But this was also the century of pollution, and the nitrate contamination in the aquifers of Brittany and Normandy was, alas, only the first of a multitude of qualititative problems that will only increase in the future.

1.3 Current branches of research

1.3.1 Applied hydrogeology

Hydrogeology in the 21st century faces a challenge: how to supply safe drinking water to the Earth's 9 billion inhabitants in 2050? And this in a context where the concept of sustainable development has taken hold? The hydrogeology of the future will certainly be one of active aquifer management (Detay, 1997). If global resources are judged satisfactory on the quantitative level, protection against pollution will probably be the principal outcome of hydrogeologic studies.

At the country scale (France), an immense amount of work remains to be done: putting into effect the October 23rd, 2,000 EU directive. It mandates that, by 2015, all water bodies, including groundwaters, with certain justifiable exceptions, must be made to conform to EU standards. But new sources of pollution have emerged (antibiotics, hormones), derived from human and animal consumption; they are dumped into the natural environment where their effects remain poorly understood.

The management of organic, chemical, or nuclear waste raises the problem of long-term aquifer contamination. How can we be certain that nuclear waste, buried in rock deemed impermeable and stored in sealed containers, will not, over hundreds of years, be attacked by the degrading effects of groundwater and contaminate our descendants' water for thousands of years?

1.3.2 Fundamentals of hydrogeology

A few research interests deserve to be highlighted here, such as the role of water in tectonics and magnetism, the depth of groundwater circulation, the mechanisms governing the formation of the great karst systems (Fontaine de Vaucluse, Port Miou), the modelling of karst flow, and the role of microbiology in the physical and chemical properties of groundwater.

Lastly, at the time of writing, hydrogeology is extending out onto other planets, as the fabulous data and images being sent back from Mars by the European Mars Explorer and the rovers Spirit and Opportunity bring proof of Martian water circulation, which may still be present in a liquid state below the surface of the red planet. The traces of a salty sea have been discovered, and numerous topographical features indicate, not only the presence of surface water in the past, but also the existence of pseudo-karst springs and slumps linked to groundwater circulation.

Chapter A2

Groundwater's Place in the Earth Sciences

Groundwater is a general geologic agent; it plays an active role in geodynamic processes, thanks to its wide spatial flow distribution and its high tendency to interact with the environment (Toth, 1999). These two properties exist, with varying intensity, at all temporal and spatial scales. Chemical interactions include precipitation/dissolution, hydration, hydrolysis, reduction, acid attacks, base exchange.... Physical interactions include concentration, nanofiltration, lubrification, and changes in pore pressure. Hydrodynamic or kinetic interactions include convection, with mass (water, solute, particle) transfer or energy (heat) transfer.

1 GROUNDWATER AND EXTERNAL GEODYNAMICS

In external geodynamics, groundwater plays two fundamental roles: that of vector and that of solvent. As a solvent, groundwater has, throughout geologic time, had a role in mineral dissolution. Depending on their solubility and/or their susceptibility to alteration, the Earth's surface will evolve at a more or less visible rate on the human time-scale. For example, a single precipitation event over a salty diapir in an arid region will result in instantaneous changes in morphology, a rapid water flow in gypsum will cause visible slumps and collapses on a yearly basis, the karstification of limestones and dolomites will only just be perceptible on a human time-scale, and the weathering of endogenous rock will occur with morphological effects visible only over several centuries.

On the other hand, in its role as vector, water transports substances in solution, in emulsion, or in suspension. Due to the variable size of open spaces in the subterranean environment, water will be able to carry only certain small ions (this is the case for impermeable clay barriers in certain oilfields), or all substances in solution (this is generally the case for most aquifers), or even solutes plus suspended particles (clay, organic particles such as parasites, bacteria, viruses) in the case of aquifers with distinct drainages (gravel channels in alluvial aquifers, fractures in consolidated rock, karst passages).

Within the water cycle, the division between runoff and infiltration will therefore have a high impact on the erosion of soil and rock in drainage basins, on the steepness of flood peaks, and on the dry season discharge of rivers. This division is a function of both the permeability of soils and bedrock, and the type of precipitation. For example, a Mediterranean storm in marly terrain will engender a violent, short-lived flood and high turbidity in suface waters, while an oceanic precipitation event of the same magnitude over a poorly-karstified chalky plateau will provoke only a very dampened increase in surface water levels, without increasing turbidity.

2 WATER AND OIL

In oil fields, hydrocarbon deposits (oil and gas), expulsed from the rock in which they matured due to lithostatic pressure, migrate towards the surface by replacing denser water in rock pores, until they encounter a trap: a reservoir rock covered by a poorly permeable (clayey or compacted) unit, in a favorable configuration (pinchout, anticline, fault). Oil and gas follow the lateral flow of groundwater; differentiated only by their density and viscosity, they obey the same flow laws as water. Nevertheless, hydrocarbon migration is slow, and grounwater circulation can modify the size of open spaces within a rock (cementation or dissolution of grains—Machel, 1999). In very poorly permeable environments, the chemical composition of originally saline water can be modified to become more concentrated (oil field brines).

3 WATER AND MINERAL DEPOSITS

As much in the domain of the great sedimentary basins as in that of hydrothermalism (Garven *et al.*, 1999), groundwater is a vector for mineralisation. In the first case, the slow flows in environments with differing porosities, and in the second, the upwelling of deep water through fractures, allows the crystallization of minerals. For example, brine migration in the fractures of the Variscan (Hercynian) platform, thanks to the difference in elevation, allowed the accumulation of giant lead-bearing deposits in North American carbonates.

4 TRANSFER OF DEEP FLUIDS

Fluid circulation in fractures at the crustal scale allows thermomineral circuit upwelling, characterized by the high concentration of certain dissolved compounds and of certain gases (carbon dioxide, radon, carbo-gaseous springs). This mineral content, the therapeutic properties of which are used in hydrotherapy, can also be a source of health hazards (arsenic, barium, fluoride, radioactivity).

5 THE ROLE OF WATER IN MAGMATISM

Groundwater plays a major role in the dynamics of volcanism. In normal periods, the infiltration of meteoric water (rain or snow) on volcanoes, which are often areas of high relief, and therefore receive more precipitation than the surrounding foothills, feeds the production of their steam plumes. In the case of massive groundwater influxes at depth (outflow of an aquifer into a chimney, exceptionally high precipitation) this vadose water sets off volcanic eruptions, as it can vaporise upon contact with hot lava. Explosive eruptions follow, which pulverise the lava plug blocking the chimney. Maars and phreatomagmatism are types of volcanic environments in which water plays an even greater role, by reinforcing the explosive nature of eruptions.

Chapter A3

Applications of Hydrogeology

1 WATER—SOURCE OF LIFE

Water is essential to human beings, who, at rest, consume two to three litres per day, half of which is provided by food. In fact, the survival of all plant and animal species depends on water, which makes up 70% of animals and 90% of plants.

The water needs of humans have considerably increased over time and touch on more and more numerous domains, in order to satisfy our demands for comfort and pleasure, and to accomodate an increasing economic demand.

Water consumption for domestic purposes has undergone a very noticeable increase, independent of demographic progress (see chap. C1). The average daily consumption per person today is over 200 liters, while it was 160 liters in 1990, 145 liters in 1980, and 130 liters in 1975. Dietary needs represent only a small portion of this quantity, on the order of 4% (1% for drinking and 3% for cooking), and it is therefore the other uses of water that have increased the most, following increases in quality of life and comfort levels.

It has additionally been noted that, due to increasingly strict health standards and to the recent development of deep wells, groundwater has been increasingly exploited, as it is better protected from pollution than surface water.

Other water uses do not require potable water, but represent the majority of demand. Their progression over time is equally spectacular, for the same reasons, as well as in response to the need for economic viability and the demands of the market.

Aside from hydroelectric dams and cooling systems for nuclear power plants, which consume large quantities of water but take them mainly from rivers, other activities are relying more and more on groundwater resources, easily accessible today and not directly influenced by the "reserved discharge" required for surface waters.

Groundwater extraction is increasing rapidly in Europe and in the United States, where it often leads to waste. Its distribution is, however, very unequal, and zones of intensive use are not always ones which nature has provided well for. Furthermore, this resource is relatively scarce in certain countries of Asia, the Middle East, and Africa, which are faced with increasing instability.

2 WATER—SOURCE OF TROUBLE

Groundwater has a very important influence on most construction and civil engineering problems, on development projects, and on the protection of people and property.

Its role has often only belatedly been recognized, in the aftermath of veritable catastrophes or after smaller accidents resulting in construction delays, unforeseen environmental effects, the destruction of projects, or even the loss of human life.

The intervention of a hydrogeologist has become the norm, and can be categorized within the scope of large projects and various development project studies:

- excavation projects and surveying studies (roads, highways, and rail lines);
- deep excavation projects reaching the water table or cutting across water-bearing formations;
- large-scale construction sites requiring a prolonged lowering of the water table;
- tunnels and underground construction;
- dams;
- the study and prevention of landslides and flooding.

3 PROTECTION AND MANAGEMENT OF WATER RESOURCES

Drinking water, water used in cooking, and water used in food production must be up to increasingly strict sanitary standards. Other uses are distinctly less regulated, but often have their own quality criteria, in order to guarantee the protection of the material being used or of the product being treated or manufactured.

The protection of the physical and chemical properties of water, based on its different uses, is receiving more and more attention, particularly with respect to human consumption. This has resulted in impact studies before the execution of projects likely to alter water resources (landfills, dumping of toxic substances, storage of dangerous materials) and in the definition of protection zones intended to increase the safety of drinking water sources.

The increasing demands on groundwater resources and the excessive pumping in certain aquifers are not always appropriate given the recharge rates of those aquifers, and can lead to the impoverishment of the available resources. The need for integrated management of aquifers, both from a qualitative and quantitative perspective, is becoming more and more pressing. This vision has become more widespread over the last few decades, and benefited greatly from the January 3rd, 1992 Law on Water in France and its decrees. This decrees allow for groundwater to be taken into account in a global development, protection, and management process, also integrating the entirety of the human and natural environment, and increasing the role of the hydrogeologist.

4 HYDROGEOLOGY’S PLACE AND ITS APPLICATIONS

In today’s society, the hydrogeologist occupies a more and more important place in the politics of land development, particularly in regions with a high population density and/or which are home to intensive agricultural or industrial development.

The hydrogeologist intervenes in a number of areas of public life:

- teaching and research within educational institutions (CNRS, INRA, Ministries);
- research on, study of, protection of, and management of groundwater resources;
- examination of the influence of groundwater on large-scale construction and on civil engineering projects, as well as of the impact of those projects on the hydrogeologic environment;
- analysis of the role of water in mass wasting (rockslides, landslides, cave-ins) and prediction of critical flooding events.

The hydrogeologist is also more and more frequently integrated into interdisciplinary teams (administrations, elected officials, city planners, landscapers, hydrologists, economists), either to help with diagnostic, management, or planning programs, or to help with preliminary studies on the scale of a region, basin, group of communities, community, or even one large structural project.

CHAPTER A4

Water Cycles

The circulation and residence time of water below ground are one step in an endless process, the water cycle. Through precipitation and runoff, a fraction of the water caught up in this cycle seeps into the ground. By renewing the water in underground reservoirs, infiltration feeds the deep circulations that then supply springs. But there is also an internal water cycle, which captures a small percentage of surface water and carries it to depth, through subduction zones, and then restores it to the surface through volcanism.

1 THE INTERNAL CYCLE

1.1 The origin of water on Earth

The detection of water elsewhere in the Universe is made difficult by the Earth's atmosphere, which absorbs much of the incoming radiation. Instruments must therefore be placed outside the atmosphere. The data thus collected, particularly by the European Space Agency's infrared telescope, ISO (Infrared Spatial Observatory), and the American satellite SWAS (Submillimeter Wave Astronomy Satellite), show that water exists almost everywhere in our galaxy. It is widely distributed throughout the universe.

Hydrogen has been present since the first moments after the Big Bang. The oxygen atom in the water molecule originated some time later, in nuclear fusion reactions within stars. Water exists in the universe as gas, ice, or hydrates, and also in liquid form, on planets (Reeves, 1981). Thanks to its distinctive spectral signature, water has been detected on the surface and in the immediate surroundings of low-temperature stars, as well as in interstellar molecular clouds (Figure 2). The Earth was born, around 4.5 billion years ago, out of dust and gas aggregates, which already contained hydrated silicates and ice. These grains formed larger, kilometer-scale masses through accretion, and eventually became the young Earth, within which volcanism and impacts allowed the degassing of water vapor.

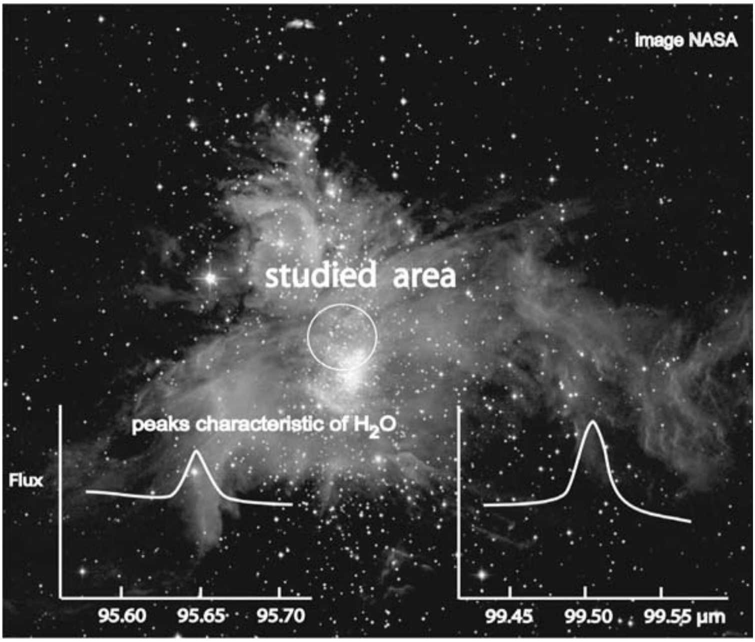


Figure 2 Infrared absorption spikes indicating the presence of water in the Orion nebula (from the Harvard-Smithsonian Center for Astrophysics).

Comets may also have played an important role in bringing water to Earth. Indeed, ice is a major component of comets, as confirmed by ISO on the Hale-Bop comet (Figure 3). The Rosetta probe, launched in 2004, should reach the Churuymov-Gersimenko comet in 2014 and provide information on its composition. Comets can also sometimes collide with planets, as was observed during the impact of Shoemaker-Levy 9 on Jupiter in 1994. They can therefore contribute to the water supply. However, the isotopic ratio of deuterium to hydrogen is higher in the comets that have been studied than on Earth, indicating that they only provide a partial contribution.

Three remarkable properties enable the presence of liquid water on the Earth's surface:

- the Earth is at a distance from the Sun which allows the existence of water in all three of its states;
- the presence of the atmosphere causes a greenhouse effect without which the average surface temperature would be –15°C;

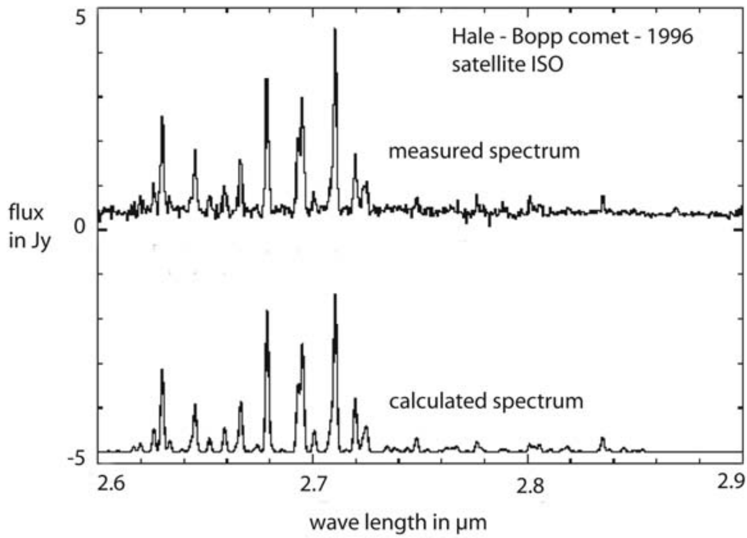


Figure 3 Spectral signature of water in the Hale-Bopp comet, measured by ISO (from Crovisier *et al*., 1997).

- water, when it freezes, expands and therefore floats. It forms an insulating layer, which protects the liquid water below from freezing. If the opposite were true, ice would sink to the bottom of the oceans and the Earth could be much colder.

It is estimated that around 4.4 billion years ago, the Earth was already at its current size, and had an atmosphere and a hydrosphere.

Water is present in both the continental and the oceanic crusts. In the Earth's interior, mantle rocks today contain approximately 0.3% water, which represents a volume one to two times greater than that held by the oceans. This deep reserve gives birth to an estimated annual volume of a few km^3 of young waters, a negligible amount in the short term (Castany, 1998), but one which, through accumulation over hundreds of millions of years, made a significant contribution to the creation of the hydrosphere.

1.2 The internal water cycle

Water in the mantle is returned to the surface in part by basaltic magmas, or directly through hot springs and highly mineralized vents such as the black and white smokers found at mid-oceanic ridges. Analyses of the material issuing from the upper part of the mantle indicate the presence of water. Hawaiian lavas (USA) can contain up to 0.45% water, and lavas in the Deccan Traps (India) up to 0.6%. Similarly, water is present in peridotite fragments originating from deeper in the mantle.

At the bottom of the oceans, sea water seeps into the crust and hydrates the rock. This altered crust can have a water content of up to 1 to 2 %. In subduction zones, the crust is dragged down into the mantle, which then becomes water-enriched.

It is estimated that the amount of water entering the mantle falls between 5 and $16{\cdot}10^{11}$ kg per year. The balance is difficult to quantify. It is considered to be in equilibrium since sea level remains relatively stable.

The presence of water in the mantle is very important, as it changes the physical and chemical properties of rock and certainly plays a role in the convection mechanisms responsible for plate tectonics (Gillet, 1993) by modifying the melting points and the viscosities of minerals.

2 THE DISTRIBUTION OF WATER

Water exists as a gas in the atmosphere, as a liquid in oceans, rivers, and aquifers, and as a solid in snow, glaciers, ice caps, and ice floes, but it is also present in most rocks:

- compositional water, which is part of a mineral's chemical formula;
- water present in closed pores (pumice, peat);
- adsorbed water, electrically fixed to ionic surfaces, and in some cases extractable by plant roots;
- finally, gravitational water, which can circulate in pores and open discontinuities in rock. This is the domain of hydrogeology. The important volumes of gravitational water present below ground constitute more and more sought-after reserves (Figure 4).

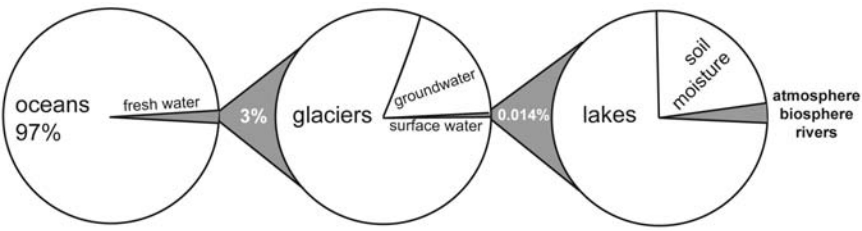


Figure 4 Different types of water on the planet.

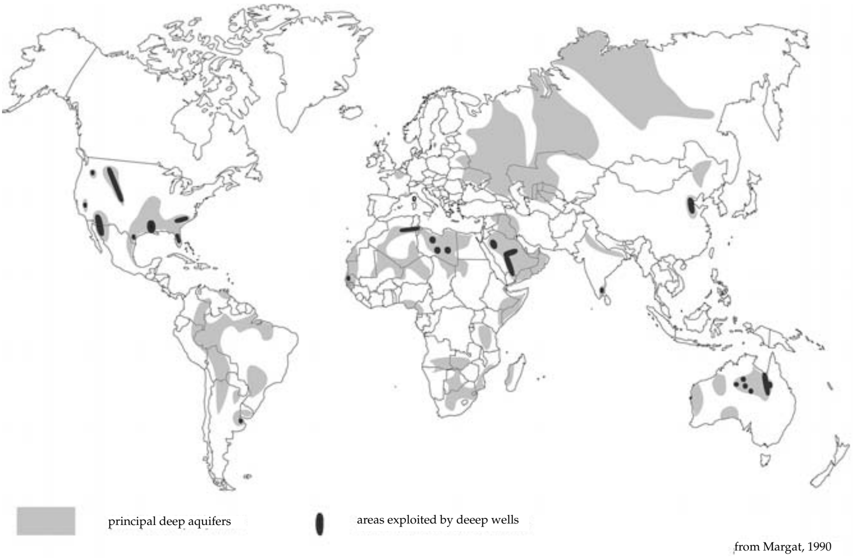


Figure 5 Global distribution of the principal deep aquifers.

Table 1 presents the estimated distribution of water across the planet. It is only a guess, as the evaluation of groundwater reserves is very variable depending on the author, going from 7 to 30 x 10^6 km^3.

2.1 The water cycle

2.1.1 Driving forces and radiation budget

From the time it degasses from the planet's interior to the time it reaches the hydrosphere, water is constantly passing from one reservoir to another, caught up in an endless cycle powered by the sun and by geothermal fluxes. The Earth (including its oceans) and its atmosphere reflect part of the incoming solar radiation, while another part is absorbed by these two media. The Earth then radiates this energy back into the atmosphere, which radiates it both back towards the surface and out into space. The surface receives an average of 94 $W \cdot m^{-2}$. Figure 6 outlines the respective percentages of emitted, reflected, and absorbed radiation.

The Earth's radiation budget is balanced on a global scale; the planet receives as much incoming radiation as it emits, ensuring that it is neither an arid sphere nor a ball of ice. On a regional scale, however, the budget is unbalanced. Polar regions, receiving sunlight at a shallow angle, experience a deficit, while the equator, where the incoming radiation is at a maximum,

Table 1 Estimated Global Distribution of Water on Earth.

	Volume of water stored		
	Total	**Freshwater**	
	in 10^3 km^3	in 10^3 km^3	in % of total freshwater
OCEANS and salty ice floes	1,350,000		
SALTY LAKES	100		
ICE: icecaps, glaciers, snow, permafrost	23,000	23,000	60
WATER BELOW GROUND			
Aquifers 0–800 m below ground	8,000	16,000	39
> 800 m below ground	8,000		
Soil moisture	16	16	
CONTINENTAL SURFACE WATER			
Lakes	176	176	
Riverbeds	2	2	1
ATMOSPHERE	13	13	
BIOLOGICAL WATER	1	1	
HYDROSPHERE	1,390,000	40,200	100
GLOBAL (0.3 % of the mantle)	2,000,000		

According to the BRGM, there are around 200 exploitable regional aquifers in France, ranging from 100 to 100,000 km^2, and containing some 2,000 km^3 of water. It is estimated that 100 km^3 per year flow out to springs and rivers, and that 7 km^3 per year are drawn from these aquifers.

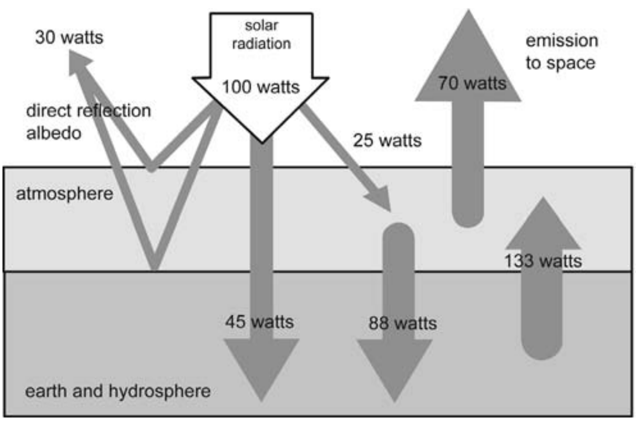


Figure 6 Solar radiation.

experiences a surplus (Figure 7). The tilt of the Earth's axis, the spatial distribution of continents and oceans, variations in elevation, atmospheric circulation, and ocean currents all locally modify this scenario to produce the different climates present on Earth and thus define the highly variable quantities of precipitation and evapotranspiration.

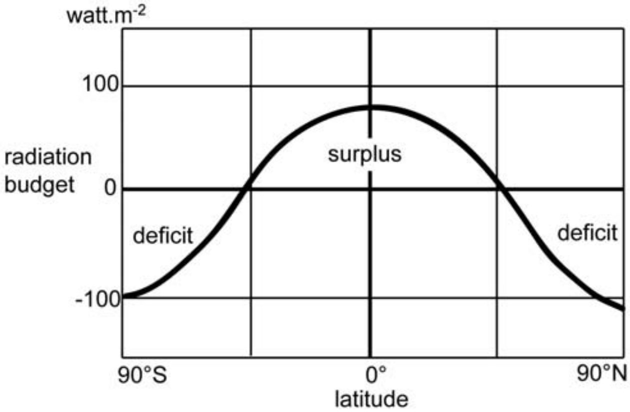


Figure 7 Radiation budget by geographic position.

Due to heating by solar radiation, water from the oceans and from the surface of continents passes into the gaseous phase and rises into the atmosphere, where it condenses to form raindrops (Figure 8). It falls back into the oceans and onto land in the form of rain or snow. The annual volume

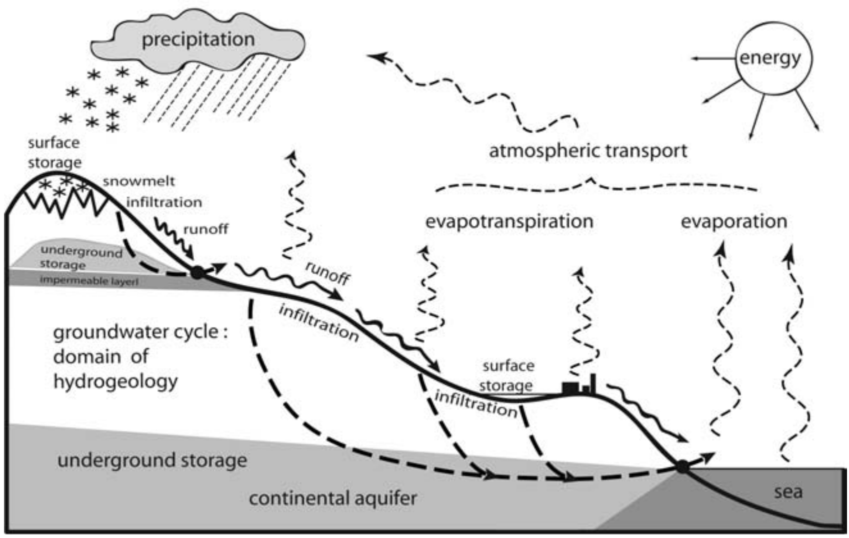


Figure 8 External water cycle.

of these precipitations is estimated to be 577,000 km^3. They feed ice and snow deposits in cold regions. Part of the precipitation can be intercepted by vegetation and returns to the atmosphere through evaporation or sublimation. In hot regions, rain not intercepted by vegetation turns into runoff, which accumulates into rivers. It can also be be taken up by living organisms and constitute biological water. Part of the total precipitation seeps into the ground and makes up infiltrated water, domain of hydrogeology. Indeed, once water reaches a permeable surface, infiltration can occur. Infiltration is partial and diffuse in most cases, or quasi-nonexistent in impermeable rock (clay), but it can be total and concentrated in certain karst systems, where rivers seep into underground cavities (see chap. A8).

Hydrogeology is primarily concerned with the subterranean part of the water cycle, between infiltration and reemergence. This segment of the cycle can be very rapid, but it can also be very slow, as in the case of the Saharan fossil aquifers, within which the passage of water can take several thousands of years.

Table 2 Residence Time in Different Reservoirs.

Natural environment	Residence time
atmosphere	a few hours to a few days
continental glaciers	a few hundred to a few thousand years
soil surface	a few days to a few months
aquifers	a few weeks to several hundreds of thousands of years

Aquifers and glaciers therefore play a long-term regulating role for water passing through continents.

With the exception of infiltrated water, which is protected from incoming solar radiation, the other classes of water are subject to phase changes due to:

- sublimation of ice and snow;
- evaporation of surface and ocean water;
- use and transpiration of water by living organisms, particularly plants.

These three processes are grouped under the term evapotranspiration (ET). They can affect a layer of soil a few meters to a few tens of meters deep, depending on the climate. For open surface water or in areas with no vegetation cover, evaporation and evapotranspiration are lumped as one term.

Over a certain area:

$$P = Q + I + ET + \Delta R$$

where P is precipitation; Q is discharge; I is infiltration; ET is evapotranspiration, and ΔR is the change in storage. Values are generally given in mm.

Effective precipitation (EP) is the amount of water actually available to feed runoff and infiltration.

$$EP = P - ET$$

2.2 Hydrologic systems and budgets

The water cycle can be considered on a global scale, but also on the scale of the structural or geographic units forming hydrologic sysems. These systems can be classified into three domains.

2.2.1 Hydrologic basins

These correspond to the drainage basin of a river and its tributaries, generally defined by topographic highs, with the exception of certain cases such as karst zones (see chap. A8). On the basin scale, the budget is balanced over the long term. The volume of effective precipitation is theoretically equal to the total outflow.

$$PE = Q_T$$

where Q_T: total discharge, in mm

However, Q_T is not easy to quantify, as part of the water circulates below ground, and can leave the system unseen, for example, by flowing into a different basin or directly into the sea, in coastal areas.

2.2.2 Aquifers

Aquifers (from the Latin *aqua fero:* to carry water) are permeable geologic structures containing water, such as, for example, river alluvium, fissured granite, a limestone plateau, etc. The water held in an aquifer, originating from infiltrated precipitation, circulates below ground and feeds one or more springs, or flows unseen into a receiving body, such as a sea, lake, river, or other aquifer. An aquifer is characterised by its geometry, its areal extent and its depth, and by the intrinsic characteristics of the rock from which it is formed: lithology, porosity, permeability, fracturation, homogeneity, etc.

Aquifers can store infiltrated water in varying quantities and for varying amounts of time; their residence times can range from a few hours to several hundreds of thousands of years.

2.2.3 Hydrogeologic basins

These systems correspond to the underground sections, containing water, of a part of, the entirety of, or several hydrologic basins. They are made up of one or more aquifers.

2.2.4 Budgets

In order to study hydrologic systems, measurements are taken and budgets calculated, quantifying inflows and outflows, in order to evaluate the volume of water circulating in different reservoirs in the water cycle.

$$P = Q + ET + \Delta R$$

where P is precipitation; Q is total discharge, including runoff and groundwater outflows; ET is evapotranspiration; ΔR is the change in storage (groundwater, ice, snow) during the study period. Values are given in mm or in m^3.

This budget is calculated over a hydrologic year, a period of 12 months chosen so as to minimise ΔR, the change in storage.

The frequency and duration of measurements are very important points. Due to climactic variations, data going back at least 10 years is essential in order to define a representative hydrologic year. The ideal would be to have access to continuous measurements, something that technological progress is now making financially accessible.

During applied hydrogeologic studies, the importance of collecting sufficient data is often the point it is the most difficult to persuade project directors to take into account, as the problems involved in applied hydrogeology (increased pressure on resources, the fight against pollution) generally require a more rapid response.

2.3 Evapotranspiration

Of all the different parts of the water cycle, evapotranspiration is the most difficult to evaluate. Unlike rain or runoff, which can be satisfactorily, if not precisely, quantified, it is currently very difficult to directly measure the flux of water vapor to the atmosphere.

Evapotranspiration depends on a number of factors:

- soil, air, and water temperature;
- air moisture;
- state and quantity of soil moisture;
- solar radiation;

- wind and atmospheric pressure;
- nature and state of vegetation;
- topography and exposure.

2.3.1 Calculating evapotranspiration

a) Theoretical calculation

On the scale of Europe, it is considered that approximately 60% of water in precipitation returns to the atmosphere through evapotranspiration.

Various equations exist to calculate evapotranspiration. It is important, at this point, to differentiate between potential evapotranspiration (PET), which is the amount of water that an open water surface could theoretically evaporate, and actual evapotranspiration (AET), which is the amount of water that actually evaporates, and is dependent on natural conditions (vegetation, nature of the soil) and on the amount of available water in the soil, called available water capacity (AWC). This amount includes *easily used available water or field capacity* that is relatively easy for plants to extract from the soil. It also includes water that is more difficult for plants to extract. It can range from 0 (empty shallow reserve) during the dry season, to a maximum value that depends on the porosity and thickness of the soil cover. It corresponds to a layer of water that can range from a few tens of mm over compact rock, to 400 mm in deep soils.

To link these concepts to those used in agrometeorology, the empty reserve corresponds to less than the permanent wilting point, and the full reserve to more than the field capacity (c. chap. A5.1).

$$\text{If } (P_d + UR_{d-1}) \geq PET_d, \text{ then } AET_d = PET_d$$

$$\text{If } (P_d + UR_{d-1}) < PET_d, \text{ then } AET_d < PET_d$$

$$\text{where } d = \text{day}$$

Desert areas therefore have a very high PET but a very low AET, given their UR equalling zero.

The reference evapotranspiration (ET_0) used in agronomy, is the evapotranspiration of a reference surface, under a given climate in well-defined conditions, corresponding to a homogeneous lawn in active growth covering the entire surface, with a plentiful water supply.

PET can be calculated with the help of a number of equations (Thornthwaite, Turc, Primault, Penman, FAO-Penman-Monteith, etc.).

b) Thornthwaite's equation

$$PET = 16\ (10\ t/I)^{a}\ f(\lambda)$$

Where:

- PET: monthly potential evapotranspiration (in mm)
- I: heat index for a given year = Σ i of the 12 previous months (thermal memory)
- with the monthly index $i = (t/5)^{1.514}$
- t: average monthly temperature (°C)
- a (coefficient dependent on I) = $6.75 \cdot 10^{-7}\ I^3 - 7.71 \cdot 10^{-5}\ I^2 + 1.79 \cdot 10^{-2}\ I + 0.4923$
- f(λ): factor dependent on the latitude and season, given by reference tables

This equation is well-adapted to climates with regular precipitation (oceanic, equatorial), but does not work well in climates with a distinct dry season.

c) Turc's equation (1961)

This equation works over any time period (month, decade, day). Unlike the previous equation, this one takes into account solar radiation, which can be measured with a pyranometer or reconstructed from the duration of insolation measured by a heliograph.

$$PET = 0.013\ n\ [t/(t + 15)]\ (Rg + 50)\ [1 + (50 - hr)/70]$$

[The last term is necessary only when the relative humidity (hr in %) drops below 50% (Mediterranean climate or drier).]

Where:

- PET (in mm);
- n: length of the period under consideration in days (1 day, 10, 30,…);
- hr: relative humidity in %;
- t: average temperature over the period (°C);
- Rg: global solar radiation ($cal \cdot cm^{-2} \cdot day$), measured with a pyranometer. If only a heliograph is available, one can estimate with Rga: incoming extraterrestrial radiation ($cal \cdot cm^{-2} \cdot day$) given by the Angot tables, based on Angstrom's equation, dependent on latitude and season

$$Rg = Rga\ (0.18 + 0.62 \cdot h/H)$$

where:

h: actual duration of insolation;

H: maximum possible duration of insolation (astronomical length of day), given by tables, in function of latitude and season.

d) Primault's equation (1962)

Applicable over any length of time (month, decade, or day), this equation takes into account the relative humidity, the elevation, and the season.

$$PET = c\ [A\ [(103 - hr)/100]\ (ts + 2\ tp) + B]$$

Where:

- PET (in mm);
- tp: length of the period under consideration in days (1 day, 10, 30,…);
- hr: relative humidity of the period in %;
- ts: duration of insolation in hours;
- $c = -0.5068 \sin[(2\pi/365)\ j + 0.5593] - 0.0711 \sin[(4\pi/365)\ j + 0.6112] + 0.6271$
- where j: number of the day of the year;
- $A = -0.12 + 0.00306\ h - 2.83 \cdot 10^{-6}\ h^2 + 9.45 \cdot 10^{-10}\ h^3$
- $B = 0.5387 + 0.0003263\ h - 6.525 \cdot 10^{-7}\ h^2$

where h: elevation in m.

This equation is well-adapted to regions with high relief (300 to 1 200 m) such as the Jura.

Other equations, such as the Penman or the Penman-Monteith, include additional parameters tied, for example, to wind or humidity, for which data is not always available. They are generally used only by agrometeorologists.

Table 3 Comparison of PET Values in Voinesti (Lower Carpathians, Romania) Calculated by Different Methods (from Maftei, 2002).

Formula	Thornthwaite	Turc	Penman	FAO Penman-Monteith
Year value	639.77	743.87	1118.25	704.11

One notices great variability; Turc's equation and the FAO Penman-Monteith equation seem to be the most well-adapted.

Figure 9 shows an estimate of PET in the different climate zones across the planet, calculated according to the Priestley-Taylor method, derived from Penman's equation.

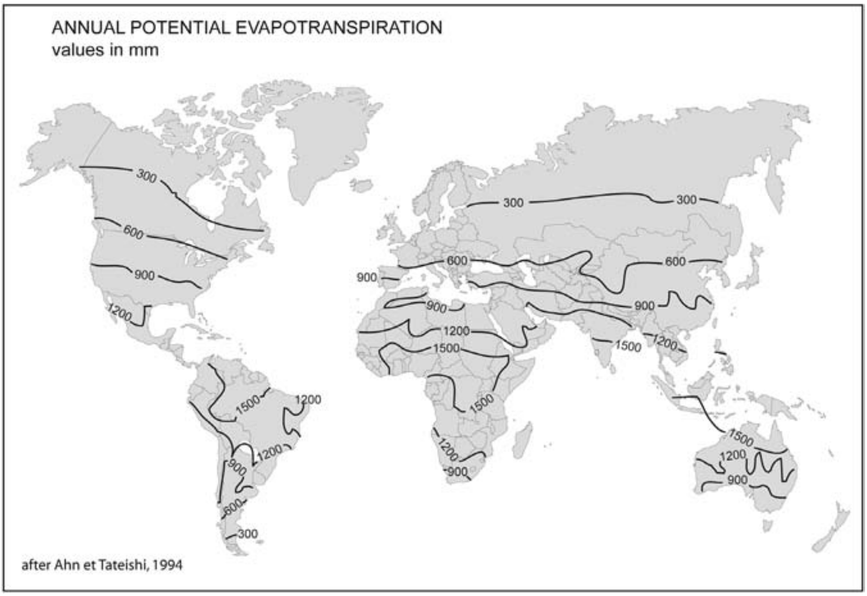


Figure 9 Annual potential evapotranspiration across different regions of the globe (from Ahn & Tateishi, 1994).

e) The hydrologic budget method

One can well imagine that, given the great number of parameters and the diversity of natural environments, the experimental approach can be as precise as calculations. Actual evapotranspiration can thus be determined by creating a long term budget of all inflows and outflows of water over well-defined hydrologic or hydrogeologic units. If, over the entirety of the basin, the amount of precipitation and the discharge of rivers are well-known thanks to a network of pluviometers and the installation of streamgages:

$$AET = Q_e - Q_s \pm \Delta R$$

where Q_e is total inflow; Q_s is total outflow; ΔR is the change in storage.

If these measurements can be acquired over several years, so as to minimise the uncertainty tied to the renewal of groundwater reserves, then the term ΔR becomes negligible as infiltrated water is restored through outflows, and $AET = Q_e - Q_s$

f) Experimental methods

AET can be experimentally determined with the help of a lysimeter, a container holding soil, with or without vegetation cover, for which the amount of runoff and infiltration are measured and compared to the amount of inflow due to precipitation. These measurements can be made by weight or by collecting the infiltrated water.

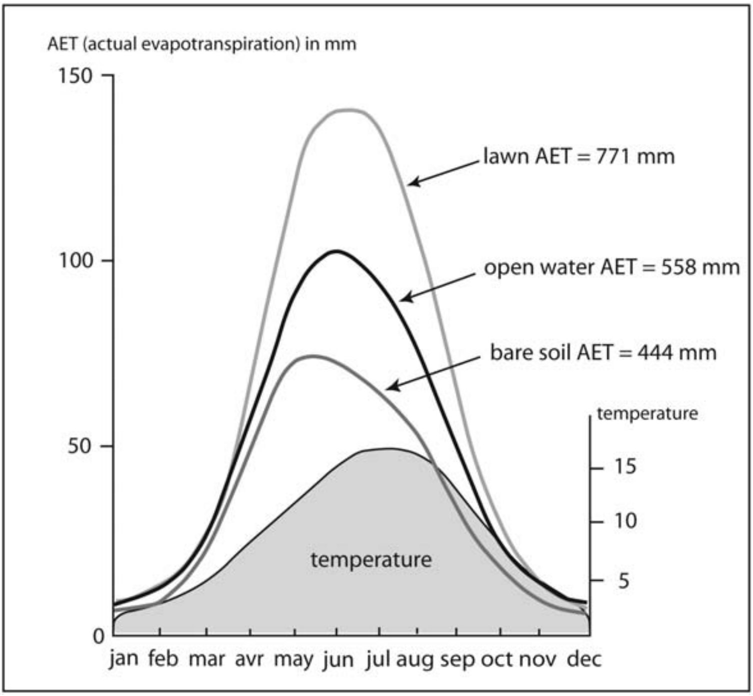


Figure 10 Actual evapotranspiration measured on plots in the Netherlands (from Lambert, 1996).

g) Direct measurements

Remote sensing allows the creation, based on thermal infrared satellite images, of surface temperature and actual evapotranspiration maps (Vidal, 1991).

At Europe scale, one considers that 60% of rainfall water returns back to the atmosphere due to evapotranspiration (Figure 11).

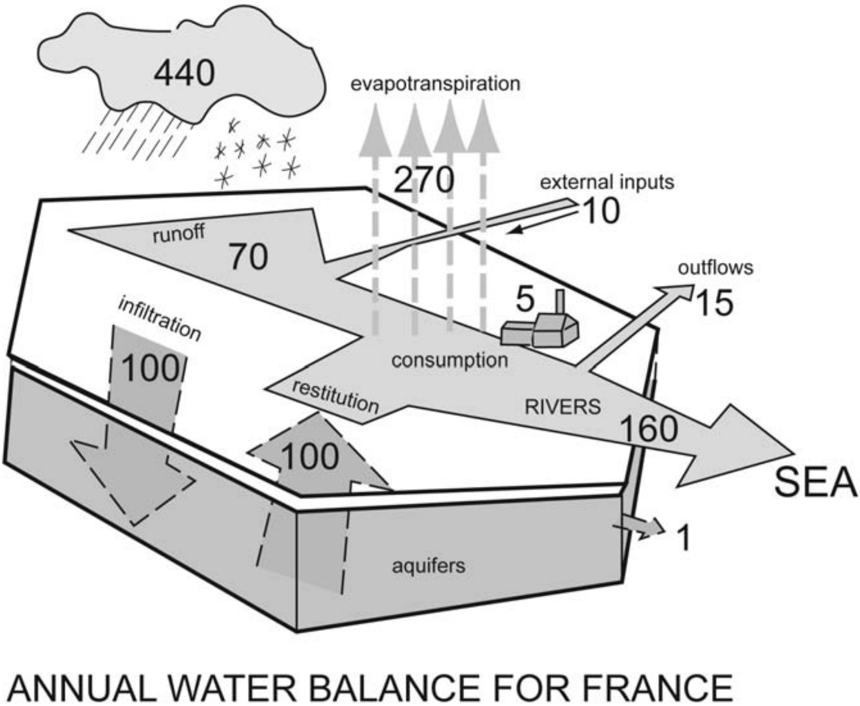


Figure 11 Annual water budget for France (in billions m³).

CHAPTER A5

The Infiltration of Water Below Ground and the Concept of an Aquifer

1 THE MECHANISMS OF INFILTRATION

The term infiltration is imprecise, as it indicates both the process of water seeping into the upper soil layer (zone of infiltration or zone of aeration) and that of water reaching the water table, the surface of the zone of saturated or vadose zone. This permanently saturated area is called groundwater. Porosity is the volume of open space in a material divided by its total volume.

Role of the soil: interface between the atmosphere and the aquifer, the soil dampens incoming signals and spreads them out over time. The soil's influence depends on its clay content, the slope, and the nature of the surface. Within the soil, the infiltration of water depends on the relationship between microporosity (slow flow) and macroporosity (rapid flow).

Upon encountering clayey bedrock, water seeps into a thin layer of weathered material and circulates at the top of the unaltered clay (hypodermic flow).

In porous terrain, rainwater seeps downward with a more or less even infiltration front. For example, in the pozzolanas of the Puys range (center of France), a 60 mm rainfall will penetrate to a depth of 1 to 2 m, depending on the local porosity of the material and its permeability.

In very open, fractured regions (tectonic accidents, karstified areas), downward drainage is rapid.

Water coats the surfaces of solid materials, and then replaces the entire atmosphere present within the soil (improperly called "air"). Infiltrated water can therefore temporarily saturate the porosity of the soil (Figure 12).

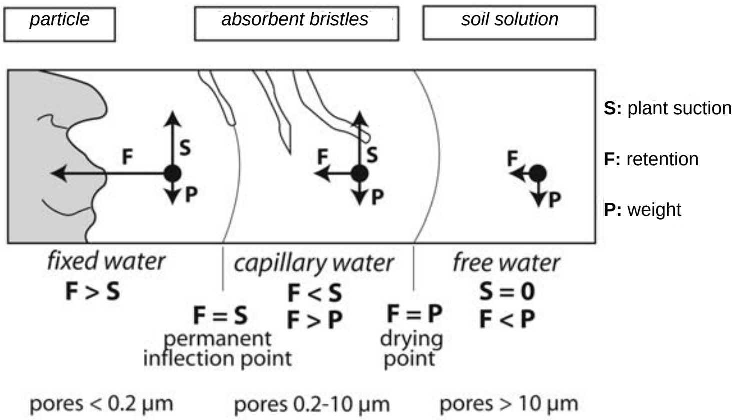


Figure 12 Types of water within a solid material (from Gobat *et al*., 1998).

The water filling large pores is subject to the force of gravity, and therefore flows downward. Water in small pores, on the other hand, while still subject to the force of gravity, is more influenced by capillary forces.

Water present at shallow depths is subject to evaporation, and the zero-flux plane (Figure 13) separates water returning to the atmosphere as a gas from water flowing downwards as a liquid towards the water table

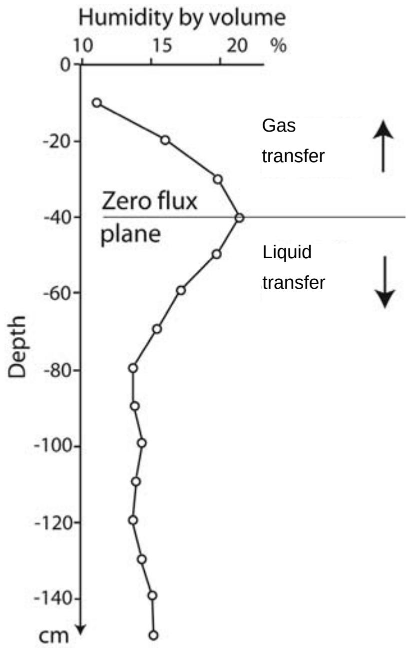


Figure 13 Distribution of water in a soil profile.

("true" infiltration). The zero-flux plane is defined by its maximum water content; above this plane, the salinity is increased and the heavy isotope content is enriched. The general characteristic of water circulation during infiltration is, with the exception of lithologic heterogeneities, a strong vertical component. However, the presence of clay lenses can force water to flow laterally before reaching the water table. The downwards transfer of water translates into a progressive de-saturation of the soil (Figure 14). While the liquid phase is dominant, water flows downward due to gravity while the gas in the soil is immobilized. The stage at which the gas phase becomes continuous and is in open exchange with the atmosphere allows the evaporation of water, and it is the liquid phase which is no longer mobile.

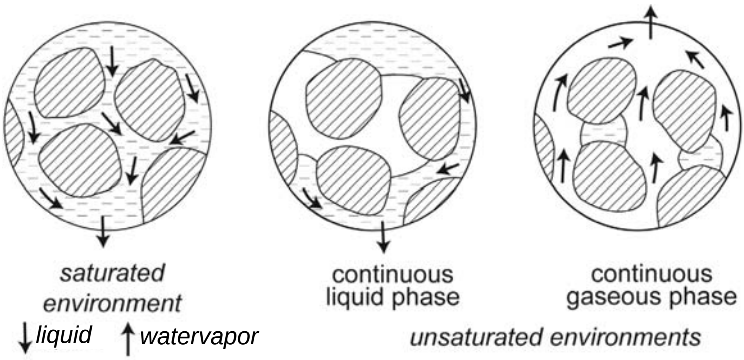


Figure 14 Progressive desaturation of a soil.

Once infiltrated, water reaches the water table, molecules follow a primarily horizontal path towards the outflow point.

The term aquifer includes the group of geologic formations bearing water; it therefore encompasses the zone of infiltration as well.

2 THE ROLE OF STRUCTURE AND LITHOLOGY

If the water table is located in porous water-bearing formations in vertical communication with the atmosphere, the aquifer is termed unconfined (Figure 15). The consequences of such an arrangement are:

- the immediate inflow of water into boreholes or wells as they are created as soon as they reach the water table or the first water-bearing discontinuity (stratification joint or fracture);
- the aquifer's ease of recharge;

- the presence of oxidating conditions favorable to the persistence of metallic compounds (iron, manganese) in the form of solid minerals (oxides, hydroxides);
- the mineralization of humic organic compounds or pollutants (positive aspect);
- the exposure of the resource to inorganic surface pollution (negative aspect).

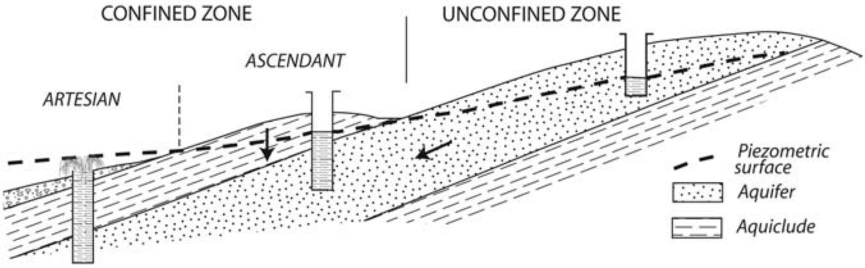


Figure 15 Unconfined aquifer and confined aquifer.

If the surface of the aquifer is constrained by an impermeable roof preventing water from reaching the piezometric surface, it is said to be confined. Recharge can then occur only through lateral transit from areas in which the aquifer outcrops at the surface (unconfined zone), or through weak vertical flow passing through the poorly-permeable roof (descending drainage). The result is an environment more protected from surface pollution, but also more isolated from sources of oxygenation, which leads to anoxic conditions favoring the persistence of organic molecules and the dissolution of undesirable metallic cations (iron and manganese).

In an artesian aquifer, any well or borehole will remain dry until it reaches the geologic roof of the aquifer. During the construction of a well in a site where the piezometric surface of the confined aquifer is at a higher elevation than its roof, water will rise in the well if the topographic surface is at a higher elevation than the piezometric surface (ascendant water). Water will flow out at the surface if the topographic surface is at a lower elevation (artesian flow). The term artesian comes from the Artois region, in Northern France, where this is a well-known phenomenon.

The impermeability of the aquifer depends on the lithologic nature of the roof formation: in geologic series, clay layers, if they are not fractured and if they are thick enough to not be disconnected by faults, constitute effective impermeable caps.

In alluvial plains, water-bearing Quaternary gravel is often covered by younger silt layers, deposited by a river with a lower carrying capacity. This less-permeable silt partially constrains alluvial gravel and sand aquifers, and gives them a semi-confined character.

Lithology therefore plays an important role in hydrogeologic features: aquifers within which water circulates due to gravity, thanks to large-scale solid elements (gravel, sand, sandstone), aquitards containing water with low mobility (silt, clayey sand), aquicludes containing water that is slow to renew (clay, marl).

Structure plays a major role in determining the drainage and communication potential across aquifers. Sedimentary structures (channels and gravel bodies within clays) in detrital continental formations, tectonic structures, and faults allow both the drainage of coherent formations (sandstone, limestone, granite, gneiss, basalt) along the fault, but also hydraulic communication between compartments, sometimes reaching across different aquifers.

Bedding dip determines the geometry of confined aquifers: in sedimentary basins, the alternation of water-bearing and impermeable layers creates a multi-layered aquifer, the drainage of which may be interrupted by brittle tectonics.

Structural geology allows for the identification of water “traps”: monoclines terminating against impermeable layers due to a fault, synclinal axes, grabens; and therefore, for the understanding of the geometry of aquifers. These structures can also be better understood with geophysical surveys.

3 DIFFERENT TYPES OF AQUIFERS (POROUS, FRACTURED, KARST)

One can classify different types of aquifers according to the nature, and therefore the origin, of the spaces containing water: if the voids are intergranular spaces of sedimentary (pores *sensu stricto*) or diagenetic (open spaces left by dissolved crystals) origin, they make up intergranular porosity or true porosity. These aquifers are called porous aquifers. They are made up of blocks, pebbles, gravel, sand, silt, sandstone, chalk, biolithics, bioclastic carbonates, volcanic scorias, sandy granite regolith, etc.

These aquifers are, among other things, deltaic, fluvial, or lacustrine alluvia, fluvio-glacial cones, colluvia, scree, weathered mantles, scoria cones, as well as porous marine series (detrital, bioclastic, or originating from coral reefs). These aquifers can therefore be made up of unconsolidated formations (often heterogeneous continental formations) or of coherent cemented layers.

Series deposited before the Quaternary have generally undergone diagenesis and been transformed into coherent rock.

Diagenesis, gravity, and tectonic constraints have created diaclases within them, transforming poorly porous environments into fractured environments. In addition to the fractures on a sub-meter scale, one must also consider all the fractures up to a multi-kilometer scale.

Fractured aquifers develop in igneous rock (granitic and gabbroic masses, extrusive flows), but also in metamorphic (gneiss, mica schist, pelite) or sedimentary (sandstone, carbonate) rock.

Generally, fractured aquifers can be found in series with poorly soluble minerals resistant to weathering (silicates). Of particular note are series of fractured rocks composed of soluble minerals (evaporites, carbonates), as they will have undergone the process of karstification. Pure water is, indeed, capable of dissolving a large quantity of halite, and a lesser quantity of gypsum, and water containing carbon dioxide (CO_2) is capable of dissolving calcite, aragonite, and dolomite. In such a situation, the porosity and permeability of fractures is greatly increased from the original fractured environment. This increase in permeability can occur only if the rock unit can eliminate ions in solution, as well as insoluble residue (clay, quartz, silicates), and if the carbonate minerals do not precipitate in the fractures that were previously enlarged through dissolution. If this is not the case (insoluble particles accumulate, carbonate precipitates), evolution of the karst system will be blocked.

Karstification remains functional when hydraulic gradients are high enough to maintain a steady flow.

These three types of aquifers therefore present different characteristics. The size of the representative elementary volume (REV), a concept describing the properties of a medium, varies with the medium's homogeneity.

The size of the REV of the three aquifer types changes in orders of magnitude: indeed, to statistically represent the average properties of a water-bearing medium, one must consider a few m^3 of a porous marine rock, a few tens of m^3 of a porous continental rock, a few hundreds of m^3 of a fractured rock, and a few km^3 of a karstified unit. The size of this last REV may include the entire hydrosystem.

4 RELATIVE IMPORTANCE BASED ON STRUCTURAL ASSEMBLAGES

Depending on the nature of the outcropping bedrock, on the aquifers' lithology, but also on the geodynamic conditions under which they formed, aquifers of each of the three major types can be found in different geologic contexts:

Table 4 Properties and Representative Elementary Volume of Typical Geologic Environments.

	Porous marine environment	**Porous continental environment**	**Fractured environment**	**Karst environment**
Homogeneity 10^{-1} m	Homogeneous	Homogeneous	Homogeneous	Homogeneous
Homogeneity 10^{2} m	Homogeneous	Very heterogenous	Homogeneous to slightly heterogeneous	Very heterogenous
Isotropy	Isotropic	Very anisotropic	Isotropic to anisotropic	Very anisotropic
Size of REV (m)	10^{-2} to 10^{1}	10^{1} to 10^{3}	10^{1} to 10^{2}	10^{2} to 10^{4}
Expected productivity	Poor to irregularly medium	Medium to irregularly high	Poor to regularly medium	Poor to irregularly very high

4.1 Ancient igneous and metamorphic units

Aquifers in igneous units (ancient masses and volcanic flows) often present a complex geometry (shape of batholiths, flows following preexising valleys). Intrusive units were exhumed at different time periods. This is the case for the Variscan (Hercynian) units (Vosges, Massif Central, Armorican Massif, Corsica, Maures), but also for the crystalline masses of the Alps and the Pyrenees. In all of these units, made up of "hard" fractured rocks, fractured aquifers predominate, as the rocks have, since the Paleozoic, undergone first the Variscan, then the Pyrenean or the Alpine orogenies. Their weathered mantles are porous aquifers likely to store water restored to the fractures of deeper, unweathered rock.

4.2 Sedimentary basins (Paris Basin: Figure 16, Aquitanian Basin, Alsacian Plain, Limagne)

In these basins, clay horizons alternate with porous aquifer horizons, resulting in multilayered structures. The current layout of the basins, with a center at low elevation and outcrops of permeable rock at higher elevation around their periphery, results in centripetal drainage from the outcrops towards natural outflow points or exploitation zones at structurally low points. The result of these elevation differences between the peripheral recharge zone and the outflow zone in the center is the frequent occurrence of artesianism. In such a basin, under natural conditions, tectonic disturbances affecting the intermediary aquicludes tend to allow deeper waters to flow up into shallower aquifers.

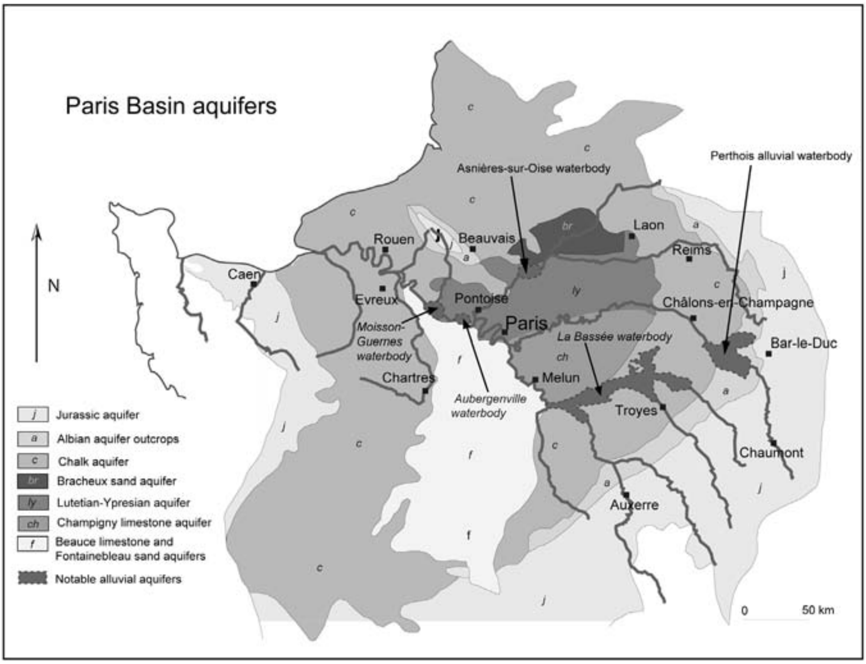


Figure 16 Principal aquifers of the Paris Basin (from the Seine-Normandie Water Agency).

4.3 Alpine and mediterranean ranges (Pyrénées, Languedoc, Provence, Alps, Jura)

The epicontinental basins, which preceded orogeny, included carbonate platforms. The defining characteristic of the external zones of the French Alps is their carbonate backbone, interlayered with marl, with limestone alternating with marl layers. Often having been subjected, since the Cretaceous or the Paleogene, to meteoric alteration, these carbonates have been karstified and are home to karst phenomena famous in the French alpine domains: the Pierre-Saint-Martin and Fontestorbes (Pyrénées), the Vercors, the Chartreuse, or the Monts du Vaucluse (Alps).

4.4 Piedmonts of the alpine ranges

The Mediterraneo-Alpine mountains are generally bordered by depressions within which outcrop porous Neogene and Quaternary formations (Miocene molasse, Plio-Quaternary marl and sand). These porous aquifers are recharged, often through unknown paths, by the nearby reliefs, where the effective rainfall is greater. These resources can be found in the Rhodanian (Miocene molasse of the Valence, Carpentras, and Valréas basins, Pliocene molasse in Bresse) or coastal ("Astien" in Montpellier) plains.

4.5 Volcanic regions

Classic volcanic structures, consisting of an emission source and of lava flows, combine a porous aquifer made up of high-capacity pozzolanas and a fractured aquifer developed within lava flows, which rapidly drains water from the cone towards springs at the foot the flow. These structures can be found in the French Massif Central.

4.6 Limestone plateaus

Around the edge of the Massif Central, the Jurassic transgression deposited limestone and marl onto an eroded Variscan platform. The resulting limestone plateaus, known for their landforms and for their karst water resources, can be found in the Vivarais, the Causses, the Quercy, in the Berry, as well as in Charente and in Bourgogne. Cut apart by sometimes-deep valleys (Ardèche, Tarn, Lot), they make up a mosaic of different aquifers.

Chapter A6

Porous Aquifers and Groundwater Circulation

Porous environments make up a highly varied category of aquifers. Porosity is the volume of open space in a material, divided by the total volume of the material.

Detrital marine sequences are ones with a simple geometry and distribution of properties, within which vertical variation is small (sedimentologic characteristics conserved over a certain depositional period) and the horizontal variability is such that the properties being measured can often be extrapolated over several km^2. The thickness of the water-bearing formations, determined by marine sedimentation, is only slightly variable over great distances. In terms of surveying, both the depth of the target and its thickness and petrophysical properties are easily predicted. Within the domain of porous environments, two other contexts are less predictable:

- areas undergoing sedimentation which are compartmentalized by contemporary or preexisting tectonics, which enclose porous environments varying in thickness depending on the depositional location (horst, graben). Additionally, due to synsedimentary movements, the nature and therefore the properties of different environments vary;
- all non strictly marine depositional environments (marginal, coastal, deltaic, lacustrine, fluvial) presenting a complex geometry (bedrock erosion, channelisation). These environments are characterised by their high lateral and vertical variability in facies; they are therefore highly heterogeneous and anisotropic.

In young fluvial environments, the bulk of the alluvium was accumulated during periods in which the climate was wetter than it is today, when rivers had a higher competence than they have now. Thus, gravel beds are observed at depth, overlain by younger, finer-grained beds of silt or clay. The hydraulic consequence is the semi-confined nature of certain fluvial or deltaic alluvial aquifers (lower Rhône or Var valleys), and the qualitative consequence is the isolation of the aquifer from atmospheric oxygen. Lacking exchange with the atmosphere, such an aquifer finds itself placed under reducing conditions favorable to the dissolution of undesirable metals, such as iron and manganese, as well as toxic heavy metals.

1 HYDRODYNAMIC CHARACTERISTICS

The major hydrodynamic characteristic of porous environments is that, their interconnected porosity being a sedimentologic property, drainage occurs over the entire cross-section of the aquifer, with relatively low, homogeneous velocities due to the large flow cross-section. The consequence for exploitation is the high probability of finding the same hydrodynamic characteristics within a certain radius around a catchment project. However, this observation cannot be applied to a deltaic aquifer, within which drainage is highly channelized, and therefore where the distribution of flow velocities will be be very heterogeneous: very high in gravel channels, quasi-null in silty, clayey banks.

2 DARCY'S LAW AND ITS APPLICATIONS

The basic experiment describing hydrogeology in a continuous medium was performed by Darcy in 1856.

In a vertical cylinder with a cross-sectional area A, a height Δh of water percolates through a thickness L of sand. Darcy observed that the discharge Q of water passing through the sand section is proportional to the value of $\Delta h/L$. This relationship is called the head loss, or hydraulic gradient i, and the proportional factor between the hydraulic gradient and the discharge is termed the coefficient of filtration K.

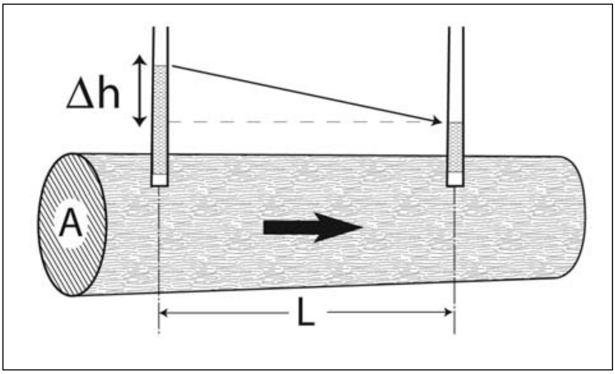


Figure 17 Darcy's experiment applied to horizontal flow in an aquifer.

The results of this experiment can be applied to "horizontal" flow within an aquifer (Figure 17).

Darcy's equation: $Q = K \cdot A \cdot \Delta h / L$.
By dividing both sides by A, one obtains: $Q/A = K \cdot i$
$Q/A = U$, the filtration velocity.

The inconvenience of U is that it applies to the entire cross-section of the aquifer, as though it were an open channel of flowing water without a solid skeleton. As a result, this minimalist velocity is not supported by tracer test results (Figure 18).

The velocity given by tracing tests is the actual velocity of water molecules in a porous medium. This actual velocity is equal to the Darcy's flux velocity divided by the porosity. So, for example, in the pores of a sandstone with a porosity of 10%, the actual velocity will be 10 times greater than the Darcy's flux velocity.

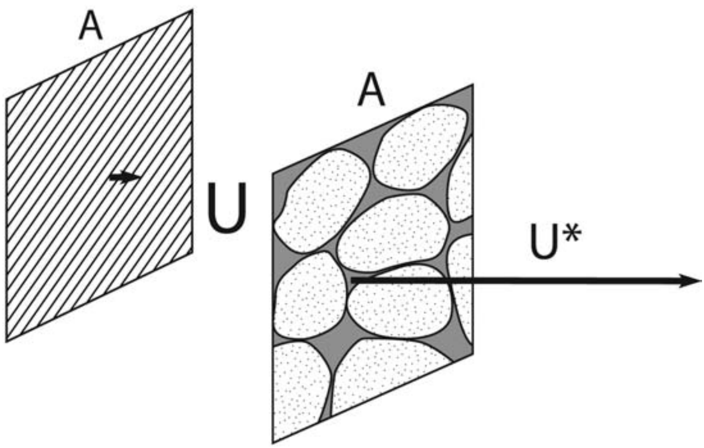


Figure 18 Darcy's flux velocity and actual velocity of water.

3 HYDRODYNAMIC PARAMETERS OF AN AQUIFER

The **permeability** K of a reservoir describes the ease with which water passes through it under the influence of a hydraulic gradient.

It is a coefficient, defined by Darcy's law, corresponding to the discharge Q (en m^3/s) flowing through a section unit A (in m^2), under a unitary (of one unit) hydraulic gradient (i).

Given by the equation $K = Q/A.i$, it corresponds to a filtration velocity and is expressed in meters per second ($m \cdot s^{-1}$). It ranges in values from 10^{-1}

or 10^{-2} m·s^{-1} in the most permeable terrain to 10^{-7} m·s^{-1} in poorly permeable formations.

Permeability offers a point by point representation of an aquifer, but presents high lateral and vertical variability, depending on the lithologic nature of the horizon under consideration and on the density of the fracture network. This is why more holistic notations are frequently used, which characterize more important and homogeneous volumes of the aquifer: transmissivity and storativity.

The **transmissivity** T represents the discharge of an aquifer over its entire thickness, in units of width and under a unitary hydraulic gradient.

It corresponds to the product of the average permeability K (in m·s^{-1}) and the thickness of the aquifer e (in m), or T = K·e, and is expressed in m^2·s^{-1}.

The **storativity** S is the relationship between the volume of water freed per unit of surface area, under a unitary hydraulic head, and determines the storage capacity of the reservoir.

It describes, for an unconfined aquifer, the drainage capacity of the rock, and can therefore be assimilated with the aquifer's effective porosity. For a confined aquifer, it results from the decompression of the rock and of the water contained within its pores.

Its value varies from 0.2 to 0.01 for unconfined aquifers and from 0.001 to 0.0001 for confined aquifers.

The **diffusivity** T/S governs the propagation of external influences within the aquifer. It is expresses in m^2 and determines, most notably, the transfer of water masses and of pressures.

4 GROUNDWATER CIRCULATION: PIEZOMETRY

The flow of water below ground is termed convection (or sometimes advection), and obeys Darcy's law.

A piezometric survey consists of simultaneously determining the elevation of water over a spatial set of points (wells, boreholes, piezometers, springs, surface waters) during a characteristic hydrologic period (dry season, average water level, and flood). In the field, the depth to water from the head of the tube (piezometers, boreholes) or the lip (wells, springs) is measured. This depth is read from the graduated line of an electrode probe (Figure 19).

In order to turn these depths into elevations, referenced in France in relation to the General survey of France (NGF), it is necessary to determine the elevation of the wellheads. This done, it will be possible to draw piezometric profiles (linear) or piezometric maps (spatial).

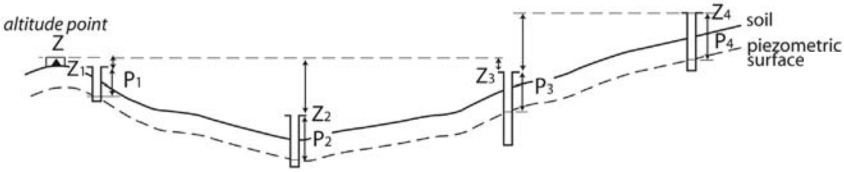


Figure 19 Topographic calibration of piezometry.

The curves interpolating the elevation of the water table between measurement points (called isohypses, isopiestic lines, or pressure curves) present the appearance of a topographic map of a drainage basin at the surface, groundwater flowing perpendicular to the curves, from the tops of the aquifer towards its low points.

Analysis of the piezometric surface (Figure 20) allows the determination of an aquifer's limits, as well as of zones of high or low transmissivity in the case of a heterogeneous environment, and of zones of inflow and outflow in a homogeneous environment.

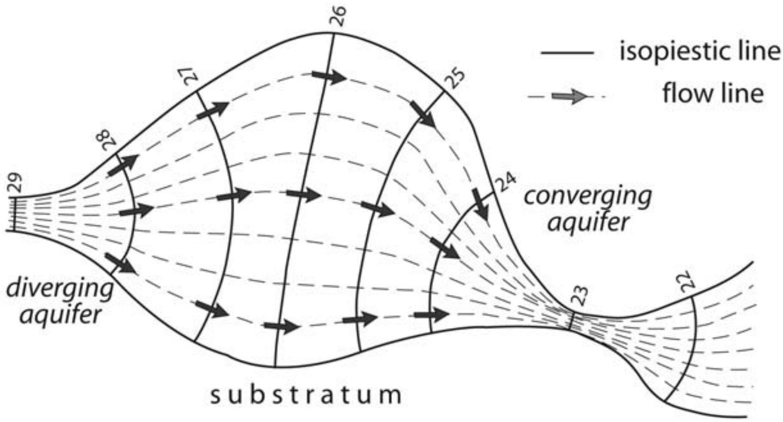


Figure 20 Appearance of the piezometric surface with flow lines.

The aquifer's reaction to events such as precipitation and flooding can be followed with piezographs, limnigraphs installed in piezometers. The measurements thus obtained, called piezograms, allow the determination of the best time periods for piezometric surveys and the cautious interpolation of their values.

Chapter A7

Fractured Aquifers

Basement rocks or their ancient sediment covers, previously considered impermeable bedrock due to their very poor matrix porosity, have, since the 60s and 70s, been drilled into and exploited, due to the following factors:

- hydrologic: the absence of alternative local resources (intertropical zones);
- climatic: droughts (starting in 1970 in the Sahel, and in 1976 in western France);
- technological: the development of the down-the-hole hammer. Previously, cable-drilling, a slow drilling mechanism, was used, and drilling was therefore costly.

Hard basement rocks have a variable primary porosity: the interlayer porosity of metamorphic rocks can reach 7.5%, while in granites and gneisses it does not generally exceed 1.8%. These rocks underwent fracturing due to contraction as they cooled, then tectonic fracturation over the course of their long geologic history. They include fractures tens of meters long as well as fractures that can be mapped over hundreds of kilometers. Water is therefore present within them in a discontinuous manner, and prospecting for it appears chancy: the productivity of exploration wells varies greatly, from poor to excellent.

1 GLOBAL DISTRIBUTION AND ECONOMIC IMPORTANCE

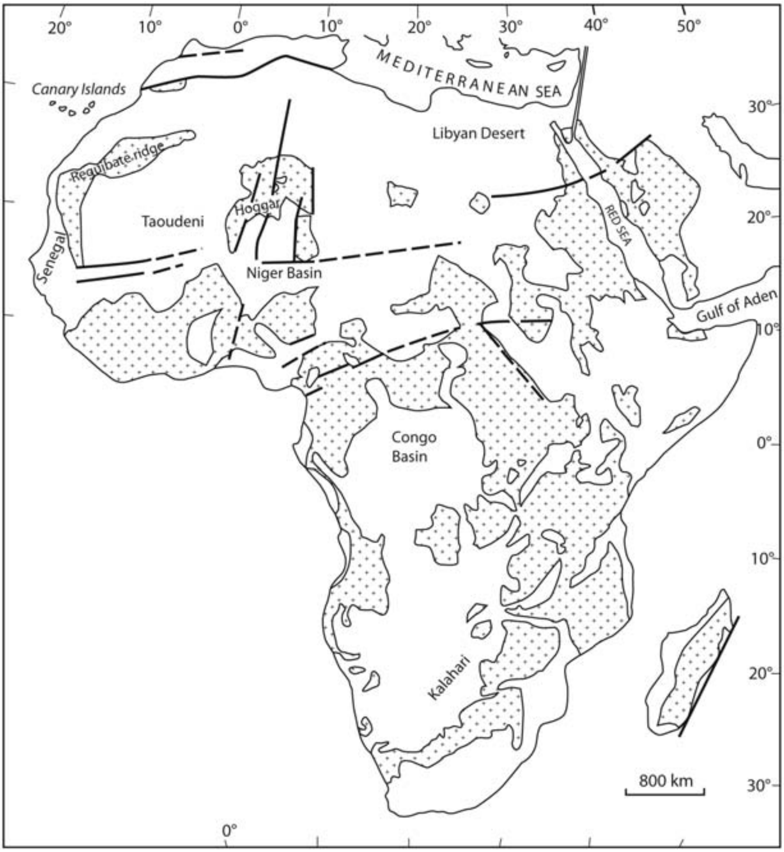
On Earth, crystalline rocks represent 30% of the continents. They cover a wide extent in western, central, and southern Africa, in Asia (the Middle East, India, South Korea), in South America (Brazil), in Scandinavia, in Australia, in a wide variety of physiographic and climactic contexts.

Historically, springs were tapped in the fractured rocks of temperate zones, but they often stopped flowing during the dry season. In Africa, village wells were dug in fractured environments. Paradoxically, the construction work (research, development, engineering) was done with the goal of studying and using the impermeability of these rocks (tunnels, storage of radioactive waste).

The prospecting of basement rock began in intertropical zones, but programs with a broader scope were subsequently developed in temperate or boreal zones.

2 AFRICAN HYDROGEOLOGY

Africa contains (Guiraud, 1988) extensive outcrops of Lower and Middle Precambrian basement rock (Figure 21).



Africa Lower and Middle Precambrian shields

Figure 21 Lower and Middle Precambrian outcrops of basement rock in Africa.

Due to its low relief, Sub-Saharan Western Africa constitutes a latitudinal climatic model, with monsoon-type precipitation (winter or rainy season), increasing from an average of 200 mm in the Sénégal valley up to 4,000 mm on the coast of the Gulf of Guinea (Liberia). An intense level of evapotranspiration (over 1,900 mm·year^{-1} in the Ferlo or around Lake Chad) modulates this entry signal. The current recharge rate is low (0 to 150 mm·year^{-1}), but the inter-annual variability in the hydrologic budget is very large. In Sub-Saharan Africa, these geotypes are home to a rural population. The generally low productivity of the wells (1 to 20 m^3·day^{-1}) is enough to serve the needs of these small communities. The aquifers in this region seem to have under-used potential.

Drilling is often stopped once the basement rock is reached, but the major difference with other aquifers is that the principal water stock is located in the weathered cover rock. One observes a difference between micaceous metamorphic rocks, which weather into clay and are therefore *a priori* not very productive, and granites and gneisses, which weather into coarse-grained quartz sand that is more capable of storing water.

These shallow aquifers are not costly to exploit, but their storage capacity is low and their vulnerability high. Their recharge flux being highly variable, fractured aquifers regulate their inter-annual recharge better than surface waters and their thin alluvium deposits, but less effectively than porous aquifers, due to their more limited storage capacity and their discontinuous character.

Due to this discontinuous geometry in fractured aquifers (clay-filled or recrystallized fractures), flow laws within them are poorly understood; prospection in such environments therefore requires probabilistic methods in choosing drilling locations: remote sensing (Figure 22), emanometry (radon, CO_2), geophysics (geoelectricity, electromagnetism).

These methods detect contrasting parameters, and therefore abnormal areas, the hydrogeological interpretation of which is possible only after drilling. Nevertheless, these location guides allow the detection of hydraulically conductive fractures.

Materials can range from relatively homogeneous, with the presence of fractures with an equivalent role (Figure 24a), to a double permeability with small fractures connected by more transmissive accidents (Figure 24b).

The small needs of the concerned human communities, which amount to a hydrogeology of survival (distance to the one water source for the village, human labor, parsimonious water use), result in village-scale projects directly drilling only exploitation wells. On the other hand, urban development programs drill several reconnaissance wells before equipping one for exploitation, so that it may then be connected to a mini-distribution system or to irrigated plots.

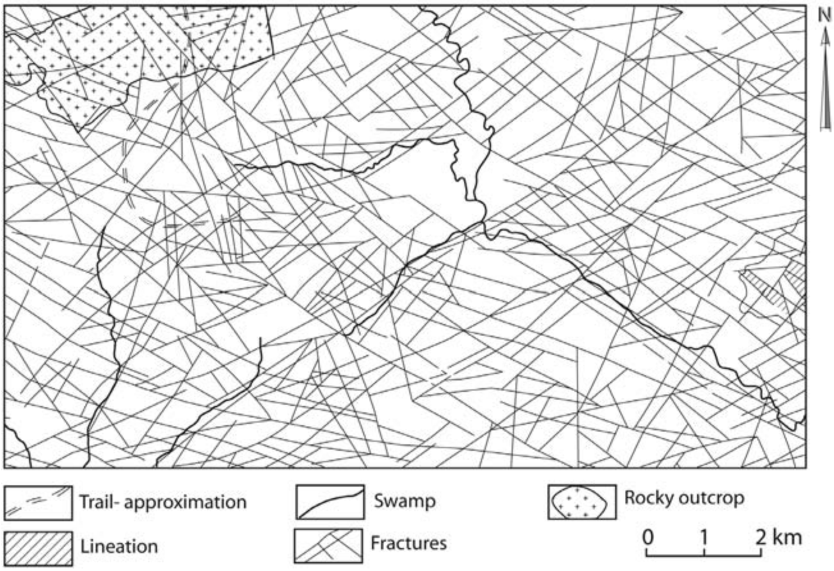


Figure 22 Location of discontinuities determined through photo-interpretation (Burkina Faso) (from Engalenc, 1978).

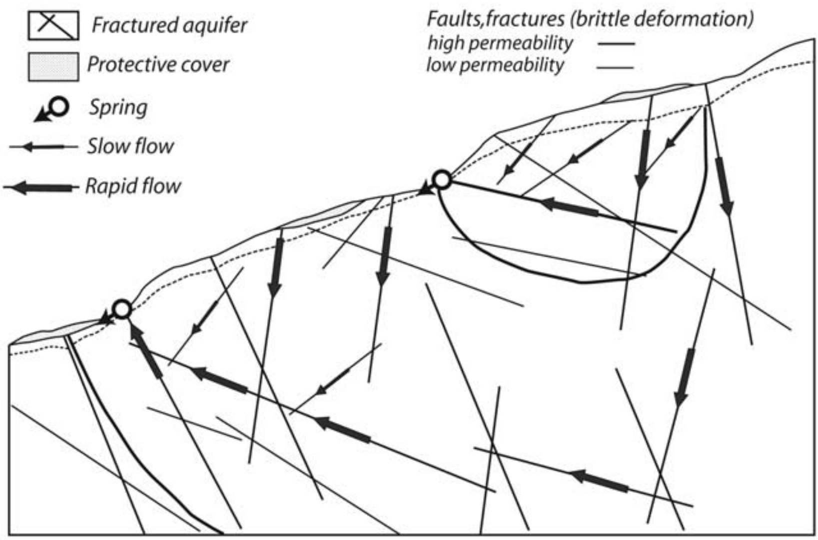


Figure 23 Double permeability of a fractured environment.

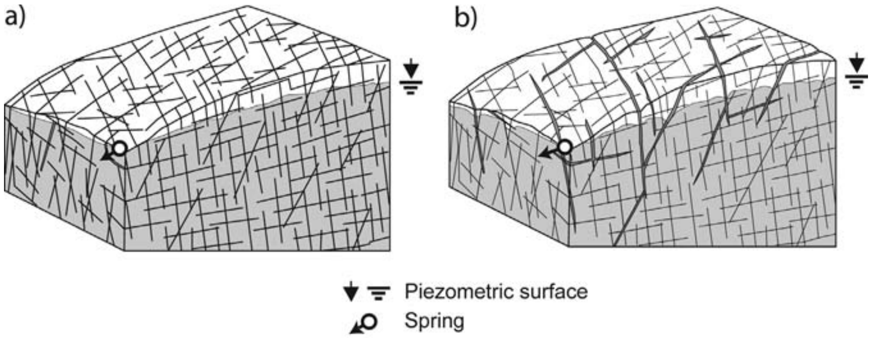


Figure 24 Heterogeneity of fissured and fractured environments (OFEG, 2003).

Interpretation models for slug tests cannot use hydrogeologic concepts for homogeneous environments, and Theis or Jacob's methods must be replaced by models considering drainage (Walton-Hantush, Boulton), which include the weathering mantle-basement rock pairing, by single-fracture models (Gringarten and Witherspoon), or by double-porosity models with transmissive and matrix fractures (Warren and Root).

Chapter A8

Karst Aquifers

At once relief, hydrosystem, and water resource, karst is a particular environment, defined as the group of surface and subterranean features created by the dissolution *of certain rocks, particularly carbonate rocks*, a process called karstification.

Karst is therefore presented as a typical morphology, first defined in the Kras in Slovenia, the formation conditions of which include soluble lithology and underground drainage. The rock is resistant enough to allow the preservation of forms created through dissolution.

The hydrogeologic consequence is the existence of a very heterogeneous, atypical aquifer, which is anisotropic on all scales.

1 KARSTIFICATION

1.1 The phenomenon

The phenomenon of karstification can develop only in rocks composed of minerals which are soluble in pure water (gypsum) or in water made more aggressive by the addition of a strong acid (oxidation of metallic sulfurs, sulfured hydrogen in oilfields), or in the great majority of cases, by the dissociation of a weak acid, carbon dioxide (CO_2) dissolved in the water.

The principal sources of CO_2 (Bakalowicz, 1979; Plagnes, 1997) are the soil (meteoric karsts) or deep inflows of water (hydrothermal karsts). They also include the mineralisation of natural organic material (humic and fulvic acids), which can provide up to 30% of the bicarbonates in water, as well as polluting anthropogenic organic material, such as the organic carbon in sewage, in livestock farming effluents, or in fertilizers.

In order for acidic water to seep into the ground, dissolution must occur in preexisting discontinuities (stratification joints, diaclases, faults), which will then allow a subterranean drainage path for water and the ions and insoluble residues produced by dissolution (clay, silicates) that it carries.

Karstification is therefore an evolving process, which increases the permeability of the rock mass as long as the rock remains capable of evacuating its insolubles.

The speed of this evolution is a function of the state of undersaturation of the solution relative to the minerals composing the surrounding rock, but, above all else, the solubility of these minerals and the flux of water carrying the ions going into solution (effective rainfall).

As a result, the evolution of karstification in gypsum is visible on the yearly scale, while the karstification of carbonates is visible on the century scale.

The spectacular aspect of karst is its surface and subterranean morphology (Figure 25), with the accompanying hydrogeologic consequences:

- differentiation between zones of diffuse (bare or covered karren), locally favoured (sinkholes), or concentrated (ponors or swallow holes) infiltration;
- hydraulic equilibrium with a high piezometric variation between surface water and karst water table (poljes, estavelles, overflows) due to the saturation of conduits;
- small number of springs with a high discharge, flowing out from conduits draining a vast watershed.

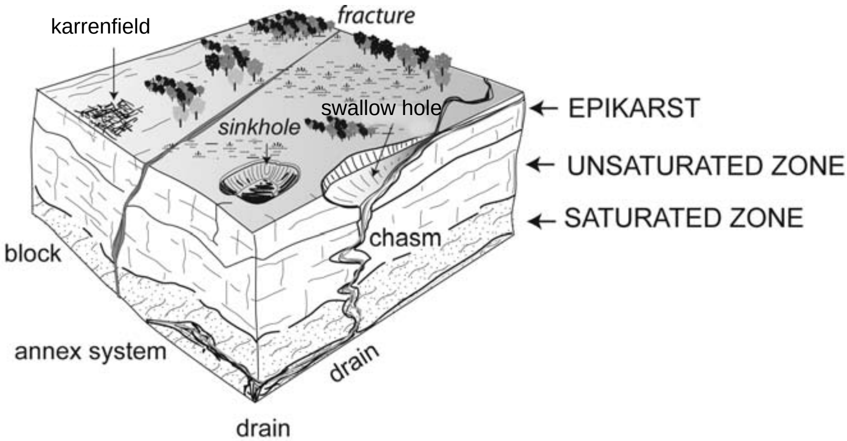


Figure 25 Karst model and geologic functioning.

1.2 Polyphase system

Karstification begins as soon as carbonate rocks are subjected to the erosive action of fresh water. For example, it affects coral reef flats as soon as they emerge due to eustatic changes or tectonic uplift. The karstification of a limestone region can therefore be spread over thousands of years. The double motor driving karstification is on the one hand chemical, and on the other hand hydraulic. The chemical driver is mineral undersaturation. The hydraulic driver is the potential energy between catchment and discharge areas, capable of transporting undersaturation downstream below ground. The evolution of this potential energy over time can be induced by increased permeability, an orogeny, neotectonics, or eustatic variations. The polyphasic genesis of karst regions makes them into geometrically complex environments (alternating phases of down cutting and equilibrium with the local base level), which translates into the modification of drainage patterns over time (plugging of passageways, re-excavation, circulation reversals).

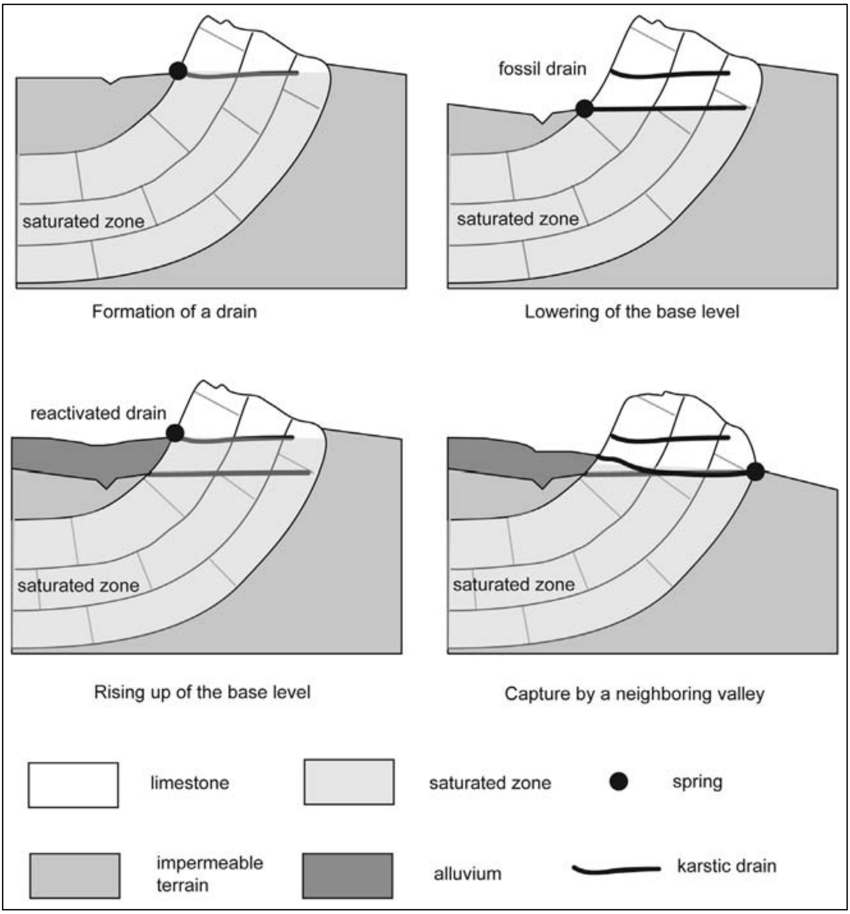


Figure 26 Polyphase karst system.

2 THE KARST HYDROSYSTEM: SPATIAL ORGANISATION

2.1 General principles

Unlike a porous aquifer, karst displays a heterogeneous and anisotropic structure on all scales. The concept of REV does not apply, this volume corresponding in some cases to the total volume of the karst hydrosystem.

Spatially, the karst hydrosystem is in opposition between three permeability structures (Figure 25):

- high-capacity, low-transmissivity micro-fissured blocks, with a hydraulic behavior similar to that of a coarse-grained porous medium;
- lower-capacity, high-transmissivity drainages (velocities of tens to hundred of meters per hour). The geometry of these drainage networks varies significantly from upper (numerous submillimeter-scale fractures) to lower (single meter-scale passageway, accessible to cavers) parts. It is therefore very hierarchical;
- high-capacity annex-to-drain systems, poorly connected to the main drain. Some of these cavities, located near the principal drainage axis, may have been connected to it in the past (paleokarsts).

From the upper portions of the basin to the drainage exit, karst appears as a surface hydrographic network where the small drainages from the upper regions flow together towards the lower, giving greater and greater drainages in smaller and smaller numbers.

Vertically, karst differentiates itself from other hydrosystems by its unsaturated zone, with a differentiated structure (Mangin, 1975). From top to bottom, it can be divided as follows:

- the epikarst, decompressed zone within which dissolution has acted in all directions to enlarge discontinuities. The epikarst is less anisotropic than the rest of the unsaturated zone. It is a highly permeable environment, capable of storing a non-negligible percentage of precipitation. In Mediterranean karsts, the epikarst corresponds to an AWC of 15 to 30 mm. The superficial character of the aquifer that it can contain (epikarst aquifer) allows the reconcentration of heavy isotopes (oxygen-18, deuterium) and of rain-derived solutes (halides, alkalis);
- the unsaturated zone in the strictest sense, not very open, cut through by tectonic accidents. Unsaturated indicates that the entirety of this zone is not filled with water, nevertheless, perennial outflows are observed, as in the European Inter-Disciplinary Underground Science and Technology Laboratory (i-DUST) in Rustrel (in the underground

galleries of the abandoned army outpost in Albion, South France), where they amount to less than one L/minute, or in the underground Albion river in Saint-Christol (Vaucluse), where they can reach several tens of L/second;
- the saturated zone, characterised by microfissured blocks, large drainage passageways, and annex-to-drain systems.

2.2 Examples in France

On the scale of a large rock unit, the spatial organisation of a karst system can reveal itself to be very complex, requiring an in-depth knowledge of the local geologic structure and paleogeography in order to be understood. The above vertical structure can also be lateral. For example, in the Berger chasm system (Vercors), water circulates primarily at the roof of the marl underlying the Urgonian limestone (Figure 27). The saturated zone is quasi-nonexistant, except in the distal part of the system, where the monoclinal structure gives way to a synclinal basin enclosing a saturated zone draining towards the spring at the Cuves de Sassenage.

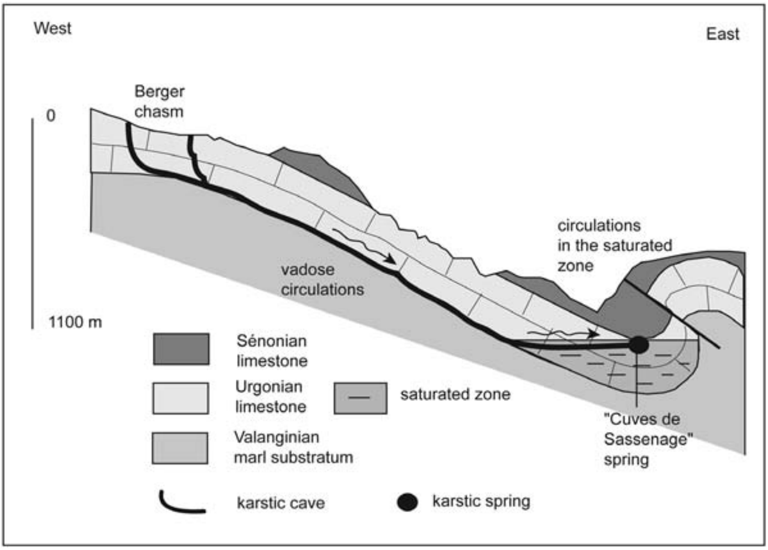


Figure 27 Spatial organization of flows through the Berger chasm (Vercors, France).

In the Atlantic Pyrenees, the underground hydrologic system of the Saint Vincent river (Lonné-Peyret chasm, Pierre-Saint-Martin chasm, Arphidia cave) totals over 100 km of explored galleries, containing multiple rivers. The water infiltrated into canyons circulates at the roof of the Paleozoic substratum. At the Pierre-Saint-Martin, the lowering of the regional base level allowed stream capture by Devonian limestones within which formed Arphidia system's galleries, which drain to the Bentia springs and fossilize the old Aranzadi gallery drainage (Figure 28). Given this particular context (a thick transgressive limestone layer overlying folded Paleozoic basement rock), without the deployment of considerable geophysical means, the deep geologic structure remains unknowable from the surface, and speleologic exploration therefore provides irreplaceable information.

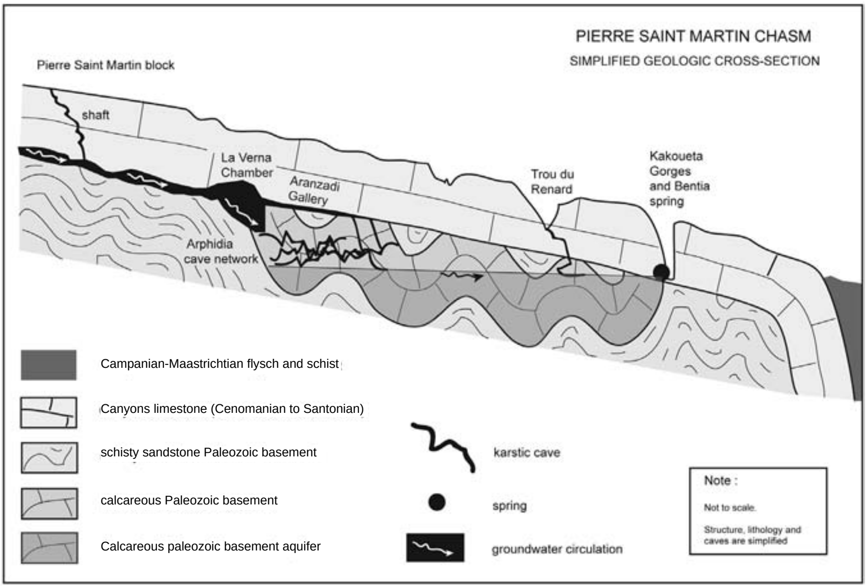


Figure 28 Withdrawal of the Saint Vincent river by the Arphidia network in the Devonian limestone of the Paleozoic basement of the Pierre-Saint-Martin chasm system (Altantic Pyrénées).

3 FUNCTIONAL CONSEQUENCES

3.1 Hydraulic functioning

The hydraulic consequences of this highly differentiated structure are that:

- flow paths in the saturated zone have a strong horizontal component, with drainage passageways playing an important role. Flow is turbulent in these very open channels, resulting in the remobilisation of sediments and a good mixing of solutions with different states of mineral saturation;

- the unsaturated zone in the strict sense primarily allows flow paths with a strong vertical component;
- in the epikarst, water circulates primarily horizontally, due to the permeability contrast between the epikarst and the unsaturated zone;
- between low water and flood periods, the piezometric inversions between passageways and the surrounding rock change the direction of flux exchanges (Figure 29): in low water periods, the passages drain the surrounding rock. In flood periods, the main passage, accepts inflows of infiltrated water and recharges the adjoining rock, which water infiltrating vertically is otherwise slower to reach.

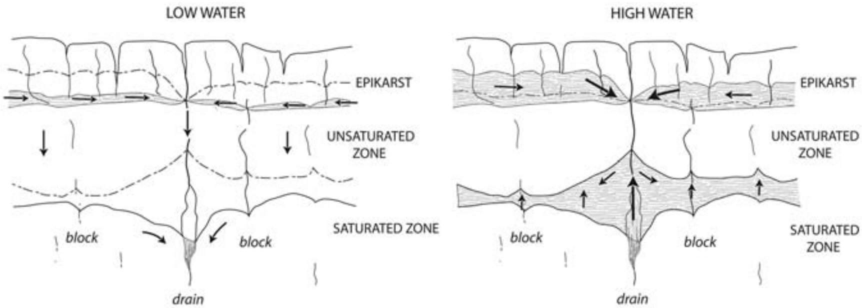


Figure 29 Hydraulic behavior of karst: drainage-fracture exchanges.

3.2 Qualitative consequences

The qualitative consequences of this structure are that:

- the hazard of pollution does not carry the same risk everywhere, depending on whether it is located on the draining system or on a poorly transmissive area;
- the environment being very heterogeneous and very open in terms of drainage passageways, there is no mechanical filtration, and, in flood, turbidity from the upstream watershed, as well as from sediment stirred up by turbulent flow in the conduits, passes downstream out to the emergence point. This turbidity can serve as a vehicle for heavy metals or adsorbed organic micropollutants, as well as for bacteria and viruses;
- the residence time of water in the network of passages, often less than a week, does not allow for a significant decrease in the bacterial load derived from the upstream basin (swallow holes, sewage dumped directly into the subterranean environment).

4 THE GREATEST KARST AQUIFER IN FRANCE: THE FONTAINE DE VAUCLUSE

4.1 General description

4.1.1 Location

The Fontaine de Vaucluse is the largest spring in France (23 $m^3 \cdot s^{-1}$), located at the southwestern end of the North-Provence block, a triangular limestone unit including the Mont Ventoux and the Montagne de Lure (alt. 1909 m) to the north, the St. Christol plateau in the center (alt. 1256 m) and the Monts de Vaucluse (1000 m) to the south (Figure 30). It includes a deep basin located at the base of a steep scarp, above a dead-end karst valley, and an assemblage of perennial exsurgences located between 60 and 83 m of elevation.

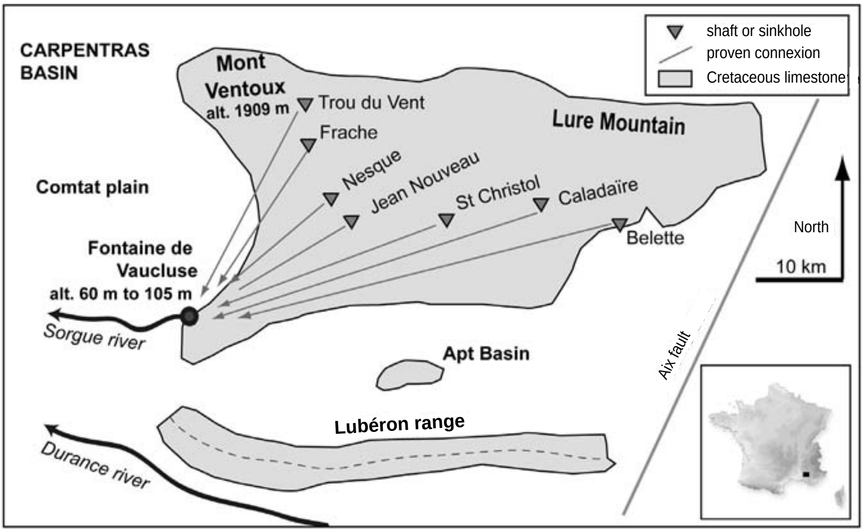


Figure 30 Location of the Fontaine de Vaucluse and position of tracer tests.

The basin is an equilibrating chimney for the system, its level varing with the discharge (Figure 31). In high water periods, it overflows at the elevation of 105 m a.s.l. In low water periods, its level drops 20 m. Numerous diving attempts with an aqualung finally succeeded in reaching a depth of 205 m (Hasenmayer in 1984), the limit of human exploration, and the rest of the submerged chasm was explored with remote controlled robots. The bottom of the chasm, 308 m deep, was reach by the Modexa ROV in 1985 (328 m below the level of the spillway, so 224 m below sea level).

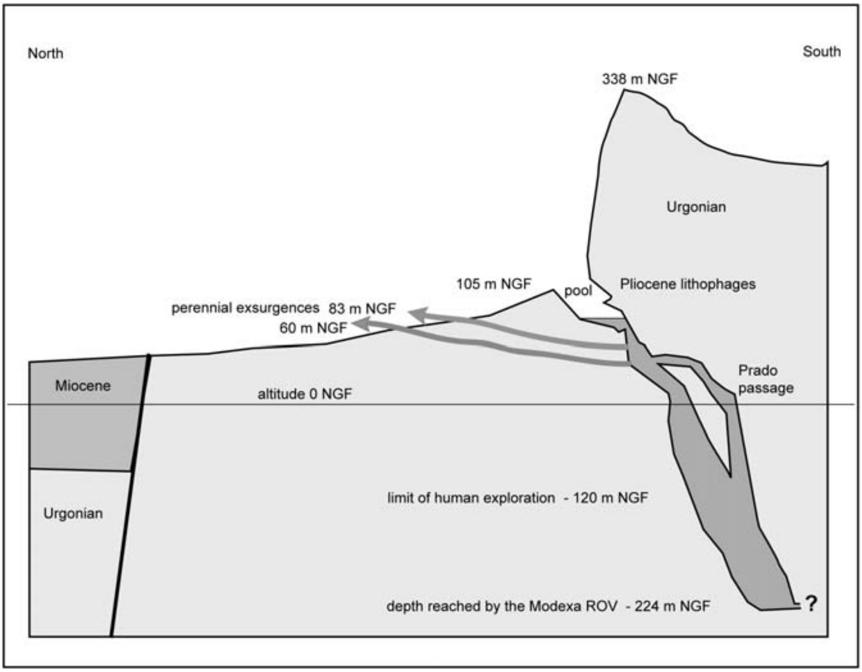


Figure 31 Schematic cross-section of the Fontaine de Vaucluse.

More recent explorations show that the conduit is complex, and cannot be simplified to a simple gallery. The volume becomes greater and greater with increasing depth, giving the impression of a vast, bell-shaped sinkhole. Its exact shape remains undefined, and the rest of the cavity is unknown. Two small galleries at 40 and 50 m a.s.l. feed perennial springs.

4.1.2 Geology

The fountain is hollowed out of Urgonian (Barremo-Aptian) limestones. These are between 500 and 800 m thick, and are part of a limestone series approximately 1500 m thick. The general structure is a monoclinal block dipping south, and cut across by a network of north-south faults (N 30° and N 145°). To the west the karst is barred by the Cavaillon/Fontaine-de-Vaucluse fault, which puts the Cenozoic series of the Plaine du Comtat and Carpentras basin into contact with the Urgonian limestones. To the south, they sink beneath the marly syncline of the Apt basin. Farther south still, the marly core of the Lubéron anticline forms a hydrogeologic barrier. To the extreme east, the Durance fault system bars the karst. The impermeable substratum is composed of Neocomian marl.

4.1.3 Hydrogeology

a) Hydrometry

Discharge measurements on the spring over long time periods have allowed the precise quantification of the amount of water flowing out. The discharge ranges between 4 and 100 $m^3 \cdot s^{-1}$. Analysis of the flood curves shows rapid reactions to precipitation, which indicates a well-evolved and very much hierarchised karst. The slow recessions show the importance of the reserves (Mangin, 1975). Tracer tests on the Monts du Vaucluse and hydrogeologic budgets now allow the clear delineation of the fountain's watershed, which has a surface area of approximately 1200 km^2 (Puig, 1987; Mudry and Puig, 1991). The Apt borehole, 605 m deep, found the same Urgonian limestone, poorly connected to the Vaucluse aquifer. The study of temporary springs and of a few drilling projects near the edges of the Montagne de Lure show that the Aix fault is the Eastern limit of the aquifer (Rousset, 1997).

b) Hydrochemistry

The study of intrinsic or dissolved trace indicators in the water (carbonates, magnesium, chlorides, oxygen-18) indicates the contributions of several different sources:

- very rapid infiltrated water (residence time: 2 days), with a high concentration of soil-derived tracers and a very low discharge, originating in the plateau's well-developed epikarst (sinks, karrenfields) (Blavoux & Mudry, 1986);
- rapid infiltrated water (residence time: a few days), responsible for mighty floods and for overflow of the spring, as well as for its decreased mineralization (Bakalowicz, 1979);
- water with a residence time of several weeks in the unsaturated zone (slow infiltration with chemical markers from gas phase in the soil), which can be remobilised by subsequent infiltration events (Lastennet & Mudry, 1997; Emblanch, 1997);
- water with a residence time of several years in the open voids of the saturated zone, which contribute to sustaining flow during dry periods (Evin *et al.*, 1967; Michelot & Mudry, 1985).

4.2 Origins of the system

Two hypotheses are generally put forward to explain the existence of a vertical conduit extending below sea level at Vaucluse:

- the spring has always been an outlet located along the Cavaillon fault trace, the location of the deep drainage being a result of a more favorable rock type in terms of porosity. It is, however, difficult, in such an arrangement, to justify the reason for a drainage more than 300 m deep rising up the current exsurgence, given that limestone is normally bedded and fractured. The density of discontinuities should allow the emplacement of outlets near the top of the karst aquifer, as is commonly seen elsewhere (Ford & Williams, 1989). However, the difference in potential energy between recharge area and exsurgence (analogous to difference in electrical potential) requires only that water flow from one point to another, without dictating the path that the water will take;
- the spring uses an inherited karst morphology (chasm or swallow hole), and emplaced during a Messinian paleogeographic context very different today's (Julian & Nicod, 1984; Mudry & Puig, 1991; Clauzon *et al.*, 1997).

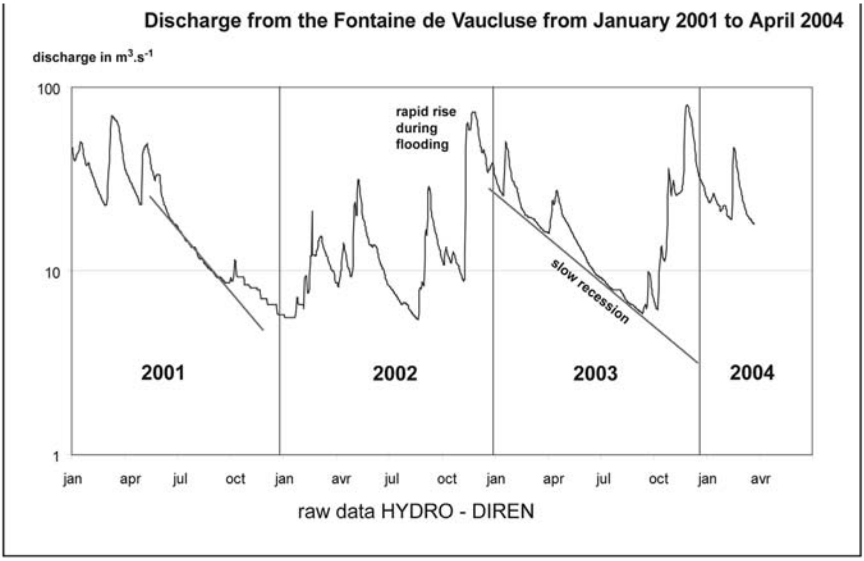


Figure 32 Discharge from the Fontaine de Vaucluse, from 2001 to 2004. The rapid spikes during flood periods indicate a highly evolved karstification. The slow recessions highlight the size of the reserves. Note: the flood peaks were not acquired.

The exploration robot's observations of karrens in the walls of the chasm at a depth of 250 m could indicate a phase during which the fountain was dry, and the presence of Pliocene lithophages in the basin support the second hypothesis (Figure 33). The system would then have been emplaced during the Messinian, or even at an earlier period, with a very low regional base level, the aquifer being drained by an outlet located more to the south or

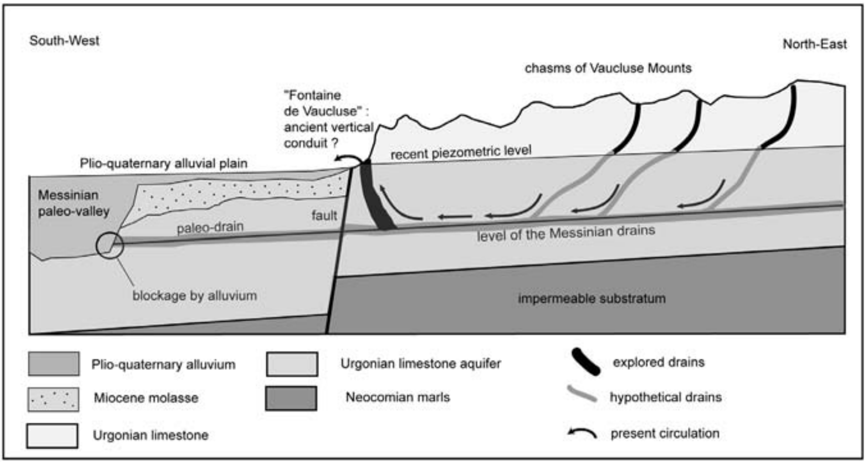


Figure 33 Messinian hypothesis for the spatial organisation of the Fontaine de Vaucluse aquifer's deep drainage system.

to the west, in a deep tributary valley of the Rhone. Fluvial sedimentation induced by rising lea level blocked the deeper drainage and forced the water to use preexisting drains. This model fits well with observations from coastal karst aquifers (see chap. A9.2.2).

Chapter A9

Island and Coastal Aquifers

1 THE INTERSECTION OF TWO ENVIRONMENTS

The water in aquifers, when they are recharged, circulates towards the local base level. On islands and in coastal zones, aquifers therefore flow out into the sea. However, an aquifer being, by nature, permeable, sea water can also flow into it. The two environments will therefore interact following theoretically simple laws, which, in practice, become highly complex, particularly for karst aquifers. The penetration of sea water into a coastal aquifer can sometimes have irreversible effects.

1.1 Distribution and economic importance

Coastlines tend to be densely populated, and the economic importance of these aquifers is constantly increasing, but their use is restricted by the problem of contamination by sea salt. The particular case of coastal karst aquifers must be highlighted here. Numerous high-yielding springs, located in the most populated zones, cannot be used due to their high salinity. Port Miou (8 $m^3 \cdot s^{-1}$) near Marseille and the Almyros (10 $m^3 \cdot s^{-1}$) near Iraklion (Crete) are two examples, which have been the object of numerous projects and studies for almost half a century without resolving the problem.

In just the Mediterranean Sea, it is estimated that 1,000 $m^3 \cdot s^{-1}$ of water pours out from karst aquifers into the sea, generally at a total loss. Given an individual consumption of 250 L per day, such an amount could theoretically have served over 350 million people.

1.2 Saltwater intrusions

In a porous or fractured aquifer, the two environments, protected from turbulence, do not mix often. Porous coastal aquifers were studied at the end of the 19th century by Ghyben and Herzberg. Fresh water, which is less dense, floats on seawater with a sloping contact simplified as a plane, the interface, the position of which is dependent on the density difference between the two environments, 1.000 for fresh water and approximately 1.025 for salt water (Figure 34). At equilibrium, the weight of the fresh water column is equal to the weight of the salt water column. The Ghyben-Herzberg law defines the position of the contact between the two environments at equilibrium:

$$\rho_1(P + H) = \rho_2\ P \text{ or, approximately, } P = 40 \cdot H$$

where P is the depth to the interface; H is the hydraulic head (or the piezometric level); ρ_1 is the density of fresh water; ρ_2 is the density of salt water.

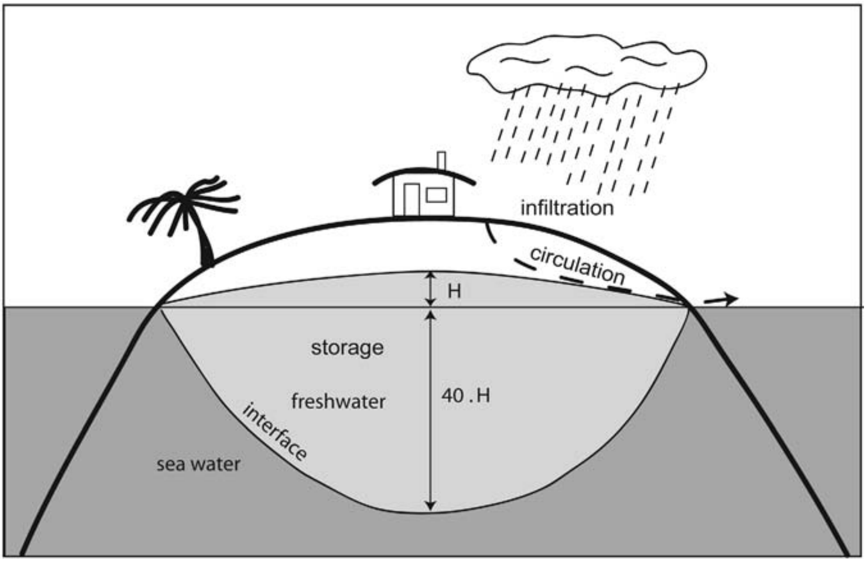


Figure 34 Theoretical geometry of the saltwater interface of an island aquifer.

In reality, mixing occurs through diffusion and the system is not entirely static, as the aquifer drains into the sea, which is subject to tidal oscillations. The two environments can therefore mix and form a layer of brackish water of variable thickness. In addition, the anisotropy of the aquifer translates into variations in the hydraulic gradient, which transforms the interface into a complex surface with many lobes. The water table can also intersect with the surface to form ponds or lagoons within which evaporation locally lowers the piezometric surface, allowing the interface to rise.

The penetration of salt water can occur over several kilometers into the interior of the continent, depending on the geometry of the aquifer and the hydraulic gradient, but also on the mineralisation of continental waters, which increases with depth (see chap. A 10).

1.3 Anthropogenic actions

Exploitation modifies the piezometric surface and causes the establishment of a new equilibrium and the migration of the saltwater intrusion. Extraction by pumping causes a vertical rise of the intrusion under the pump, around 40 times the drop in the water table (Figure 35). The discharge must therefore be very precisely adjusted in order to limit drawdown.

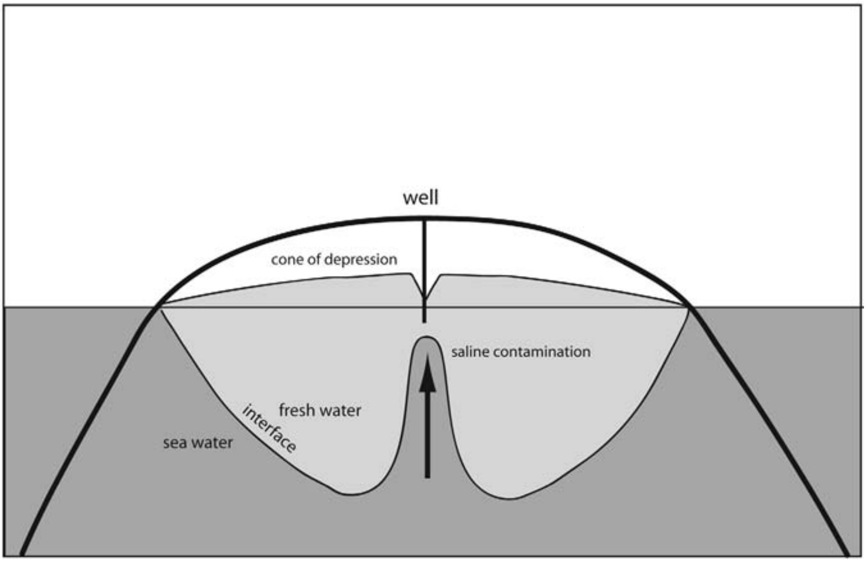


Figure 35 Saline contamination due to pumping in a coastal aquifer.

The penetration of salt water can occur over several kilometers (Figure 36). In touristic areas, coastal resources are massively drawn upon during the summer, the period during which the aquifers receive little recharge. The risk of saline intrusion therefore increases, particularly given that, the water table being close to the surface, private wells are often numerous.

On the Atlantic coast, salt water intrusions affect the aquifers of the Gironde estuary (Soulac and Rochefort regions). On the Mediterranean, this risk is present for most coastal aquifers, between Perpignan and Fréjus. For example, the Astien aquifer, between Agde and Béziers, an important water resource for the department of Hérault. It provides between 3 and 5 million $m^3 \cdot year^{-1}$, or 15% of the water for the sector. Its good quality and shallow depth (generally between 20 and 100 meters) favored the development of numerous wells.

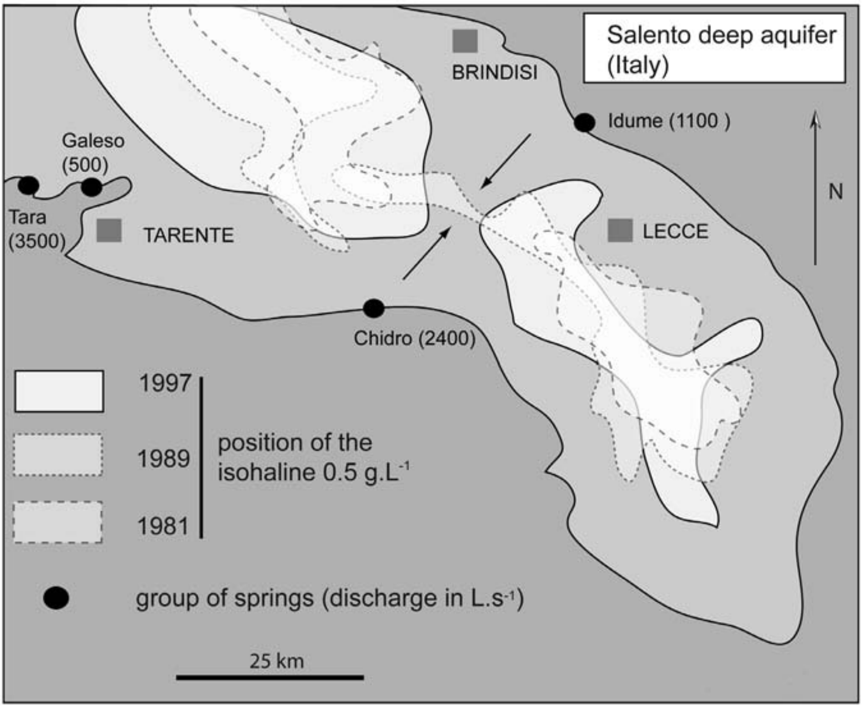


Figure 36 Variations in salinity observed south of Brindisi (from Polemio & Limoni, 2001).

1.4 Variations in sea level

There are three types of variation:

- oscillations linked to the tides: by decreasing the hydraulic gradient, they modify the hydrodynamic functioning of the aquifer. The latter is, in fact, also subject to more or less dampened tidal effects, depending on its intrinsic physical characteristics;
- historic oscillations: the level of the oceans has known numerous positive and negative variations. The astronomical parameters of the Earth's rotation and its revolution around the Sun determine Milankovitch cycles, the analysis of which can explain the observation that a cooler phase provokes a glaciation approximately every 90,000 years. The contraction of sea water and the storing of ice on the

continents lowers the global sea level. During the Würm, the last glaciation, sea level dropped approximately 120 m from present-day levels. Rises and drops in sea level occur in successive phases, with stages whose existence is attested to by the presence of coastlines and notches (Collina-Girard, 1996). The post-glacial rise began 18,000 years ago, with several arrests. The last pause lasted approximately 2,000 years, as indicated by the relative homogeneity in the elevation of ancient ports in zones of low tectonic activity;

- finally, tectonic activity can sometimes isolate portions of the sea for which inflows from precipitation and rivers are less than losses to evaporation, which causes a drop in their level. The Dead Sea is now located at an elevation of 450 m b.s.l. Scenarios of this type are sometimes proposed to explain the paleoreliefs and the evaporite deposits at the bottom of the Mediterranean and in the Gulf of Mexico.

These great variations in base level of course had consequences on the functioning of surface and subterranean aquatic environments, but also, especially, on the spatial organisation of aquifers, for example, by defining successive phases in the downcutting of valleys and their infilling by alluvium, or by allowing the emplacement of deep karst systems. The Rhone valley, a typical example, was highly incised during the Messinian, to more than 600 m deep in Arles, and was then flooded by the Pliocene sea up to Lyon.

Hydrogeology in coastal regions cannot do without the study of these variations. Hydrogeologic studies done during the construction of the Toulon tunnel demonstrated that paleocirculations of groundwater had existed between the Jurassic limestones of the Mont Faron to the north and the coastal and submarine karst of the Muschelkalk in the bay of Toulon to the south, through accumulations of highly soluble Keuper gypsum, when sea level was lower (see chap. D2-3.3.2). In such a context, dewatering pumping below sea level, over several years, can reactivate circulation, causing, on the one hand, the leaching of the clay filling cavities, but also the intrusion of sea water, which, by mixing with water in the karst aquifer, allow gypsum dissolution due to common ion effects.

Currently, global warming, whose natural or anthropogenic origin remains a subject of debate, has resulted in a noticeable rise in sea level, of several millimeters over the last century. The predicted rise varies depending on the scenario; it could accelerate and reach 1 meter in the next century, which, aside from the problems facing the residents of the resulting flooded areas, would have effects on the use of coastal aquifers.

2 COASTAL KARST AQUIFERS

On all the limestone coasts of the planet, springs emerge near the shore of under the sea. They are common around the borders of the Mediterranean, and have been the object of numerous studies and exploitation attempts, particularly along the Dalmatian coast, where thirty or so high-discharge springs (a few $m^3 \cdot s^{-1}$) are known between Trieste and Kotor (Mijatovic, 1986; Breznik, 1998). In Greece, the Almyros of Iraklion (Crete) has been the subject of catchment attempts for half a century; in Italy the Tarente and Mortola springs have been studied since the sixties; in France, the Port Miou spring was the subject of in-depth studies during the same time period. The most recent studies (Bini, 1994; Gilli, 2001; Arfib, 2001) show that the emplacement of these systems and their functioning cannot be explained without the existence of a paleogeographic context very different from the present day, which would explain their behavior and the cause of the failures to tap them.

Their use directly at the exit is generally impossible due to their salinity, but, these springs being the exit point for continental aquifers, their study brings precious information, which can help efforts to tap them on land. Due to the increasing population along the coasts, and the need for alternative resources in case of an accident, there is today a rekindling of interest in these resources.

2.1 Particularities of coastal and submarine karst springs

Most coastal karst springs have exsurgence conditions comparable to those for continental springs. However, unless they are separated from the marine environment by an impermeable layer, or unless the hydraulic gradient is very high, coastal karst springs are generally brackish. The salinity generally varies as an inverse function of the discharge, and is therefore highest during the dry season; yet this is generally the period during which the demand for these aquifers is the highest. The contamination mechanisms are not yet entirely resolved, but they can be approached based on the Ghyben-Herzberg law.

For submarine springs, their brackish water, being less dense than sea water, migrates vertically from the exit point towards the surface, where it forms a clearly visible ring during calm weather. The water then spreads out across the surface of the sea.

Near the springs, the mixing of waters, due to common ion effects, makes the sea water aggressive and enables it to dissolve limestone. A wave-cut notch or mushroom-shaped rocks are usually visible near such outlets.

Cavities can exist around the periphery of marine springs, functioning like estavelles, absorbing seawater or emitting brackish water, depending on the season. The ones in the Bay of Bali (Crete) absorb approximately 1 $m^3 \cdot s^{-1}$, and have been proven through tracing to be connected to the coastal springs at Syphona, 6 km away. They may also be connected to the Almyros spring in Iraklion (elevation 3 to 10 m), located 30 km to the southwest, but no tracer tests have been able to prove the connection, and recent studies (Arfib, 2001) refute this hypothesis. The estavelles of Kola (Croatia) absorb 100 $L \cdot s^{-1}$, and a tracer test has shown a link with the coastal springs of Jurjurevo.

Aspiration can occur on the coast, and is therefore visible, as in the sea-mills of Argostoli, which are one of the most surprising karst phenomenons of the planet. On the western coast of the island of Kefalonia (Greece), in the bay of Livadi, near the town of Argostoli, several coastal karst cavities absorb sea water. In the past, the throughflow was strong enough to power two mills, but in 1953, following a strong earthquake, it decreased significantly. A tracer test in 1963 with 140 kg of fluorescein indicated a connection, after 16 to 23 days of travel below ground, with the brackish springs of Karavomylos, located in Sami, 15 km to the northeast, on the eastern coast of the island. The outflow into the losses was 1.7 $m^3 \cdot s^{-1}$ and the discharge from the springs was 10 $m^3 \cdot s^{-1}$. This poorly-understood phenomenon has prompted several interpretations, including notable ones by Glanz (1965), Maurin and Zoetl (1965), and Drogue (1989). A hypothesis for the functioning of the springs is proposed below (see chap. A9-2.4).

2.2 The origin of submarine karst springs

Karst systems experience a delayed reaction to variations in sea level, which are generally rapid (+120 m in 18,000 years, for an average speed of 6.6 mm per year for the last transgression, with even greater instantaneous velocities, given the existence of pauses). Drains can form during a period of low sea level, during glaciations for example. After a transgression, if the permeability of the limestone near the outlet is low, the emergence can remain functional below sea level, as long as the fresh water is under greater pressure than the pressure of the overlying seawater. Such springs are known to exist at depths of up to 80 m (Anavalos, Greece).

Karsts are polyphase systems and their evolution can extend over millions of years. During these long periods, coastal karsts adapted to the marine base level, by hollowing out new drainages, but also by reactivating older drainages. Indeed, within an unconfined karst aquifer, the establishment of a water current, necessary for the excavation of conduits (see chap. A.8), depends on the hydraulic gradient and the fractured permeability of the rock. Water flows from recharge to discharge zones so as to minimise the loss of head, that is to say, along the most direct path, dependent on the geometry of the aquifer's fractures. The principal drains are therefore generally placed in the upper portion of the aquifer and have a sub-rectilinear profile, close to the piezometric slope. However, since the system may have evolved during the past, with the creation of drains with a greater cross-sectional area, if the water table rises above these, the head loss will be lower in these conduits than in the network of non-karstified fractures, and drainage will occur at least partially through them.

Paleokarsts are known around the edges of the Mediterranean Sea, dating back to at least the Cretaceous (Rousset, 1968). The current karstification, unaffected or little-affected by tectonic activity, probably dates from the Oligo-Miocene for relatively tectonically inactive regions, and from the Pliocene, after the last alpine phase, for other regions (subalpine ranges). This heritage is important, and the drainage of a karst aquifer can, as a result, have a sometimes-disconcerting geometry. Upstreal of coastal springs, speleologic explorations reveal more and more the presence of inherited karst passages, developing significantly below the lowest levels of Quaternary glacio-eustatic variations. The most convincing hypothesis is that these systems were put into place during the Messinian, when the Mediterranean Sea dried up, before the opening of the Strait of Gibraltar. Nevertheless, the role of tectonics must not be underestimated, as countries such as Greece show very high rates of uplift, currently exceeding 1 mm per year.

Table 5 Depth of Passages in A Few Karst Springs.

Spring	Country	Depth below sea level	Hypothesized origin
Rio el Mante	Mexico	300 m	hyper eustatism in the Gulf of Mexico
Port Miou	France	179 m	Messinian hyper eustatism
Vaucluse	France	224 m	Messinian hyper eustatism
Almyros	Greece	> 100 m	Messinian hyper eustatism
Pozzo el Merro	Italy	300 m	Messinian hyper eustatism

The impressively deep Fontaine de Vaucluse, nevertheless located 150 km away from the coast, as well as several examples in Ardèche and in the Causses of the Montpellier region, demonstrate that this mechanism affected the spatial organisation of karst systems very far from the coast (Audra *et al.*, 2003).

Table 6 Piezometry at the Outlets of A Few Brackish Springs. From Breznik, 1998.

Name	Country	Elevation in m	Maximum salinity in $g \cdot L^{-1}$	Probable depth of mixing in m
Almyros in Iraklion	Crete, Greece	3 to 10	6	450
Lake Kournas	Crete, Greece	17	-	600
Annavaloussa	Crete, Greece	12	-	500
Pantan	Croatia	4	12	160
Slanac	Croatia	27	5	1,000
Tannimin	Israel	10	-	400
Mortola	Italy	1	1,4	60

2.3 Hypotheses on functioning

2.3.1 Hydrodynamic hypothesis

Contamination could be linked to a Venturi effect. However, this has never been visually observed, and does not satisfactorily explain why the salinity increases when the discharge decreases and not the inverse.

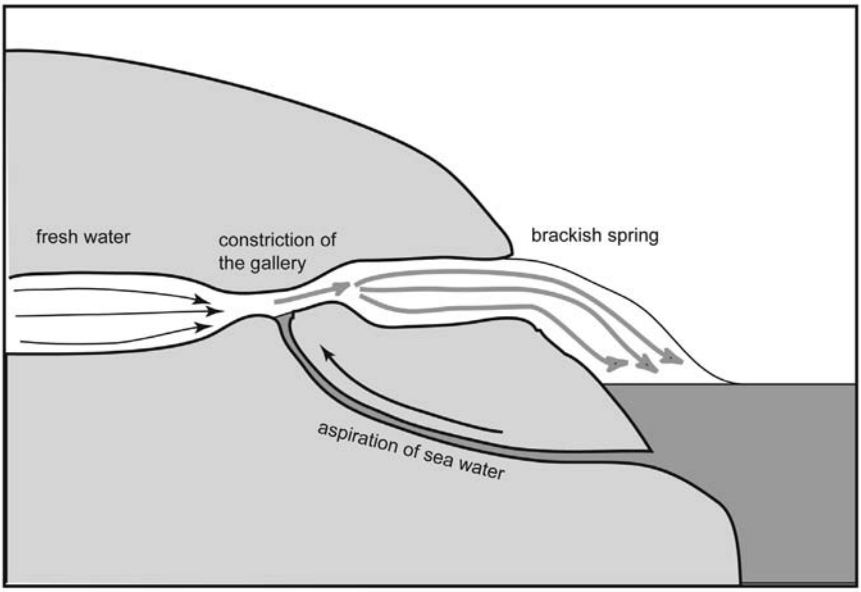


Figure 37 Aspiration of sea water by the venturi effect.

2.3.2 Geothermal hypothesis

The deep contamination of Florida's aquifer by marine convection currents, induced by geothermal flux, was put forward by Henry and Kohout (1972), to explain the salinity of Florida's coastal karsts, but this hypothesis is difficult to extrapolate to shallow systems.

2.3.3 Inherited drain hypothesis

The presence of very deep drains, inherited from a Messinian paleogeography or from tectonic movement, is a reality, as some of them have been partially explored by speleologists. This allows the consideration of the behavior of brackish springs by defining a simple model with 3 connected vases, filled; respectively, with sea water, fresh water, and brackish water (Lismonde, 2001). At equilibrium:

$$(H+\Delta H_1)\rho_1 = (H+\Delta H_2)\rho_2 = (H+\Delta H_3)\rho_3$$

where H is the depth of the drain relative to average sea level, ΔH_1 is the hydraulic head of the karst, ρ_1 is the density of fresh water, ΔH_2 is the elevation of the brackish spring, ρ_2 is the density of the brackish water, ΔH_3 is the variation in the elevation of the sea, ρ_3 is the density of brackish water.

This model easily explains the presence of brackish springs above sea-level (Figure 38).

The term ΔH_3 corresponds to variations in sea level, or to eventual depressions, in the case of the submarine estavelles of Bali (Crete), or of the sea-mills of Argostoli (ΔH_3 is then negative). It is therefore most commonly zero, if tides are neglected. Where $\rho_1 = 1$, for each system the result is:

$$H \cdot \rho_3 = H+\Delta H_1 = (H+\Delta H_2)\rho_2$$

so $\Delta H_2 = H\,(\rho_3 - \rho_2)/\rho_2$ and since ρ_3 is always greater than ρ_2, ΔH_2 is always positive.

Taking the example of drainages at a depth of 100 m and salinity at the spring of 5 $g{\cdot}L^{-1}$ (so a density of 1.004), one obtains a theoretical elevation around 2.5 m. Springs of the same salinity located at 27 m (Slanac) can therefore be explained by drains at a depth of approximately 1000 m, which would fit with the Messinian hypothesis and the thickness of peri-Mediterranean limestones.

It is certain that if such deep circulations are being considered, it also becomes necessary to take the geothermal gradient and water's temperature-related density variations into account.

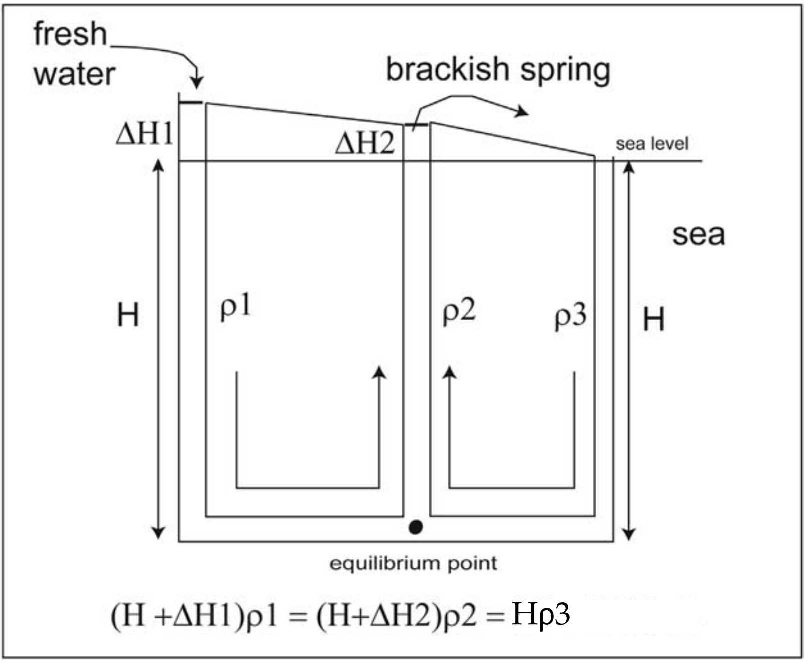


Figure 38 Inherited drain hypothesis.

A variation on this model was defined by Gjurašin (1943), called diffluence. It simplifies the system to a karst drain dividing into two branches at its end. The upper branch feeds the brackish spring; the lower branch behaves like an estavelle. When the fresh water pressure becomes large enough, the column of sea water is displaced, and the system is no longer contaminated by seawater (Figure 39).

2.3.4 Concentrated versus diffuse contamination

The preceding models deal with well-individualised conduits, but nothing prevents a situation where there is a diffuse contamination through the network of fractures around a deep karst drain. Arfib (2001) modelled the Almyros at Iraklion. The model describes the workings of the spring perfectly, by imagining a major drainage at a depth of 500 m, with diffuse contamination around the drain. A Messinien emplacement is considered likely, but there is also the possibility of tectonic tilting.

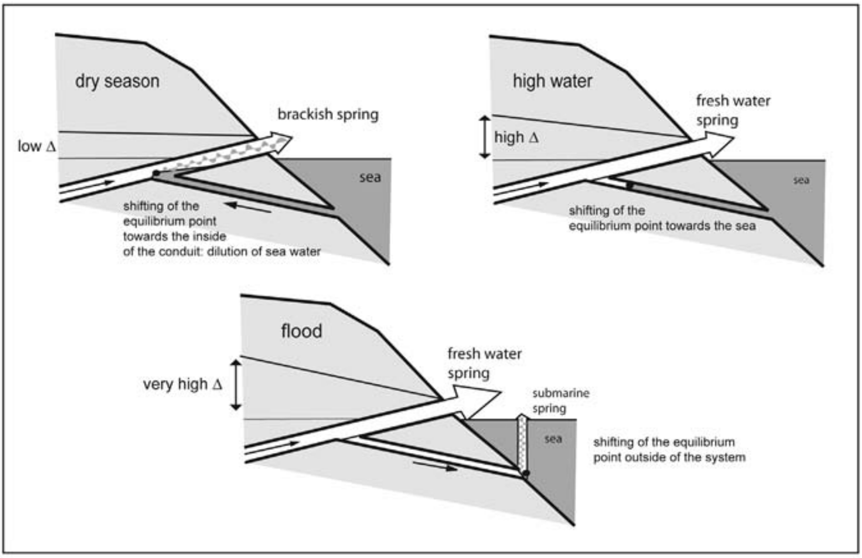


Figure 39 Diffluence model (from Gjurašin, 1943).

2.4 Example: the Sea-mills of Argostoli, Kefalonia, Greece

The preceding model can also explain the workings of the sea-mills of Argostoli. An on-site visit shows that: $\Delta H_2 = 2$ m; $\Delta H_3 = -1.5$ m. Solving the equation with $\rho_1 = 1{,}025$; $\rho_2 = 1$ and with a salinity of 5 g.L^{-1} at Sami, or $\rho_2 = 1{,}004$ gives a mixing depth of 170 m and suggests an average piezometric level for the island karst of ΔH_2 of 3 m (Figure 40).

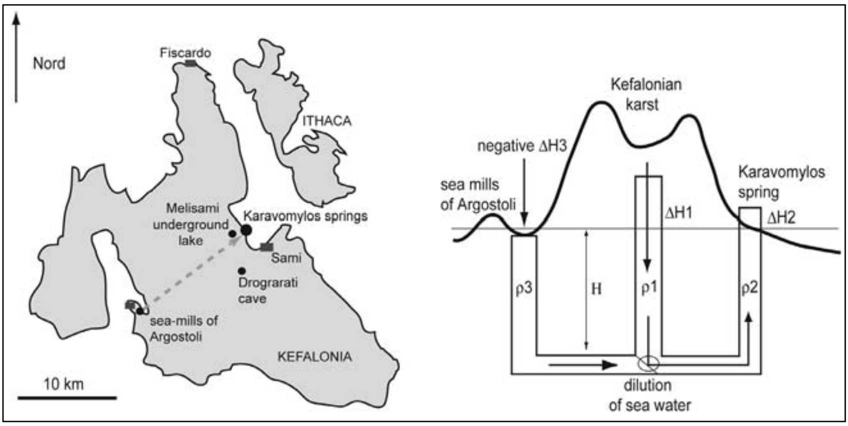


Figure 40 Model for the functioning of the swallow hole-resurgence system of the sea-mills of Argostoli (Kefalonia, Greece).

The system is perpetually in disequilibrium, since the karst is fed by precipitation. The pressure in the seawater column cannot increase, since density and height are constant. A regular influx of fresh water in the central column results in circulation towards the brackish column, causing a current between the rock mass and the springs of Sami. The influx of fresh water into the brackish column decreases its density and shifts the seawater column towards the interior of the system, maintaining the constant depression responsible for the karst passage's aspiration of seawater, which then mixes with fresh water.

In reality, the system must be considered hydrodynamically, and currents and tidal effects must be taken into account (Drogue, 1989). But velocities are low (1 $cm \cdot s^{-1}$), and the amplitude of the tides, already low in the Mediterranean, is dampened even more by the particular position of marine losses in an old polje that was submerged, where the shallow depth of water minimizes marine oscillations.

2.5 Example: Port Miou, Cassis, France

The submarine springs at Port Miou and Bestouan in the Calanques area (Marseille and Cassis) are two emergences draining the same aquifer (Figure 41). They have been known since the time of the Ancient Greeks. These brackish karst springs, despite having a discharge of approximately 8 $m^3 \cdot s^{-1}$, are not exploited. They make up the largest river between the Rhone and the Argens. They were the subject of scientific studies and speleologic exploration in the 70s, in the context of projects by the group "Société des Eaux de Marseille et BRGM" attempting to install an experimental catchment system (SRPM, 1978). Subsequent projects (1972–1975) did not, however, succeed in eliminating the residual salinity, which remained at almost 3 $g \cdot L^{-1}$, which has been attributed to leaching of continental evaporites (Vernet & Vernet, 1980). Yet, recent studies (Blavoux *et al.*, 2004) demonstrate that salinity of these brackish waters is entirely marine in origin. In addition, this salinity is present, in Port Miou, 2 km from the entrance, in a shaft that has been explored down to a depth of 179 m.

Figure 42 shows how the presence of this shaft can explain the failure of the dam, by allowing fresh water and seawater to mix near the terminal shaft. These springs show a discharge above what would be expected given their supposed drainage basin, which includes the Urgonian ring of the Beausset basin, as well as part of the Ste. Beaume, totalling approximately 300 km^2.

Inversely, it appears that to the north and to the east of the Beausset basin, despite a specific infiltration modulus of 8 $L \cdot s^{-1} \cdot km^{-2}$, the 1500 km^2 of Jurassic and Cretaceous limestone outcrops produce only around 5 to 6

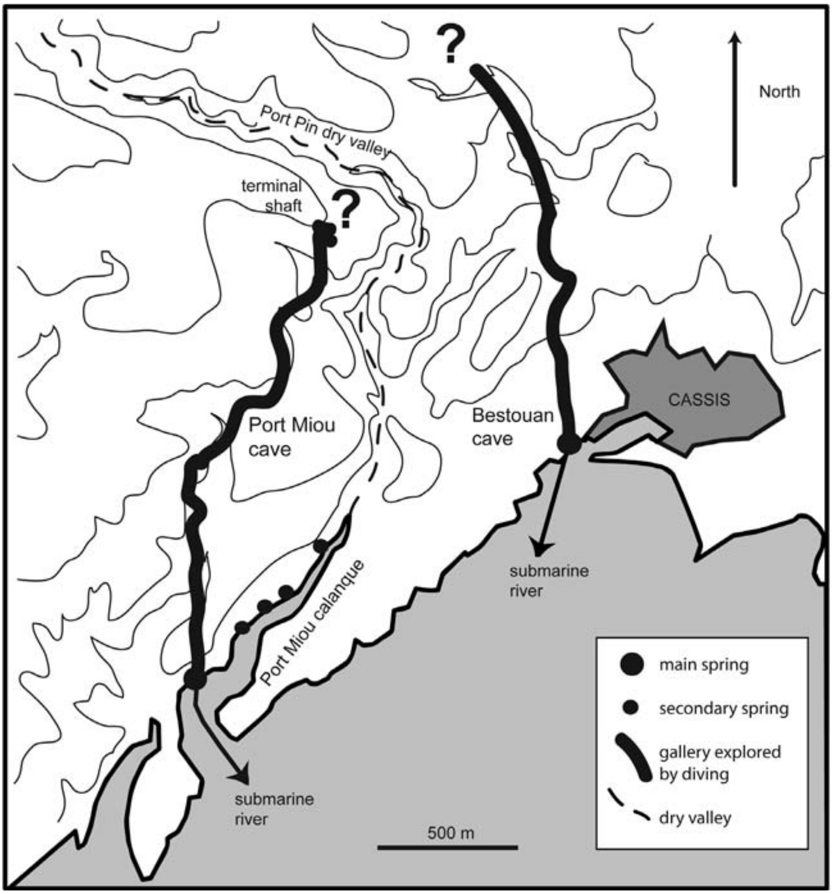


Figure 41 Location map of the Port Miou submarine spring (Marseille-Cassis).

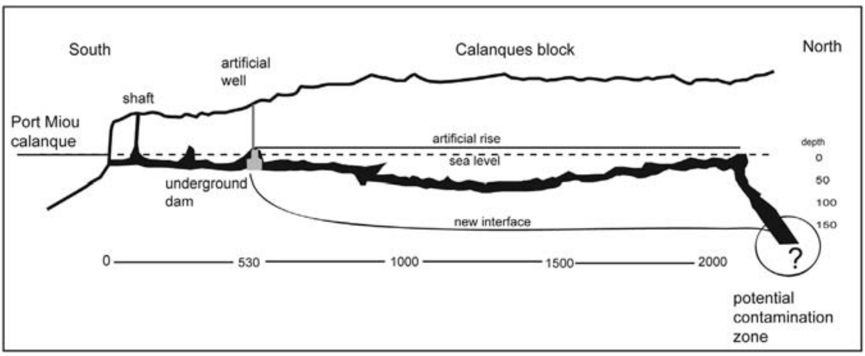


Figure 42 Longitudinal cross-section of the flooded passage of the submarine spring at Port Miou (Marseille-Cassis).

$m^3 \cdot s^{-1}$ of spring water (Cova & Durozoy, 1980). One is therefore forced to admit that a large part of Basse Provence has a water deficit of approximately 4 $L \cdot s^{-1} \cdot km^{-2}$. It is then tempting to imagine that half of the infiltrated water in the region feeds the excess discharge at Port Miou.

Keeping an average infiltration modulus of 4 $L \cdot s^{-1} \cdot km^{-2}$, a basin of around 1500 km^2 would be necessary to feed Port Miou (Figure 43). Such a basin could be drawn in a zone going up to the north, in the Arc basin, up to Sainte Victoire and extending to the east towards Brignoles. The discharge at Port Miou therefore lead one to imagine a gigantic deep karst system draining the entirety of Basse Provence. The spatial organisation of such a system imposes the imagination of a paleogeography very different from that of the present day.

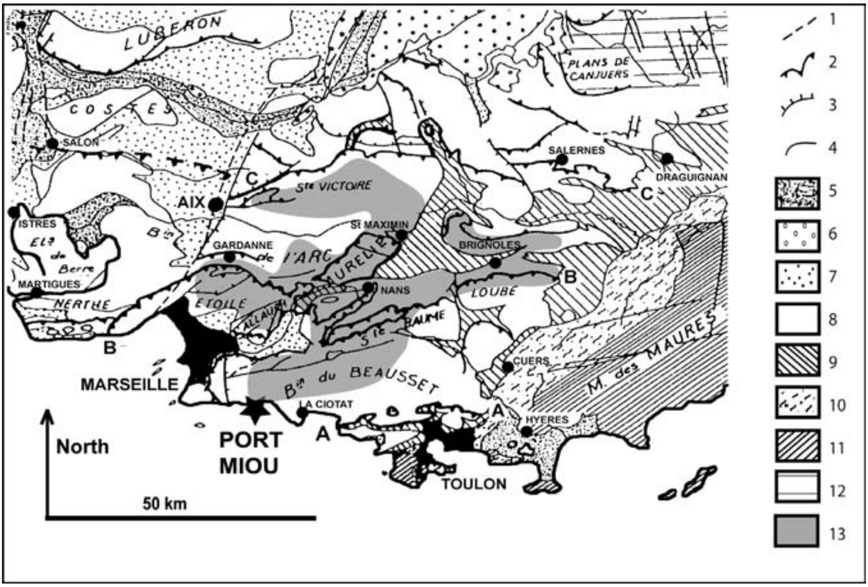


Figure 43 Hypothetical drainage basin for the Port Miou spring (from Blavoux *et al.*, 2004).

1-major crustal faults; 2-major overthrusts (A, B and C – erosion front of the principal nappes); 3-other faults; 4-normal contacts; 5-Quaternary; 6-continental Mio-Pliocene; 7-marine Miocene and lacustrine Oligocene; 8-Cretaceous and Jurassic limestones; 9-Triassic (limestone and evaporites); 10-Permian (sandstone and pelites); 11-Carboniferous and Variscan; 12- north-south subalpine chains; 13-supposed drainage basin.

Karst indicators, such as the depth of explored drains at Port Miou or the presence of a karst paleorelief at a depth of 150 m to the south of the Calanques (Collina-Girard, 1996), can be explained by a regional base level more than 200 m deep, below the current sea level. The same is true of the deep Submarine Cassidaigne canyon off the coast of Port Miou, which has a karst blind valley morphology and does not connect with any important continental valley, and could have been formed by the waters of the Port Miou paleo-spring 250 m deep (Figure 44). The whole area would then have evolved with a very low base level. Such paleogeographic conditions were observed during the major evaporation event in the Messinian. The lowering of the Mediterranean, which induced deep downcutting of the Rhône and the Durance streams, would have individualised two major karst systems, Port Miou to the south and Vaucluse to the north (Gilli, 2001). The Pliocene sea level rise and the accompanying sedimentation of continental valleys, by blocking deep drainages, forced water to use paleodrains with near-zero loss of head in order to adjust to the new base level. The marine

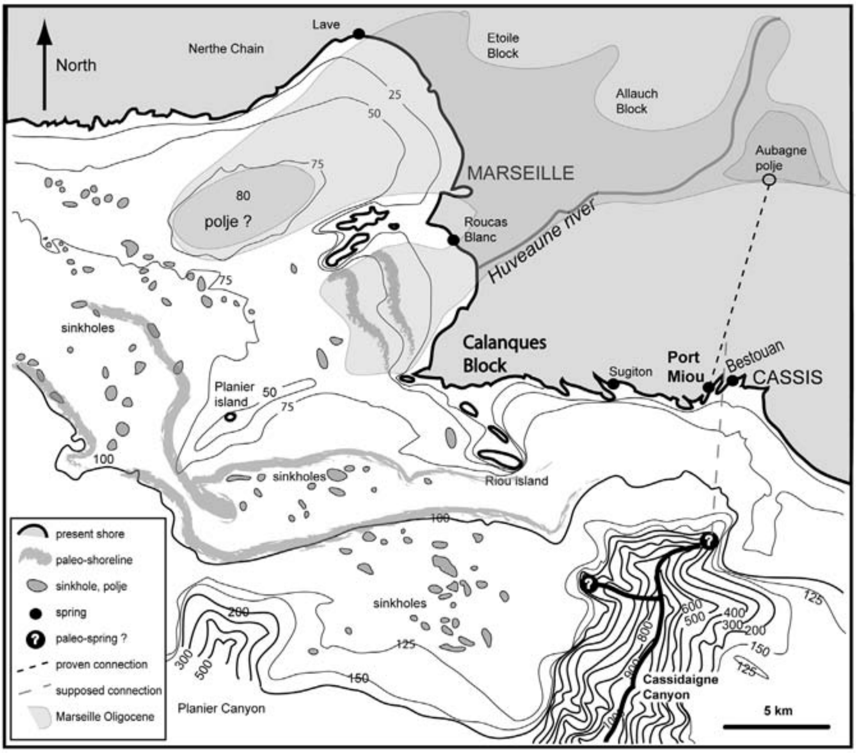


Figure 44 Submarine karst relief off the coast of Marseille and the calanques of Cassis (from Collina-Girard, 1996).

contamination at Port Miou could therefore have occurred through a paleo-gallery, as is suggested by a titanium anomaly discovered in the sediments of the Port Miou gallery (Cavalera *et al.*, 2010); the titanium could, indeed originate from the aspiration of red clay bauxite tailings, which are dumped in the Cassidaigne canyon.

In the region around Marseille, several coastal or submarine karst springs with a low discharge are warm (water inflows in the Rove tunnel 30°C, Arnette springs 30 to 35°C) (Gilli, 2002). With a gradient of 1°C per 30 m and an average surface temperature of 18°C, their salinity and their temperature can be explained by a marine contamination at a depth of around 350 m, and a sulfate-rich circulation near the geologic base level, which would support the Messinian hypothesis.

3 HYPER-EUSTATISM AND ITS CONSEQUENCES

Such a model has very important consequences for the exploitation of karst water around the Mediterranean, as it places the most transmissive zones, the most desirable ones for drilling, at a great depth, which must be determined individually for each case, as it depends on the maximum drop in base level but also on the location of geologic base levels.

In addition, this model allows for reevaluation, not only of coastal aquifers, but also of karst or alluvial aquifers in the interior of continents (Bini, 1994), as their geometry may have been influenced by Messinian downcutting (Audra *et al.*, 2003). This peri-Mediterranean model could also be extended to other parts of the globe, such as the Gulf of Mexico, where the presence of evaporites might reveal the closing and drying of the gulf.

Chapter A10

Thermomineral Water and Geothermal Energy

1 DEFINITION

Hot springs have been known since the ends of time and have been used since Antiquity for baths. Aside from their temperature, these waters generally have very particular characteristics: gases, smells, mineral content. Indeed, their increased temperature and pressure allows the dissolution of salts and gases which enrich the water in an unusual way. This water is then called thermomineral water. Its unusual properties are used in the hydrotherapy industry. Water, or the mud associated with it, are used therapeutically for bathing or in drinks.

There is no precise definition for thermal waters. Although the etymology of the word refers to temperature, its use in hydrotherapy calls upon the physical and chemical properties of the water. The definition given in the French dictionary of hydrogeology (Castany & Margat, 1977) is: "underground water which is naturally warm at its emergence (spring, artesian well) and is therefore usable for particular needs: hydrotherapy, heating."

The concept of temperature is itself delicate to evaluate given that water can appear more or less hot with respect to its environment depending on the seasons. The term thermal is used only if the water temperature is a few degrees higher than the average temperature of springs located at the same elevation. The concept of mineralisation is just as difficult to determine, as can be seen in the special case of saline coastal springs, whose properties are in fact linked to the contamination of continental aquifers by sea water. Similarly, a high mineral content can originate from the leaching of evaporites (sulfate or chloride enrichment).

2 THE ORIGIN OF HEAT

2.1 Juvenile waters

Mantle rocks contain around 0.3% water, which, through degassing, can reach the hydrosphere, carrying a characteristic assemblage of mineral salts.

Water is returned to the mantle via subduction zones. This water can then be returned to the surface through volcanism or it can feed deep hydrothermal springs in mid-oceanic ridges.

2.2 Secondary heating and mineralisation

However, these juvenile waters make up only a small percentage of the composition of thermomineral waters, which are essentially meteoric in origin. Water can, indeed, become heated by penetrating more or less deeply below ground, or by circulating closer to the surface in volcanic regions or in thermally anomalous zones. Blavoux and Letolle's isotope work enabled the proof of thermal spring water's meteoric origin (Figure 45).

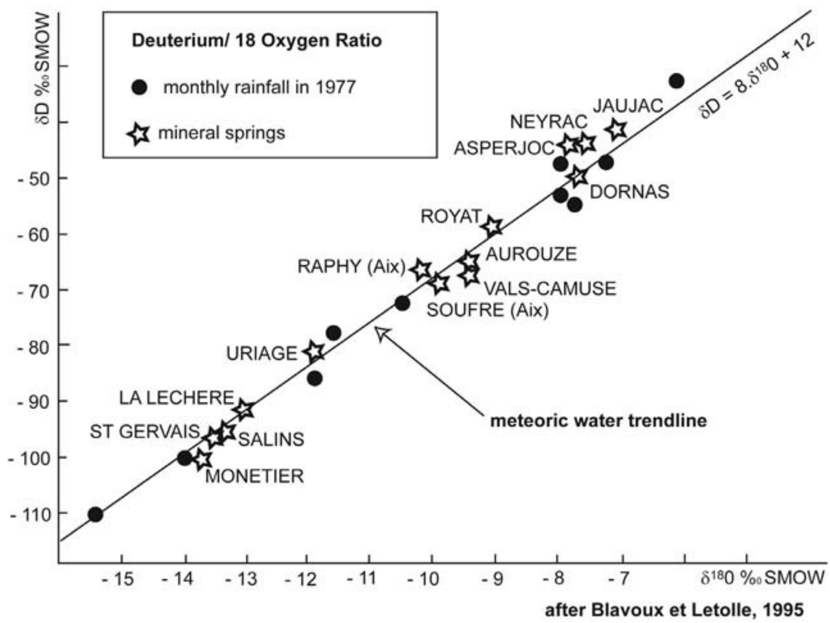


Figure 45 Isotopic analyses showing a meteoric origin for a few French mineral waters (from Blavoux & Letolle, 1995).

2.2.1 Deep circulation

As one descends through the Earth, the temperature increases gradually with a gradient close to 1°C per 30 m. Water circulating at depth therefore absorbs heat that it will then carry to the surface. At a depth of 5,000 m, the temperature is over 150°C and can often reach 200°C.

The increase in water temperature can also result from thermal anomalies closer to the surface.

It is difficult to know how far water can penetrate below the surface, and therefore what maximum temperature it can reach. The increase in pressure allows water to circulate as a liquid at temperature above 100°C. As it rises, it turns into vapor and can feed geysers.

2.2.2 Sources of mineralization

Mineralization increases with pressure. Castany (1998) cites values measured in the deep oil wells of the Parisian basin; for the deepest ones, the total mineral content is greater than that of seawater.

The increase in temperature can also increase the dissolution of certain salts, such as silicates, or, instead, favor their precipitation, like carbonates.

The residence time is also an essential factor, as certain dissolution reactions are very slow. The mineral content will therefore be a function of the maximum depth and of the residence time in the deep systems.

Table 7 Mineralization of water in the deep aquifers of the Paris basin (from Castany, 1998).

Location	Depth in m	Mineralisation in $g \cdot L^{-1}$
Chailly-en-Bière	1,690	9
Chailly-en-Bière	1,710	11
Perthes	1,815	18
Coulommes	1,890	29
Nangis	1,900	10
Nangis	2,265	80
Nangis	2,320	90
Château-Landon	2,240	110
sea water		35

2.2.3 Gas enrichment

Water can carry gases. According to Henry's Law, as pressure augments, dissolution increases.

Table 8 Solubility of Common Gases in Water (from Detay, 1993).

Gas	Solubility in mg·L^{-1}
Nitrogen (N_2)	23.3
Oxygen (O_2)	54.3
Carbon dioxide (CO_2)	2 318
Methane (CH_4)	32.5
Hydrogen (H_2)	1.6
Hydrogen sulfide (H_2S)	5 112

One notes, in this table, the high solubility of CO_2 and H_2S, which explains the prevalence of sparkling mineral waters and the sulfurous smell common to hot springs.

Enrichment with gases has effects on mineralization. The chapter on karstification (A.8) details the importance of CO_2 in the dissolution of limestone. The CO_2, which acidifies water, normally comes from the soil atmosphere. Karst then evolves from top to bottom and forms epigenetic cavities. CO_2 can also originate at depth, resulting in the formation of a hypogenetic karst. The cavities then form from bottom to top. Speleologic exploration has enabled the study of a number of non-functioning hydrothermal systems (caves of Rhar Kab Shrir, Algeria; Collignon, 1988), the high temperature and the presence of gases preventing the study of active systems.

Upon their exit, thermomineral waters, subject to a decrease in temperature and pressure, experience a shift in their chemical equilibrium towards precipitation reactions. Water degasses and becomes sparkling; a whole series of mineral deposits form near the spring. The accumulations of white tuff at Pamukkale (Cotton Castle), in Turkey, are one of the most famous examples of hydrothermal calcite deposits.

A similar mechanism depends on H_2S, originating at depth, to carve out the caves in the southwest of the United States (Hill, 1987). By combining with H_2S from hydrocarbon deposits, groundwater becomes acidic, dissolves limestone, and carves out galleries. The acid corrosion creates gypsum, which is deposited in the passageways and allows the formation of remarkable concretions (Hill & Forti, 1997).

$$H_2S + 2\,O_2 \rightarrow 2H^+ + SO_4^{2-}$$

$$2H^+ + SO_4^{2-} + CaCO_3 + 2\,H_2O \rightarrow Ca\,SO_4, 2H_2O\ (\text{gypsum})\downarrow + CO_2\uparrow$$

The cave systems are created *per ascensum*, and can have a characteristic cauliflower shape, or can form labyrinths. The gypsum created in the reaction is deposited inside the passageways of numerous cavities in the Carlsbad region (New Mexico, USA). One example, the Lechuguilla system, extends over more than 150 km and reaches a depth of 500 m.

2.2.4 Problems in the exploitation of thermomineral water

Water originating at depth can pass through other aquifers as it rises towards the surface and can mix with water of varying quality. It can therefore lose its original characteristics and see more or less alteration of its quality. Establishments exploiting this type of resource must be careful to maintain a constant and irreproachable standard of quality. Catchment systems must therefore extract the thermomineral water before it mixes with surface water.

3 GEOTHERMAL ENERGY

Thermal energy being present below ground, it is tempting to use it as is or to transform it into electrical energy. The first attempts to produce electricity took place in Italy at the beginning of the 20th century. Geothermal energy is greatly used in Iceland, where, thanks to heated greenhouses, bananas can be produced for the European market. 40% of the population depends on geothermal energy for heating, and this energy also serves to produce 30% of the country's electricity. Iceland benefits from a fortuitous location, on the Mid-Atlantic Ridge, the site of active volcanism, but in other areas of Europe, the temperature gradient can reach 1°C for 20 m.

The heat held in 1 km^3 of granite at a depth of 5,000 m can, through the injection and heating of water to 200°C from an initial temperature of 20°C, produce the same amount of energy as 1.3 million tons of petroleum, or the consumption of a 10 MWe electric plant for 20 years. The potential resources in Europe have been estimated by Shell international to be 125,000 km^3. Geothermal energy could therefore become an important European resource. It currently provides 1.5% of Italy's energy.

Depending on the temperature, resources are generally classified as one of 5 different types (Table 9).

Table 9 Different Types of Geothermal Energy.

Type	Temperature in °C	Geologic setting	Depth in m	Use
Very low energy	< 30	Shallow aquifers		heat pumps
Low energy	30–100	aquifers	500–2,500	thermal heating
Medium energy	90–150	deep aquifers, thermal anomalies	2,000–3,000	heating, electricity
High energy	> 150	aquifers in volcanic structures		electricity
Deep geothermal energy	> 150	deep dry rock	3,000–5,000	electricity

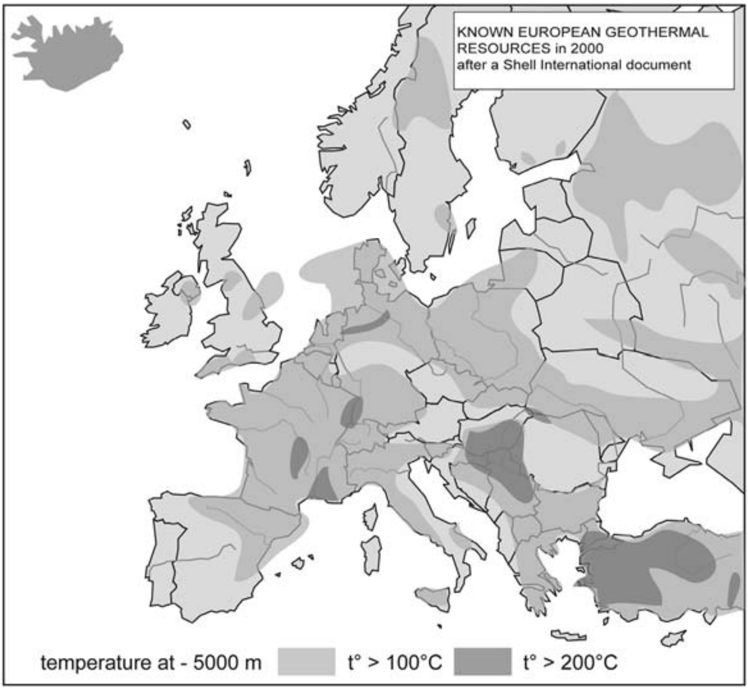


Figure 46 Known European geothermal resources (from Shell International).

It is considered that 100 $m^3 \cdot hr^{-1}$ of low energy can heat 1,000 to 1,500 households. In France, the low energy sectors are the aquifers in the Paris and the Aquitaine basins, which provide heating for around 20,000 households. The medium energy sectors are the thermal anomalies of Alsace and Auvergne (Figure 47). High energy is present in the volcanoes of the DOM. A power plant is in place in Bouillante (Guadeloupe island), and research is being done by the BRGM (French Geological survey) in the Lamentin Plain (Martinique island), as well as in Cilaos and Salazie (Réunion island).

The cost of exploiting geothermal energy is very low, but deep drilling is very expensive, and problems with corrosion and political maneuvering slow development.

Different exploitation practices have been developed, according to the principle of recuperating fluids from the hot region.

In low energy environments, hot water can be extracted from the aquifer through pumping, used, and then discharged into the natural environment. The Radio House in Paris is heated in this way thanks to the 27°C water in the Albian aquifer, pumped up from a depth of 600 m since 1963. The cooled water then goes into the sewer network. This does, of course, pose the problem of the quality of the water being disposed of, as water from deep

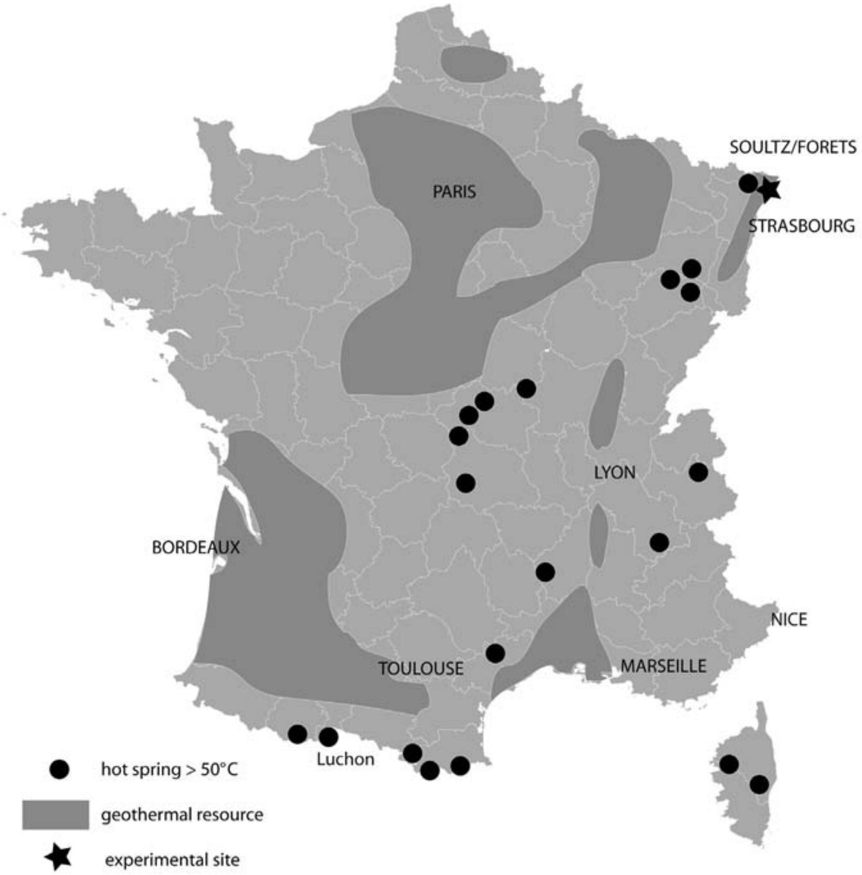


Figure 47 Geothermal resources in metropolitan France.

aquifers can have a very high mineral content; so the doublet procedure can be used as well, where the cooled water is returned to the aquifer.

For medium energy resources, several systems are under development at Los Alamos (United States), Rosemanowes (United Kingdom), and Hijiori (Japan). Depending on the context, several terms are used: HDR (Hot Dry Rock), HFR (Hot Fractured Rock), or HWR (Hot Wet Rock), the concept being to inject cold water into a hot fractured rock mass, and then to pump up the heated water.

In France, the HDR system is under construction in Soultz-sous-Forêts (Bas Rhin). Experiments done since 1997 (Gentier & Genter, 2010) showed that it was possible, by injecting pressurized water in 5,000 m deep boreholes to stimulate natural fracturation, in order to enable artificial circulation of water, heated to 200°C, between two deep boreholes. The site is located on the edge of the Rhine Graben. Since 2005 a triplet of deep boreholes enables the injection and the circulation of water into fractured granite. The main problems were induced earthquakes, corrosion and difficulties to clean the granite fractures to enable the water circulation between the boreholes. The water is laterally collected by two pumps (12 and 3 $L.s^{-1}$) and led to a thermal exchanger, which powers an electric turbine with steam (Figure 48). The first electricity has been produced in 2008 and is now delivered in the French electricity network. A larger plant, with three injection wells and six collection wells, will be built in order to increase production to 25 MWe.

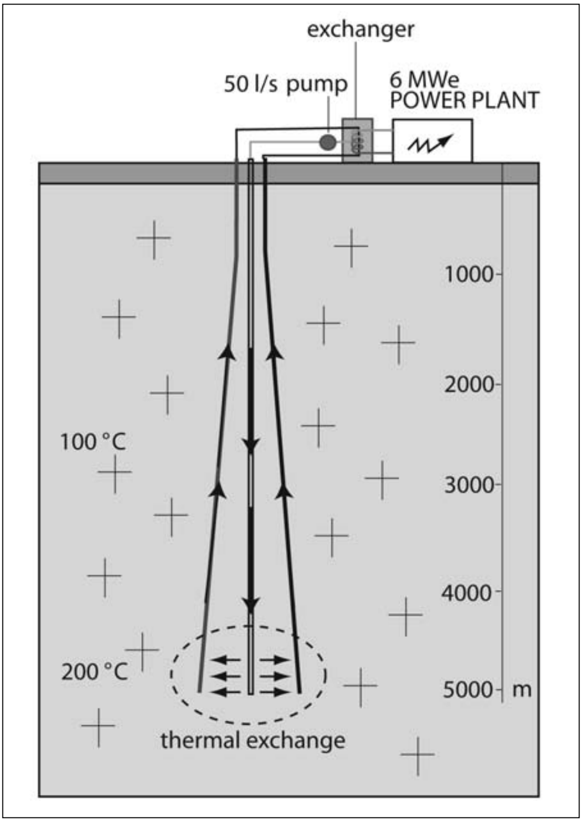


Figure 48 Conceptual mechanism at Soultz-sous-Forêts (Bas Rhin) (from Baumgärtner, 2002).

High energy sites are used in Iceland and in the USA, in Northern California, which is home to the largest geothermal power plant in the world: the Geysers (2000 MWe), one of the sources of energy for San Francisco. Its capacity is, however, currently limited to 1,200 MWe due to a decrease in the vapor flux.

Chapter A11

Water Quality

The quality of groundwater is the result of a natural mineral content (biogeochemical background noise), to which are added anthropogenic substances (pollution).

1 NATURAL CHARACTERISTICS

Groundwater acquires its physical and chemical properties as it passes through different sections of the water cycle: atmosphere, soil, surface water, unsaturated zone, aquifer.

The atmosphere carries, among other things, chlorides and sulfates, sodium and potassium from marine aerosols, but also compounds carried as atmospheric pollution (sulfates, nitrates, hydrocarbons), originating from the burning of fossil fuels (coal, petroleum): thermal power stations, domestic heating, cars, or dust from bare soil (cultivated or desert zones).

The soil, as well as weathered surface terrains (weathering mantles, epikarst), is where evaporation can act, concentrating conservative tracers from precipitation. The available water capacity (AWC) is not only a reservoir for water, but also for chlorides, nitrates, sodium, potassium, which evaporation concentrates in the soil and that the next effective precipitation will lixiviate towards the unsaturated zone.

The soil is also the first interface between water and minerals: calcium or magnesium carbonates and sulfates are dissolved there. Silicates weather into clay, releasing calcium, magnesium, sodium, and potassium.

These dissolutions and hydrolysis reactions are possible thanks to the presence of carbon dioxide in the soil produced by biologic activity, for example, respiration by microflora and microfauna (bacteria, roots).

In the soil, the decomposition of organic material produces CO_2, nitrates, potassium, and humic and fulvic acids. These last two mineralize over time (CO_2), thus creating the potential for carbonate dissolution and for the alteration of silicates in the unsaturated zone and even in the saturated zones of underlying aquifers.

The unsaturated and saturated zones also represent water-rock interfaces, in which water becomes enriched in minerals.

2 NATURAL CONTAMINANTS

2.1 Dissolution and alteration

Due to slow kinetic reactions, silicate weathering generally produces a moderate level of mineralization, with reaction times not exceeding a few months or years. The weathering of certain primary schists, on the other hand, in the Anti-Atlas (Morocco), containing 10,000 ppm of Cl^- in their unweathered state, can provide 4,300 $mg \cdot L^{-1}$ of Cl^- to water.

Carbonate dissolution, controlled by the calco-carbonic equilibrium (limiting the solubility of calcite and dolomite), does not generate excessive mineralization either.

Evaporites, on the other hand, (sulfates, chlorides, nitrates, borates), with a very rapid dissolution reaction and composed of highly soluble minerals (gypsum $CaSO_4 \cdot 2H_2O$, anhydrite $CaSO_4$, niter or saltpeter KNO_3, borax $Na_2 B_2 O_7, 10 H_2O$), are likely to send the ions they are composed of, into solution as natural contaminants: they can reach concentrations of several $g \cdot L^{-1}$ of SO_4^{2-} and several hundreds of $g \cdot L^{-1}$ of Cl^-. In arid and semi-arid regions (including the Mediterranean regions), these ions make some surface and groundwater resources unusable. In France, the Triassic and Oligocene evaporites in Provence and the Jurassian border are examples of this phenomenon. Concentrations of 10 $g \cdot L^{-1}$ can be found at the Eau Salée borehole in Malaucène (Vaucluse), located on a Triassic diapir.

The evaporation of surface water (sebkhas, salt pans) and soil moisture in dry tropical climates causes salt concentrations on the surface and in the soil. For example, salty efflorescences can be seen at the surface of outcropping aquifers in Camargue.

2.2 Salt water intrusions

Another source of natural contamination is the presence of a fresh water-salt water interface below ground. Even though they are in static equilibrium, lenses of fresh water « float » on salt water from seas or estuaries, and groundwater flow can result in the mixing of the two in a heterogeneous environment (see chap. A9).

2.3 Confined aquifers

Confined aquifers, which have a low Redox Potential due to the consumption of dissolved oxygen, then of nitrates, by oxidation reactions with sulfur or with organic material, are sites where undesirable metals go into solution (iron and manganese). If the reduction conditions are more severe, ammonium, sulfide, and methane can appear.

2.4 Natural organic material

Alluvial aquifers, where rivers have brought in various organic debris (wood, leaves), can have elevated total organic carbon (TOC) or hydrocarbon levels, of the same order of magnitude as those caused by low levels of anthropogenic pollution.

3 ANTHROPOGENIC POLLUTION

Human activities produce gaseous, liquid, and solid wastes that are dumped into the environment (atmosphere, surface water, soil, groundwater) and which, directly (dumping) or indirectly, will affect groundwater. Vertical (recharge) or lateral (limits on inflows: riverbanks) infiltration, and leaching of the the atmosphere and of the soil, will all contribute to the degradation in quality of resources.

3.1 Domestic pollution

The principal pollutants are salts (sodium chloride from ion-exchange resin devices in water softeners, clothes irons, or dishwashers), surfactants (borates, polyphosphates from detergents), bacteria (*Escherischia coli*, fecal coliforms), hormones (birth control pills). Aside from ions in solution, domestic pollution also includes particles in suspension, particularly organic material. In addition, there are do-it-yourself repair materials (paint thinners, motor oil), and fertilizers and pesticides, which are heavily used in private gardens.

3.2 Urban pollution

Urban pollution includes runoff from impervious surfaces, misleadingly termed rainwater, residues from treatment of collected liquid domestic pollution, and residues from treatment of household waste.

Roofing collects the airborne fraction of unburnt heating oil (hydrocarbons, sulfates), and paved surfaces (roads, parking lots) collects hydrocarbons (lubricants), suspended particles (dust from brakes and clutches), heavy metals (zinc from paint, and previously lead from fuel), salt during the winter. Rain following a dry period washes out the pollutants on paved surfaces.

Residues from treating household waste include ash from incinerators (in the favorable event that incineration is total, air pollution is still a concern), and residue from smoke scrubbers (REFIOM). If these easily-leached residues, likely to return numerous mineral (heavy metals, salts) or organic (dioxins) pollutants to the environment, are sometimes stored in impermeable sites, where effluents are collected and treated, some were, for a long time, dumped into vulnerable areas (example: sinkholes of the Besançon limestone plateau). They are still currently used to build road embankments.

3.3 Industrial pollution

Diverse in its composition, industrial pollution includes liquid effluents, leakage from storage areas or pipelines, and solid residue which has often, in the past, been used to build embankments. Although the liquid effluent now undergoes specific, effective treatment, leaks are still difficult to detect and control, and abandoned sites result in industrial wastelands with polluted soil likely to contaminate any underlying aquifer. For example, in the Rhone valley, an aquifer covered by such material now produces, for a water union supplying 200,000 consumers, water polluted by methylbenzenes and chlorinated solvents.

3.4 Agricultural pollution

Agriculture can produce point pollution, such as leakage from livestock farming by-products: manure and silage effluent, or fertilizer or plant protection product spills, during the preparation of material to be spread or the rinsing of material. In addition, the fertilizers and pesticides spread onto fields make up a diffuse pollution source, the vegetation and soil serving as a pollutant reservoir, easily mobilized by infiltrating water. This pollution is put into circulation when meteorological conditions are unfavorable, for example, when a 30 mm rainfall follows a fertilizer application. In addition, if the phenological stage of the culture is not nitrogen-fixing, the stock accumulated in the soil will all be intact when it rains. So the spreading of liquid cow manure during a snowy period in the Haut-Doubs results in a pollution spike in the underlying karst groundwater reserves, while the same input on a prairie in full growth is significantly dampened. The solution is to increase the storage capacity of farmers' tanks, so that they can store their winter waste, and to educate them in environmentally friendly practices. In addition, the soil reacts with the molecules initially used on cultures, and certain phytosanitary products can transform into something else (for example, glyphosate into amino-methyl-phosphonic acid—AMPA, formerly atrazine into desethyl-atrazine—DEA).

4 CONTAMINATION CAUSED BY HUMAN ACTIVITY

The over-exploitation of groundwater resources, that is, the mining of a discharge higher than the normal recharge flux, can cause the inflow of highly mineralized water (salty, fluoridated). Due to this phenomenon, the wells exploiting the infra-Toarcian aquifer in Deux-Sèvres must not draw on the base of the aquifer, which has a fluoride content of about 7.5 $mg \cdot L^{-1}$.

5 SELF-PURIFICATION

Self-purification is a set of hydraulic, physical, chemical, and microbiological processes, with the effect of reducing the concentration and/or mass of an injected contaminant.

Contaminants can behave in several ways (Figure 49):

- the concentration does not significantly decrease as the contaminant moves downslope. In this case it is called a conservative (or conserved) contaminant, and the transfer occurs through convection (or advection). Example: the chlorides contaminating catchment systems in the Alsace aquifer downstream of potassic slag heaps;
- the concentration decreases, but the total mass of contaminant remains the same: only hydraulics played a role, through diffusion, dispersion, and dilution (Figure 50);
- a special case of the preceding behavior is the presence of a delay between the passage of the water and the passage of the contaminant. This delay is due to sorption/desorption events;

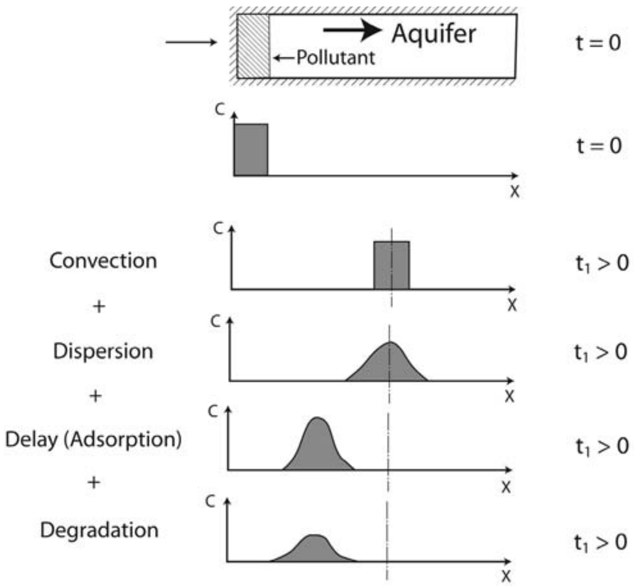


Figure 49 Transfer of a contaminant downslope.

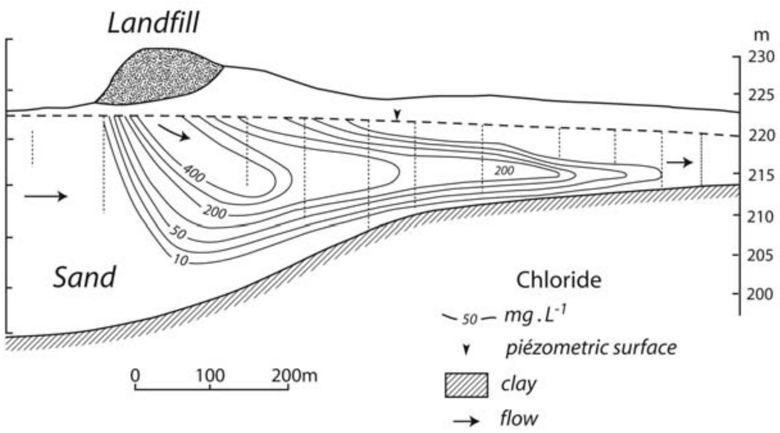


Figure 50 Pollution plume downslope of a landfill.

- finally, the mass of contaminant in the hydrosystem can decrease,
  - in the best case scenario, the contaminant degrades into a non-toxic compound through physical or chemical reactions, or through microbial attack. For example, nitrates in a confined aquifer can be reduced to non-reactive nitrogen gas.

- in a less desirable scenario, the contaminant transforms into another undesirable molecule. The model example is that of the pesticide atrazine, which remains in the environment as desethyl-atrazine.
- another still-risky scenario is that of contaminants held stable by their environment, but likely to be released if there is any change in physical or chemical conditions. For example, certain heavy metals can be adsorbed and then desorbed due to a natural or anthropogenic change in the pH or the Redox Potential of the water.

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B

TOOLS AND METHODS OF HYDROGEOLOGY

Hydrogeology can be considered at any scale:

- at the regional scale, in the general search for understanding of the regional groundwater distribution and available resources;
- at the local scale, to respond to a specific need for a new resource or in the context of a development or civil engineering project;
- at the point scale, to resolve a specific problem or an unforeseen difficulty (construction site, drainage, strengthening an instability).

Hydrogeology can concern itself with all of the aquifers in a region, whether they be totally independent or interconnected in a more or less complex fashion. It can also be concerned only with certain well-definied aquifer layers, deep, shallow, or very shallow (cover or slope aquifer).

The goal of a hydrogeologic study is to provide a good regional understanding of the natural context, and to define the limits of the hydrogeologic structures and systems under consideration, then to precisely examine the problem while synthesizing and critically examining the various data collected, while still taking care to integrate them logically into the natural context previously described.

The approach is therefore mainly progressive, and evolves in successive phases, from the general to the specific. It aims to refine working hypotheses and to select the most plausible ones as more information comes to light. It can even, in certain cases, continue until the completion of the project and benefit from the final verifications allowing for its total adaptation to real conditions, revealed by the construction.

Whatever its degree of finality, the investigation is undertaken following the same procedure, even if disparities or adaptations are necessary to take into account the scale of the project, characteristics unique to its setting, and the goals of the study. The methods to be used combine classical geologic tools with entirely hydrogeologic investigations. The direction of research is generally determined by the following succession of goals:

- the identification of the principal hydrogeologic formations (permeable, semi-permeable, impermeable), as well as their extent, and the nature of the principal aquifer (porous, fractured, or karst environments);
- the detailed analysis of the reservoirs under consideration in terms of geometry and heterogeneity;
- the definition of infiltration, circulation, and restitution conditions for groundwater;
- the spatiotemporal relationships that could relate these aquifers between themselves and with their environment (lakes, rivers, sea);
- a global analysis and an overall outline of underground circulations and of the exchanges revealed.

Chapter B1

Preliminary Documentation

It is necessary, for all projects, to collect and exploit existing documentation from the very beginning, as it allows the inventory and critique of the range of preexisting knowledge.

1 Topographic and geologic maps

Topographic maps exist at different scales, although 1/50,000 and 1/25, 000 are particularly common in the French territory, where they are created and distributed by the IGN (National Geographic Institute). They provide precious infomation on the topography and morphology of the study area, as well as on the hydrographic network and on the position of characteristic features (springs, wells, cavities). In certain regions, 1/10,000 and even 1/ 5,000 maps cover specific sectors in greater detail. The old master plans at the 1/20,000 scale, when they can be found, are often high-quality sources of information. The same is true of cadastral surveys, which can help determine the location of wells and springs. Toponymy can also help direct geologic and hydrogeologic approaches, particularly in old documents, given the frequent changes in place names on recent documents.

Geologic maps are distributed in France on the 1/50,000 and 1/ 80,000 scales by the BRGM (French Geological Survey). They give an understanding of the regional geologic setting and of the tectonic style and the lithostratigraphy of the study area. They remain very general, although variable depending on the survey, and the attached review can provide useful information, as well as a bibliographical starting point.

Hydrogeologic and geomorphologic maps concerning a certain number of regions (BRGM and universities) exist, and can usefully complement the data being collected at this stage.

2 Inventories and files

The BRGM underground database covers the French territory and can be consulted in each department. It locates and provides data on multiple objects (boreholes, wells, springs, geophysical surveys), but is not necessarily very up to date.

Other specific inventories exist, for boreholes or water bodies, but in a sparse fashion. They can be asked for and consulted in the most directly concerned organizations (MISE, DDAF) or in local groups (Departmental General councils, townships, inter-town alliances, community of townships).

Hydrometric files can concern the study area (data on discharge and water level of rivers and springs over time, piezometric surveys of aquifers). They can be found with the DREAL (French Environmental administration) for the national survey network, with the BRGM for specific surveys of certain aquifers, and with EDF (French Electricity Company) for hydrolectric systems.

Files on karst cavities and on tracer test results, generally in municipal archives, are often put together and even published by local speleology clubs, by CDS (Departmental commitees on speleology) and by certain universities specializing in karst systems.

Finally, it can be useful to consult Météo-France (French forecast administration) to determine the positions of available weather centres, as well as the nature and precision of the measurements taken, in order to evaluate their representativity with respect to the study area.

3 Publications and unpublished reports

A bibliographic search is necessary at this point in order to complete the existing understanding of the study area, beginning with geologic and hydrogeologic publications in the area under consideration (theses, colloquium and conference papers, specialized or regional reviews).

Certain regions are rich in unpublished reports, likely to provide very precise information, but accessing them may require time-consuming research, sometimes unsatisfying requests for permission, and a good dose of persuasion. The search must then turn to universities and related research laboratories, to certain state services (Water Agency, DREAL), to local groups or large public or private organisations (Departmental councils, townships, BRGM, EDF, railways and highways companies, water providers) and to consulting firms servicing the area.

Old archives lie hidden away in the drawers and folders of the aforementioned groups. Some of them can provide an unexpected richness of information, but access to them is never easy and rarely allowed, unless one demonstrates a particularly relentless persistence.

Chapter B2

The Study of the Geometry of Aquifers

An understanding of the geological context is the indispensable base for any hydrogeologic study, and the hydrogeologist must first be an experienced geologist. Indeed, a knowledge with a maximum of precision of the geometric limits of aquifers, which determine the storage capacity of groundwater and control its circulation and discharge, is absolutely necessary. This purely geologic analysis serves to construct a more or less refined model which will then support further reflection.

Multiple methods can be used, and they are presented in order of their logical apparition in the context of a hydrogeological study.

1 FIELD OBSERVATIONS AND SURVEYS

Fieldwork is indispensable in order to gain a detailed understanding of the local context, and requires an appropriate topographic map onto which *in situ* observations and measurements may be transposed. Commercially available maps may be adequate for relatively large-scale regional projects, but more precise topographic surveys are needed for a detailed understanding of the geology of the site, and for smaller-scale projects. These maps are then specifically created, often by photogrammetric restitution of aerial photos and ground-truthing, at a scale appropriate to the goals of the study (1/5,000, 1/2,000, 1/1,000). When the study area includes a coastline, bathymetric maps can be highly useful.

Examining aerial photographs with stereo lenses allows a useful preliminary morphological survey, and an understanding of the general structure and of the fracturation of large rock units. Obtaining more precise data requires a high level of experience with this type of interpretation. Aerial photos are distributed at different scales which offers both black and white and color photographs taken at various points in time. They can be taken for specific projects, in the case of large study projects. The use of satellite images (Landsat, Spot, Quickbird, Ikonos,…) is now common.

Geologic surveys must extend past the limits of the study area, and aim to cartographically pinpoint the extent of aquifers and, particularly, their contacts with bordering impermeable terrain and/or with other reservoirs. They consist of identifying and positioning a maximum number of direct observations on the map, both at natural outcrops (steep slopes, rises, shelves, little valleys) and at new or old construction sites (excavations, rubble heaps, quarries, passageways). Field mapping is directly aimed at the identification and mapping of different formations, the survey of eventual rock-type variations and zones of weathering or superficial covering, and of structural measures (strike and dip, joints, faults), which are severely lacking in commercial geologic maps.

Cartographic boundaries do not always coincide with stratigraphic limits, tending instead to identify lithologic units in terms of their hydrogeology (impermeable formations, porous, fractured, or karst reservoirs).

It is equally important to take into account the paleogeographies that succeeded each other in the study area, in order to well understand possible variations in thickness and facies characterizing certain formations, to be able to reconstitute the geometry of glacial or fluvial sediments, and to identify spatio-temporal relationships between the sea and coastal aquifers.

Certain normal or abnormal contacts can be revealed by morphologic (rises and shelves in the landscape) or hydrogeologic (dogleg turns in valleys) clues, but also by contrasts in vegetation or weathered soils.

In areas with very dense vegetation, paths are sometimes cleared in order to be able to see the nature of the terrain. It can also be difficult to precisely locate certain important observations in such areas, as well as in topographically rugged areas, which may require the intervention of a geometer or the use of a GPS.

The mapping can be completed by locating boreholes and/or geophysical surveys found during the preliminary research phase, as well as by hydrogeologic features identified through archives and on the ground (springs, wells, water boreholes, karst cavities, losses). When inventorying these features, it is always very helpful to ask the local people and the well users.

The exploration of natural cavities (caves, chasms) developed in karst terrain can also be helpful in determining the cross-section of geologic series and the position of major tectonic accidents. When they are very large or highly-developed, these underground networks can indeed provide first-class lithologic cross-sections, and can even serve as calibration by allowing *in situ* observation of the basal limit of the aquifer and the roof of the underlying impermeable unit.

- Examples of networks whose deepest sections follow the roof of the underlying impermeable layer: Berger chasm in the Vercors, Pierre-Saint-Martin network in the French-Spanish Pyrenees, Piagga-Bella network in the French-Italian Marguareis;
- Examples of networks reaching overthrusts in the subalpine units of the Alpes-Maritimes: Abel chasm on the Saint-Vallier plateau and Calernaum chasm on the Calern plateau (Figure 51).

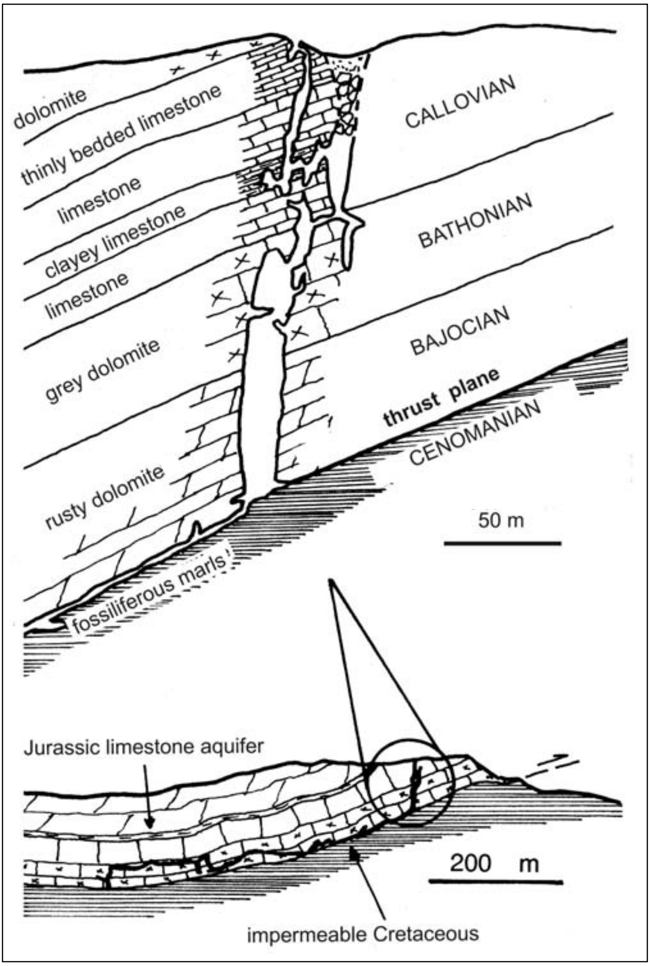


Figure 51 Cross-section of the Calernaum chasm, which passes through the Calern plateau all the way to its impermeable base and then follows the basal overthrust of the unit (Alpes-Maritimes, Cipières) (from Gilli, 1995).

The preliminary research generally leaves more or less important uncertainties, particularly in areas where the geologic formations are not directly accessible (vegetative cover, superficial deposits, urbanisation and privatisation of land). The classic survey can also reveal its limitations in very difficult natural contexts and enables various interpretations (fluvial or glacial erosion, slopes entirely masked by scree, gravitational reworking of slopes, very complex structure).

The remaining unknowns are then clarified using other techniques, the choice of which is dictated by the goals of the study, but also by the accessibility of the study area and by the project budget. The most reliable methods provide *in situ* observation and representative samples (coring, wells, pits, galleries). They allow a paleontological identification of the series in question (when it is justified) and a calibration reference for indirect methods (geophysical surveys, destructive boring, well logging).

2 GEOPHYSICAL PROSPECTING

2.1 General characteristics

The principle of geophysical prospection is to determine, based on measurements taken on the ground, the physical characteristics of the bedrock and to deduce information on its makeup. A number of methods exist based on the physical parameter in question.

2.1.1 Electrical methods

a) Spontaneous polarization or self-potential (SP)

The natural electric currents tied to the movement of water in the soil (infiltration, groundwater flow) or to the differences in potential between different aquifers are measured. They can then highlight fractures draining aquifers.

b) Electrical resistivity method

This method is based on the study of the electrical conductivity of rocks, which is a direct function of its water content. What is actually being measured is the electrical resistivity (the inverse of conductivity), which is expressed in ohm·meters ($\Omega \cdot m$). The resistivity of formations varies by a few

Ω·m for mud or muddy clay, a few tens of Ω·m for clay, marl, or composite terrain, and by several hundreds or thousands of Ω·m for limestone, granite, or dry gravel.

The principle is to inject a direct current of intensity I into the soil between two terminal electrodes A and B (emission line), and to measure the difference in potential V created between two intermediate electrodes M and N (reception line). The intensity I is read from an amperemeter and the difference in potential V is measured with a potentiometer (Figure 52). The four electrodes are aligned and set up symmetrically with respect to the center of the arrangement. The Schlumberger setup is most commonly used, where the distance MN is small compared to the distance AB. This procedure enables the determination of the apparent resistivity of the terrain ρa, calculated using the equation $\rho a = k \cdot V/I$, where k is a coefficient dependent on the setup of the electrodes.

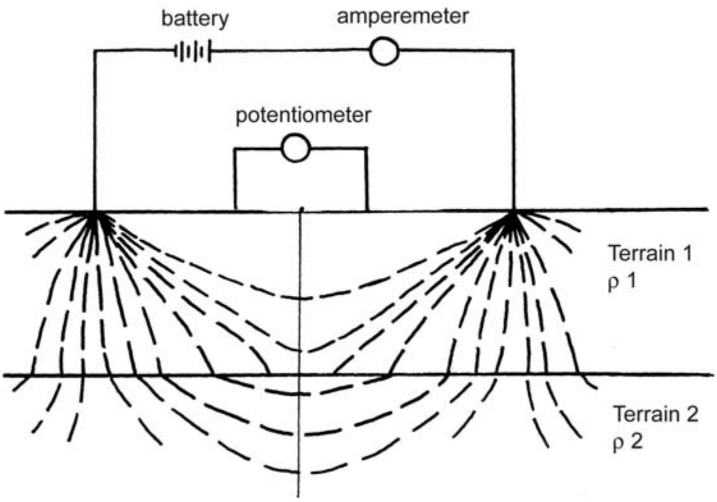
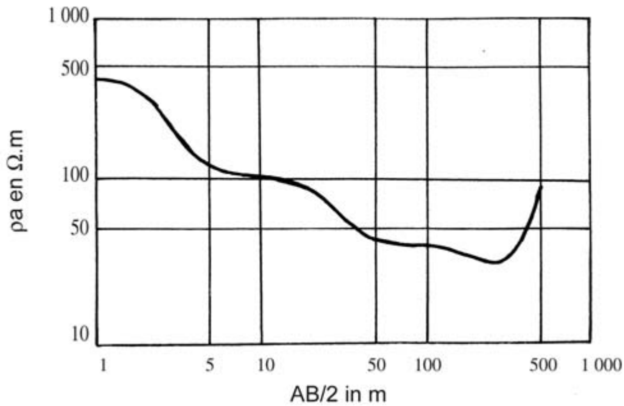


Figure 52 Principle of an electric survey.

Electric sensing can measure the apparent resistivity by progressively increasing the distance between the electrodes A and B and the center, and therefore increasing the depth of investigation below the measuring station. By transferring the apparent resistivities calculated based on the length AB/2 onto a bilogarithmic diagram, one obtains a curve characteristic of the survey performed (Figure 53). It can be interpreted in order to deduce the actual resistivity and the thickness of each formation under examination, by using catalogs of existing curves, in the case of small emission lines. For larger emission lines, however, more complex methods (auxiliary point method) or computer programs (allowing the optimization of interpretations based on the available data) are required.



Terrain 1	ρa = 480 Ω.m	thickness = 1.25 m	dry alluvium
Terrain 2	ρa = 105 Ω.m	thickness = 11.60 m	saturated alluvium
Terrain 3	ρa = 35 Ω.m	thickness = 82.40 m	Turonian marly limestone
Terrain 4	ρa = 15 Ω.m	thickness = 109.75 m	Cenomanian marl
Terrain 5	ρa = 2 000 Ω.m		Jurassic limestone

Figure 53 Electric survey curve and its interpretation. Lower Paillon valley (Alpes-Maritimes, France).

The resistivity profile is created by moving a constant A-MN-B setup over a surface or along the length of a set line. The resistivity variations in the bedrock can thus be measured at a roughly constant depth, which, often combined with electric surveys, allows for a more detailed understanding of the homogeneity or heterogeneity of the bedrock, its eventual lateral variations in facies, or the presence of a fault (Figure 54).

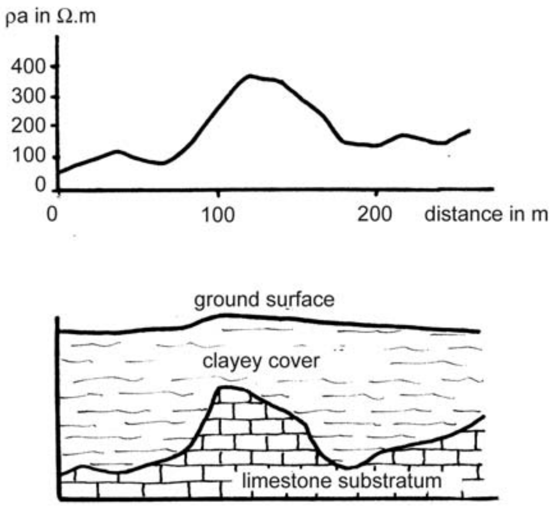


Figure 54 Resistivity profile and its interpretation.

If the measurements in the study area are dense enough, the results can be presented as resistivity maps, which provide a visual representation at different depths of the extent of isoresistive zones, and directly indicate the lithologic variations below ground. The electrical panel method allows the visualization of cross-sections.

General interpretations can sometimes lead to a marked improvement in the geophysical understanding of formations, through correlation with geologic surveys and borehole data (Figure 55).

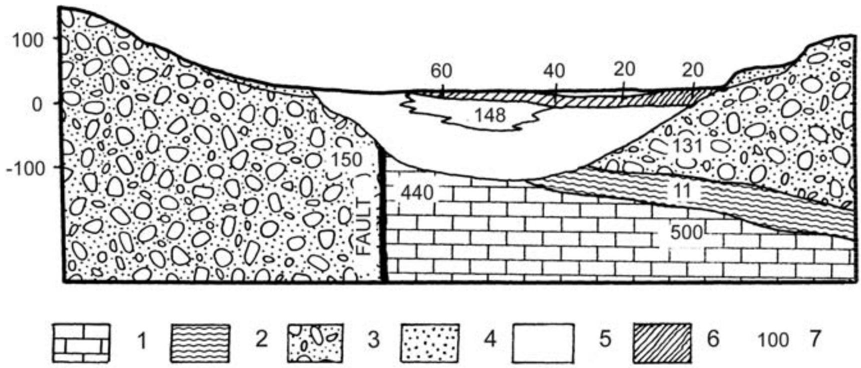


Figure 55 Example of geo-electrical interpretation. Transversal cross-section of the lower Var valley (Alpes-Maritimes) (from Guglielmi, 1993).

1 – Jurassic limestone 2 – Plaisancian marl 3 – Pliocene puddingstone 4 – Alluvial terraces 5 – Gravelly alluvium 6 – Clayey alluvium 7 – Electric resistivity in Ω·m.

2.1.2 Magnetic methods

These are based on the study of natural anomalies in the Earth's magnetic field.

2.1.3 Electromagnetic methods

A study area subjected to an electromagnetic field generates magnetic and electrical signals linked to anomalies below the surface.

For example, VLF (Very Low Frequency) uses electric fields from very low frequency military emitters, used for communication between the officers of different armies and their submarines. Other methods involve generator antennas, which are moved around in the field. The electric or magnetic components of the field can be measured and used to create maps or cross-sections.

PMR (proton magnetic resonance) measures the magnetic field generated by protons in water, which are excited by an alternating electric current circulating through a coil on the ground. The intensity of the signal is a function of the amount of water present below ground. Good results have been obtained with respect to finding karst drains close to the surface (see chap. B3-7.4.2).

Such lightweight methods generally allow shallow investigations (<50 m).

2.1.4 Gravimetric methods

These consist of searching for anomalies due to density variations below the surface. Microgravimetric methods are well-adapted to searching for shallow or more or less filled-in or flooded cavities, veins or fractured zones, or even altered karst zones or zones of alluvium.

2.1.5 Seismic methods

a) Seismic refraction method

This method is based on the propagation of elastic waves emanating from a purposeful shock. The travel velocity of the seismic waves is measured between the source and regularly spaced receivers (geophones). This velocity increases with the density of the rock it is travelling through and is highly variable, from 200 $m \cdot s^{-1}$ for surface formations to several thousands of $m \cdot s^{-1}$ for more compact terrain.

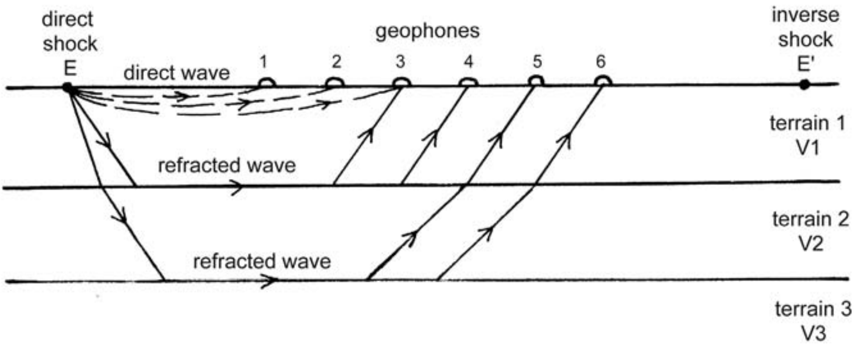


Figure 56 Principle of seismic refraction.

Seismic refraction only considers longitudinal refracted waves, and its practice requires an increase in velocity with depth. The equipment consists of a recording station, aligned geophones, and a cable linking the geophones to the recorder. The shock is created by a falling weight (for shallow investigations) or by explosives (allowing a better vertical penetration). Starting at the time of the shock, the time for the waves to propagate to each geophone is measured, allowing the creation of a T-X graph of the arrival times as a function of distance from the source (Figure 57, Figure 58). This curve can then be used to calculate the apparent velocities, then the true velocities and the thicknesses of various beds. Generally, two shock waves are used, one direct, E and one inverse, E′, in order to determine whether the contacts between layers are horizontal or inclined, and in the latter case, to determine their slope.

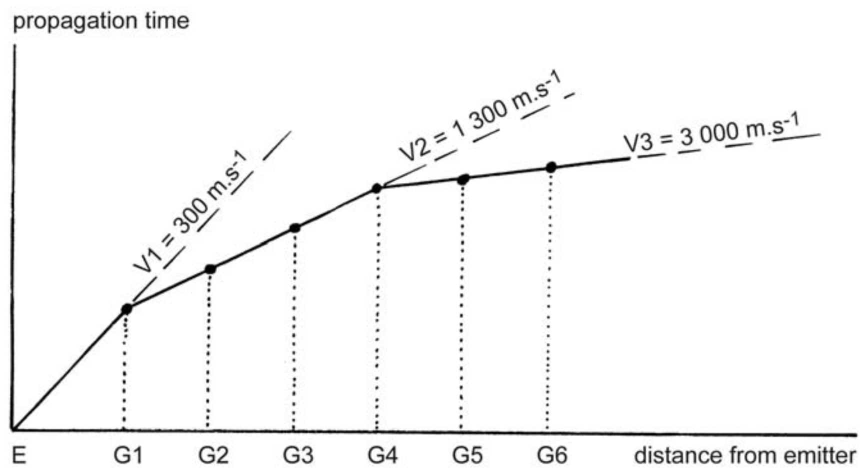


Figure 57 T-X graph for a seismic setup.

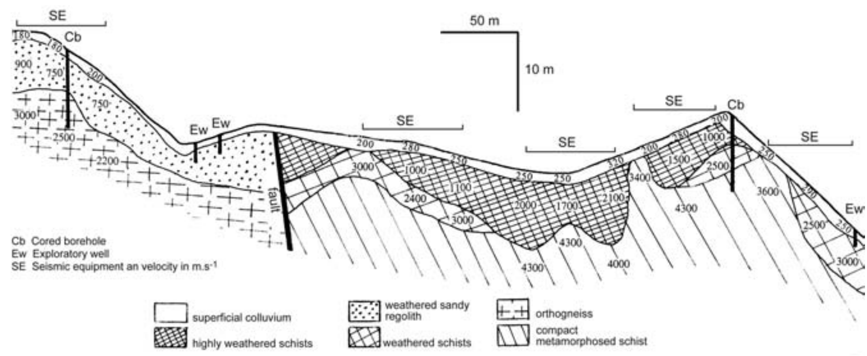


Figure 58 Interpretation of a seismic study along a road project in Upper Corsica.

This method is particularly well-adapted to mapping the subsurface topography of a bedrock layer covered by a variable thickness of material (scree over limestone for example), and to investigating the extent of the alteration zone of a compact rock unit, sandy regolith over granite for example. (Figure 58).

b) High resolution seismic reflection

The source and the geophones are moved along a line. Computer software can then create cross-sections describing the geologic structure.

2.2 The limitations of geophysical methods

In the domain of hydrogeology, the use of geophysics is generally limited to electric resistivity and seismic refraction.

The experimental determination of the values of the physical parameter under study and its variations can generally indicate several different possibilities, and only a strong initial understanding of the natural context can enable the best geologic interpretation. A geophysical survey therefore cannot provide detailed information, but can give a good overall conception of the study area as a whole. It can resolve some uncertainties, particularly with respect to whether the bedrock is homogeneous or not, and can help determine the optimal positioning for verification and calibration drilling projects. Geophysical interpretation obviously requires a sufficiently precise topographic map.

Each geophysical method has its applications and its limitations. They should therefore not be used for systematic surveys, but instead be used to answer specific questions in a manner appropriate to the given context, as a function of the topography and the nature and characteristics of the known or supposed terrain. In certain cases, several methods can be combined in order to facilitate the final interpretations. The appeal of geophysical surveying lies in its ease of application in the field, without requiring the creation of specific access points and without causing any destruction, as well as in its relatively low cost.

3 RECONNAISSANCE DRILLING

The goal of reconnaissance drilling is to provide point data on the nature and the vertical succession of the subsurface terrain. The boreholes can also be inclined in order to examine lateral structures, when access and installation conditions for the drill allow it or impose it.

There are various techniques, and the choice of which to use is dictated by the geologic character of the formations in question, by the estimated nature and depth of the hypothesized features to be examined, and by the available budget. This last criterion can be of primary importance, given the generally high costs of this method in the context of reconnaissance.

In unconsolidated terrain and at relatively shallow depths, a manual or motorized auger can be used to create a cross-section and take samples of the various units, as long as the short-term stability of the hole is secured. When the terrain is unstable, underholing allows the creation of a vertical excavation in which the walls are protected progressively by superposed concrete rings, or by metallic tubing. The excavation can be done manually if the diameter of the hole allows it, or with the help of a hammer-grab sampler (Benoto method).

For greater depths or in indurated rock formations, autonomous drill rigs on wheels or treads, or mounted on an all-terrain truck, are used. Various drilling techniques enable perforation of the ground by percussion, by rotation, or by rotary-percussion, and use cooling fluid (air or water), which also serves to carry rock fragments back up to the surface. A dense recycled mud (often bentonitic mud) can also be used to bring up rock debris and to maintain the walls of the hole. In other cases, such stabilization is provided by tubing (steel or PVC).

The level of information provided by such drilling varies greatly with the quality of the material brought back to the surface, either rock fragments (destructive drilling) or actual continuous, linear samples, called cores (core drilling).

The creation of the geologic cross-section of a borehole must be very precise, taking into account not only the information obtained by a detailed examination of the samples, but also observations made by the borer during the drilling process (speed, sudden drops of the drill, water influxes, loss of the cooling fluid, lack of cuttings returning to the surface).

Cores allow the establishment of a perfectly reliable cross-section, which it is wise to complete with and analysis of the recuperation rates in order to take into account the washing out of fine particles by the cooling fluid in unconsolidated or poorly coherent terrain.

Destructive drilling requires regular samples to be taken throughout the process, in order to not mix fragments from different depths. The creation of a cross-section can be more difficult, especially when there is little or no debris due to losses in the terrain (as is the case for karst cavities for example). Additional information can be gleaned from instantaneous drilling speed, which indicates the state and the compactness of the rock. This parameter can be automatically registered, along with the drill rig's own parameters (resistance to the drill bit, fluid pressure), which affect its value (drilling parameters).

Once the boreholes have been created, the cross-sections of the destructive boreholes can be optimized and calibrated to the cored boreholes by using drill logs. These consist of measurements along the entire depth of the borehole, taken with the help of specific probes, of the terrain's characteristic parameters. The principal methods are as follow: gamma ray probes (measuring natural radioactivity), electric logs (measuring resistivity), and sonic logs (measuring the propagation of longitudinal waves).

4 WELLS, DITCHES, AND EXPLORATORY GALLERIES

Wells and ditches can be easily put in place in sites accessible to construction machinery. They lead to relatively destructive investigations, limited to a depth of a few meters, and sometimes requiring the creation of an access route.

This method is generally limited to verifying the thickness of an unconsolidated cover (weathering mantle, scree cover) and to the excavation to the bedrock (in order to identify its nature, its age, even its strike and dip, in particularly covered regions).

The digging of an exploratory gallery is extremely onerous, and remains an option available only in large-scale civil engineering projects (dams, tunnels). It allows the observation of the actual geologic conditions in the heart of the rock mass, and it obviously provides information of great importance.

For certain construction sites, subhorizontal core or destructive drilling can provide comparable results, as long as their length does not exceed a hundred meters.

5 GEOMETRIC SYNTHESIS

During the final survey phase, the geometry of the aquifer(s) being studied is synthesized and reconstructed through maps and cross-sections. Figure 59 illustrates such a representation, concerning the region around Peille (Alpes-Maritimes), located at the heart of the subalpine range of Nice. They consist of sedimentary units running N-S to NNW-SSE, with a structure consisting of recumbent folds in which certain anticlina axes are broken and overlapping. This figure presents the geometry of two distinct aquifers, one Jurassic karst reservoir and one Turonian fractured reservoir, separated by a few hundreds of meters of impermeable Cenomanian marl.

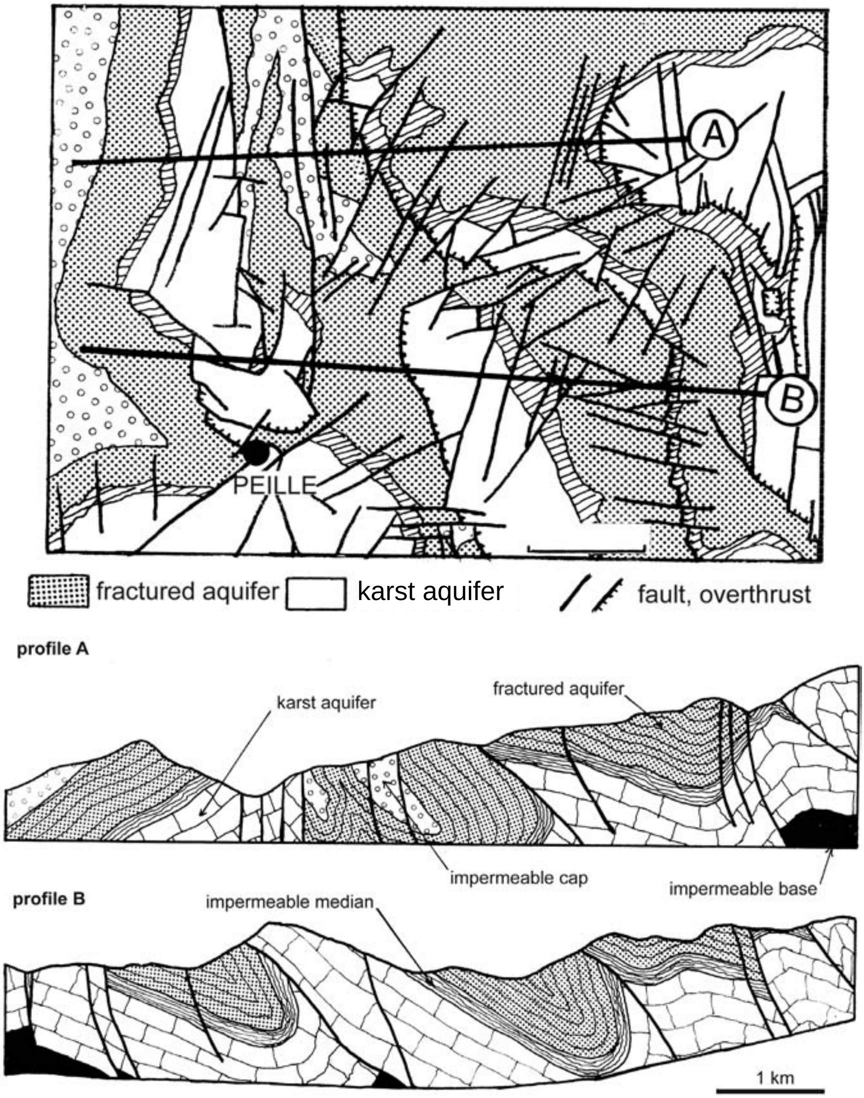


Figure 59 Geometric synthesis, map and cross-sections. Region around Peille (Alpes-Maritimes) in the subalpine range of Nice.

Difficulties can persist in the interpretation of the continuity of certain units at depth. The most probable hypotheses are illustrated in the cross-sections, based on the regional style of tectonics, the reconstructed thickness of major units, and the strike and dip of bedding measured at the surface. When the thickness of a major bed cannot be precisely determined, due to inconsistent outcropping (caused by superficial covering or tectonic effects), it can be helpful to look for it around the borders of the study area, using calibration sections in simpler areas, and then to integrate them into the relevant cross-sections.

Sometimes, the deep structure of an aquifer can be subject to multiple interpretations, which must then be described and illustrated, along with their limits and imprecisions.

When the network of available information allows it, it can be interesting to represent the subterranean structure of an aquifer with the help of an isohypsal map (curves of equal elevation) of its floor (for unconfined aquifers) or its roof (for confined aquifers). The characterization of the roof of the substratum is often of the first importance in understanding and studying the storage and circulation conditions of superficial aquifers, particularly in the case of hillside aquifers, which can exist in scree slopes covering a wide extent. Figure 60 is an example illustrating the roof of a marly bedrock unit outcropping at the foot of a slope between 105 and 110 m of elevation. The map shows the bedrock unit continuing up to elevations of 120 to 125 m, and shows the deep incuts affecting the bedrock, probably filled-in fossilized paleothalwegs.

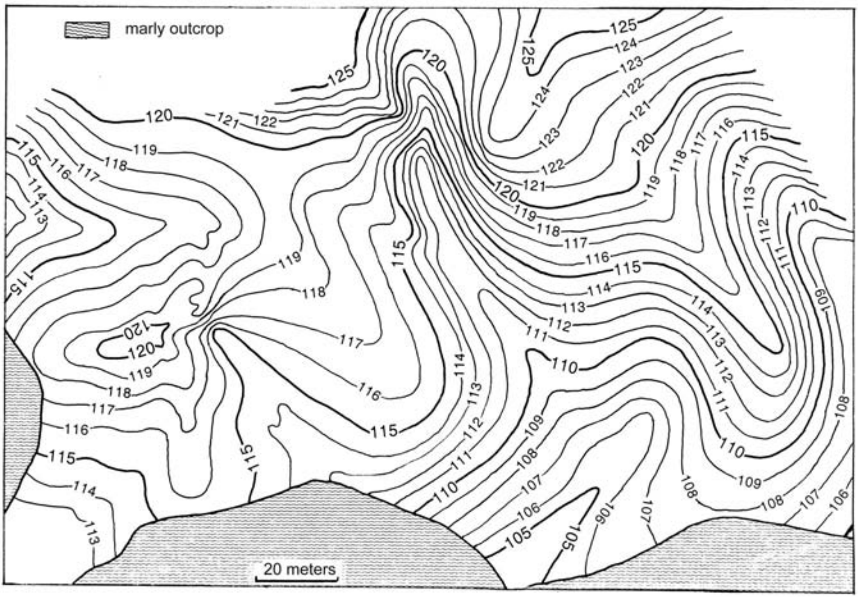


Figure 60 Scree cover on Cenomanian marl on the right bank of the Paillon in Cantaron (Alpes-Maritimes). Isohypsal map of the roof of the marly bedrock.

The same type of representation can be used for the bedrock of alluvial aquifers which outcrops laterally on hillsides. It can also be combined with transversal cross-sections following the variations in facies within alluvial deposits. This is the case in Figure 61, which provides a general visual representation of the extent of the three distinct alluvial aquifers below the city of Nice, in sandy gravel interlayered with an impermeable clay-mud horizon and a discontinuous, semi-permeable sandy silt level.

Finally, the creation of block diagrams can facilitate the spatial visualization of major structural difficulties, and illustrate the importance and the limits of remaining unknowns. Figure 62, for example, presents the tectonic style of the subalpine Castellane range, in the highlands behind Grasse (Alpes-Maritimes), which is marked by E-W fold and thrusts. The

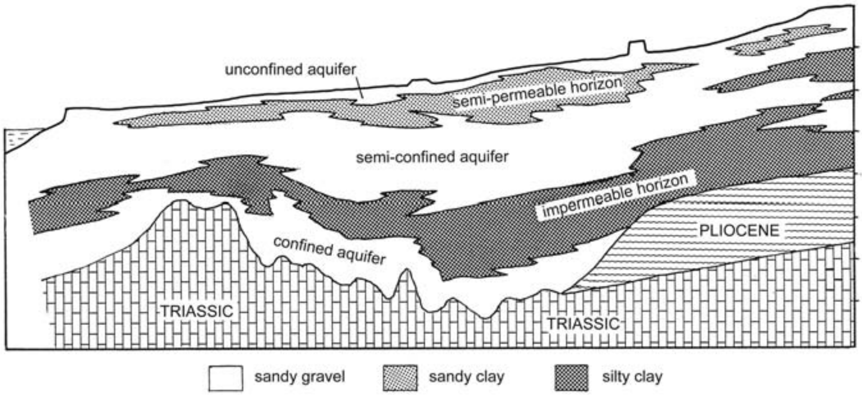


Figure 61 Geometry and extent of the alluvial reservoirs in the Paillon in Nice (Alpes-Maritimes) (from Pline, 1991).

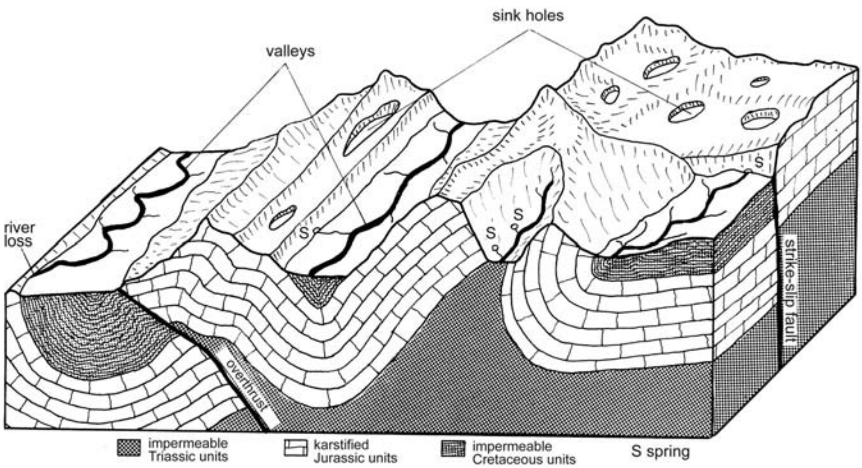


Figure 62 Representation of the tectonic style in the subalpine Castellane range, in the highlands behind Grasse (Alpes-Maritimes).

diagram also highlights the frequent uncertainty, within the overthrusts, surrounding the hydraulic continuity between the two Jurassic units and its very direct dependence on the depth of the frontal Cretaceous syncline and the uprise of the deep Triassic units along the fault.

CHAPTER B3

Characterizing Aquifers

The previously elaborated geologic model subsequently serves as a base in order to note the various hydrogeological information acquired during the preliminary research phase (documentation, inquiries and fieldwork), and specific investigations are then made in order to precisely understand the behavior of the aquifer(s) being studied:

- through direct investigation, in order to study the water seeping into the ground, as well as its subsequent reemergence at the surface;
- through indirect research, in order to define the spatial organization and the flow patterns within the aquifer, and in order to characterize the variations within the reservoir.

1 THE INFILTRATION OF WATER

Water seeps into permeable rock in different ways, depending on the environmental conditions. Infiltration varies spatially very noticeably, can be diffuse of concentrated, and can be rapid or more or less delayed.

Detailed observation of the stream system on a topographic map often enables the global characterization of infiltration into the ground, and the establishment of a preliminary regional aptitude zoning:

- high-infiltration areas, with little to no surface hydrography. This is typically the case for karst plateaus and coarse-grained detrital deposits;
- impermeable or poorly-permeable areas, criss-crossed by a tight network of ravines and streams. This is the case for marl, schist, or calcareous-marl formations and for steep slopes;
- intermediate areas, between the two preceding extremes, often characterizing composite deposits or variable topography.

Several factors determine the ease of infiltration through a permeable surface: the topography, the degree of fracturation in rock masses, the nature and thickness of the weathering mantle, and the development of an unconsolidated superficial cover.

Planar surfaces (plateaus and valley floors) facilitate infiltration, whereas inclined surfaces (hillslopes) favor runoff.

The fracture density of a rock formation, as well as its degree of openness, play a primary role in the penetration of surface water into otherwise intrinsically impermeable rock, in the absence of fractures. The same can be said for detrital rock lacking a clay matrix or highly degraded through weathering.

Inversely, superficial deposits covering an aquifer can sometime trap surface water until they are saturated, and only then allow its slow and delayed infiltration into the underlying reservoir. This is particularly common in the most decompressed zones of fractured and karst masses (at the surface of plateaus and on the edges of reliefs), where the opening of fractures and their more or less pronounced infilling by terrigenous material favor the temporary storage of a suspended superficial reservoir, allowing a delayed inflow to the deeper reservoir. This suspended aquifer, termed epikarst aquifer in karstified regions, explains the frequent coexistence in such regions of large springs at the base of the reservoir and superficial wells dug by humans in the depressions at the top of the plateau.

Over permeable surfaces, infiltration is generally diffuse, and of variable amount depending on the nature of the environment. It can also be concentrated and can bring to the reservoir a volume of water collected over a large catchment area. The amount of water infiltrated at preferential points can reach large values and plays an important role in the recharge of the aquifer. This is the case for swalow-holes in valleys, and, in a more general sense, for the surface of karst masses, for allocthonous perched valleys, dry valleys, and closed depressions.

When one has the benefit of access to results calibrated on experimental or well-equipped hydrologic systems, or of well-tested experience in comparable aquifers and in similar situations, one can consider using the specific infiltration modulus (given in $L \cdot s^{-1} \cdot km^{-2}$ or in $mm \cdot km^2$), based on the global relationship between rainfall, the recharge area of the aquifer, and the pumped discharge. This modulus evaluates the value of subterranean flow as a yearly average over sites particularly influenced by infiltration (rain and snowmelt). It allows comparisons between different aquifers of a similar nature, and provisional estimates of theoretical catchment areas or pumping discharges (Table 10).

Table 10 Examples of Water Budgets for the Aquifers of Provence.

System	Average annual discharge $L \cdot s^{-1}$	Geologic units	Geologic basin in km^2	Modulus in $L \cdot s^{-1} \cdot km^{-2}$	Calculated basin in km^2	Budget over the known basin
Vaucluse	19,000	Lure Mountain, Mt. Ventoux and Northern Lubéron	**1200**	15	1,260	correct
Port Miou	7,000	Beausset and Sainte Baume	**300**	10	700	too small basin
Argens	800	East Ste Victoire and Bois de Pourrières	**165**	12	65	too large basin
Agnis	450	Agnis	**50**	10	45	equilibrium

2 RESURGENCE OF WATER

The resurgence of water infiltrated into a rock unit is also highly variable, and can correspond to a number of situations determined by the particular characteristics of the environment.

2.1 Nature and location of springs

The positioning of an aquifer's outlets is determined by the relative geometries of the aquifer, the neighboring impermeable layers, and the surface topography.

In most cases, emergences will be located at the contact between the water-bearing formation and the underlying and adjoining impermeable layers, at the lowest possible elevation (Figure 63). These are discharge springs draining an unconfined aquifer. They can be located at the bottom of a hillside or mid-slope, depending on the local geologic context (Figure 64a).

When the basal impermeable units remain below the ground and do not outcrop at the surface, the aquifer is drained at the points which are geographically the lowest ones, generally along the hydrographic network, which forms the deepest incisions. These are called depression springs, in the unconfined water table developed in bordering units (Figure 64b).

Occasionally, springs will be located at the roof of the aquifer, at its lowest contact with the overlying impermeable unit. These are overflow springs for unconfined aquifers, which become confined immediately downslope when they pass under the impermeable cover (Figure 64c).

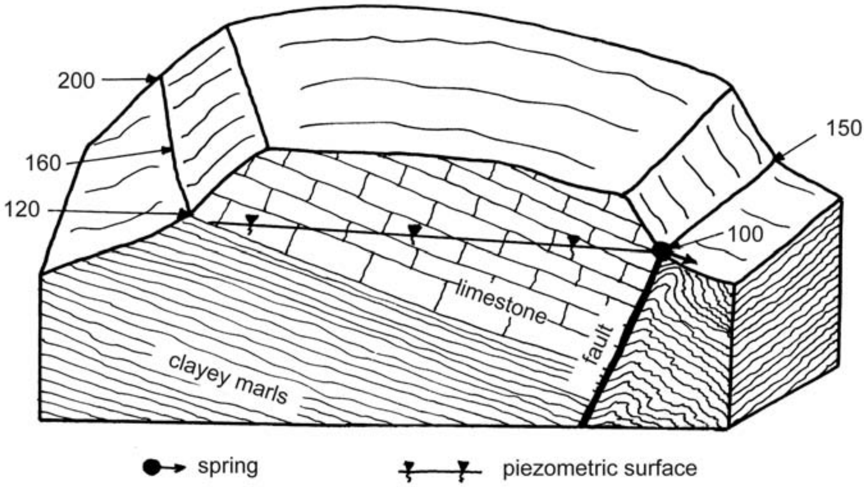


Figure 63 Position of a limestone aquifer's outlet as a function of the geologic structure and of the topography.

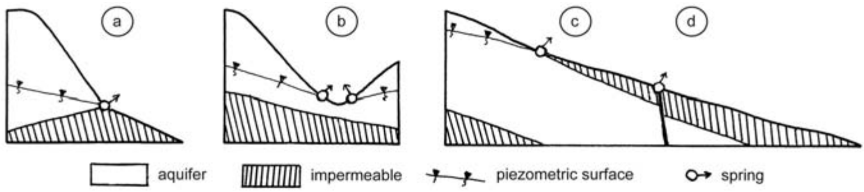


Figure 64 Main types of springs.

In certain rare cases, artesian springs can drain deep aquifers, due to lithologic heterogeneities in the overlying impermeable unit, or to draining faults allowing a rising leakage from the aquifer (Figure 64c).

2.2 Conditions for the emergence

The emergence of water from a water-bearing formation is often highly variable. In some cases originating from a point source at the mouth of a gravelly channel, a fracture, or a karst cavity, it can also occur in a more or less diffuse manner, corresponding to a multitude of scattered seeps, or lining, over a certain distance, the contact between the aquifer and an impermeable layer.

Springs are not always located where they theoretically should be, and can be displaced to a lower elevation by a hydraulic conductor corresponding to a smaller reservoir. This situation is commonly seen on hillsides, when the contact between the aquifer and the impermeable unit is coverered by a scree slope (Figure 65a). It can also be caused by the existence of permeable lenses within the basal impermeable layer (Figure 65b). Even more complex contexts can be found, requiring very detailed investigation in order to identify the true elevation of the aquifer under study.

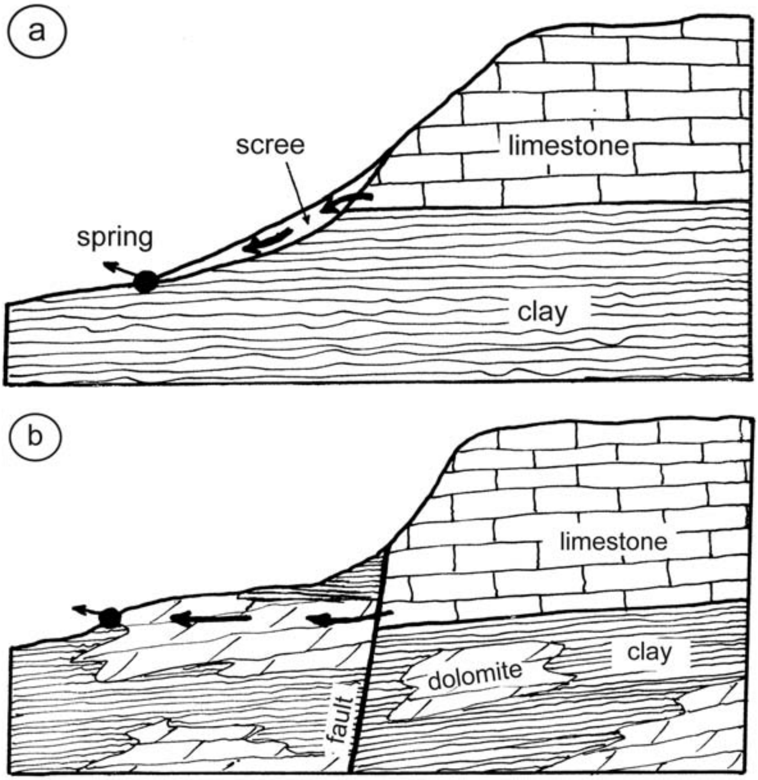


Figure 65 Examples of displaced emergences, relayed through a frontal hydraulic conductor.

In some cases, an aquifer's emergences are hidden, particularly when the springs are in a lake or river bed. The same is true for submarine springs, when the permeable formation extends into the sea.

It is, finally, worth mentioning aquifers with no outlets. Such a situation can be accepted only after a thorough exploration of all peripheral possibilities, and indicates that the aquifer drains into another aquifer (see chap. B 3.3).

2.3 Discharge and flow regime of springs

It is very important to have a thorough knowledge of the flow regimes and discharge variations of an aquifer's outlets.

Some emergences, termed perennial springs, present a permanent outflow and are generally located at the lowest points of the reservoir. They are often associated with temporary springs enabling the evacuation of overflow due to rainy periods, at a higher elevation, through generally unused passages. In some cases, the natural outflow mechanisms are even complemented by an exceptional spring, which functions only rarely, following extreme and prolonged rainfall. Such arrangements are characteristic of karst aquifers, where access points to the reservoir allow the sudden emptying of important volumes of water at an elevation significantly above the base level; in France these events are termed "crevaisons" (burst).

The measurement of discharge over time often requires the creation of specific equipment, which can be costly and constraining: the reconcentration of different rills into one channel, the raising of little fusible dams, the construction of a permanent weir, the installation of gaging equipment.

When discharge is low, the timed filling of a graduated receptacle can allow rapid and accurate data collection. For larger values, one can also proceed by measuring the flow velocity with the help of a micro-turbine flow meter, or by dilution of a chemical (dye visible to the naked eye or NaCl tracked with a conductivity meter), as long as the length and cross-section of the rivulet generated by the spring allow it.

In extreme cases (high discharge), and in order to follow the discharge over a certain length of time, it becomes essential to measure the height of the water above a weir on a staff gage or with the help of a limnigraph, and to correlate this height to the discharge, by establishing a calibration curve, which requires numerous measurements under varying conditions.

These measurements are clearly impossible in the case of springs located underwater, in lakes or oceans, where more complex and less reliable methods can nevertheless provide orders of magnitude. Outflows under rivers can; however, be quantified, based on differential measurements upstream and downstream of the emergence. Certain precautions are necessary to guarantee the reliability of the results (measurement of eventual inflows and outflows along the length under consideration), which will also greatly depend on the relative values of the discharge being calculated and the discharge of the river.

In practice, three distinct and complementary actions can be considered in order to estimate the behavior of an aquifer:

- the instantaneous measure of the total discharge from all outlets during extreme hydrologic events (floods and dry periods, for example), in order to reconstruct the rough balance of water released by the surrounding rock;

- for each outlet, the evaluation of the coefficient of variation between the flood discharge and the dry season discharge. This coefficient describes the average permeability of the reservoir and its subterranean circulation conditions. It can vary from 5 in isotropic, poorly permeable environments, to 100 in karst environments;
- the tracking over time of each outlet, in order to estimate interseasonal and interannual variations in discharge, and to allow correlations with rainfall data and the recharge area of the aquifer.

When deadlines and budget constraints do not allow a sufficient degree of investigation, inquiries with locals familiar with the natural environment can provide a rough sketch of the outlets' principal characteristics, particularly in terms of their flow volume and their coefficient of variation.

3 EXCHANGES BETWEEN AQUIFERS

It is very common for aquifers to have no specific outlets, even when they outcrop over a wide area and have a high infiltration rate.

It is also sometimes observed that the discharge from a reservoir is lower than the theoretical inflows from infiltration (budget deficit), or, on the contrary, that the discharge is greater than these inflows (budget excess).

These situations are a result of exchanges between different aquifers in the same region, allowing partial or total leakage of the infiltrated inflow over one recharge area, and contributing more or less significantly to the alimentation of another aquifer.

Only a detailed examination of the mutual relationships that are possible between different reservoirs and their surroundings (lakes, rivers, sea) can allow the definition of an aquifer's inflows and the attempt to quantify its various inputs (infiltration, losing streams, exchanges with other aquifers).

This definition and quantification can be obtained through the measurement, monitoring, and calculation of the budget's principal parameters over a representative time period (rainfall data, infiltrated volume, stream flow, spring discharge, piezometry, actual evapotranspiration), but it is a long and costly process, which, in addition, often requires some hypothesizing for certain data points (see chap. A4.1).

The analysis of the relationships between rainfall, the surface area of the recharge area, and spring discharge can sometimes provide adequate data at lower cost, based on the specific module of infiltration. It can verify the coherence between parameters examined in a particular natural context, or, on the contrary, highlight both flagrant and possible anomalies, directing subsequent research towards the understanding of leakages or towards additional inputs.

Such exchanges often provide the majority of inputs to superficial aquifers:

- in the case of hillside aquifers, where an aquifer at a higher elevation is partially drained by accumulations of scree and fallen rock or of fluvio-glacial sediment covering the basal contact with underlying impermeable rock (Figure 65a);
- in the case of alluvial aquifers, where stream losses and hillside contributions jointly provide the inputs to the aquifer (Figure 66).

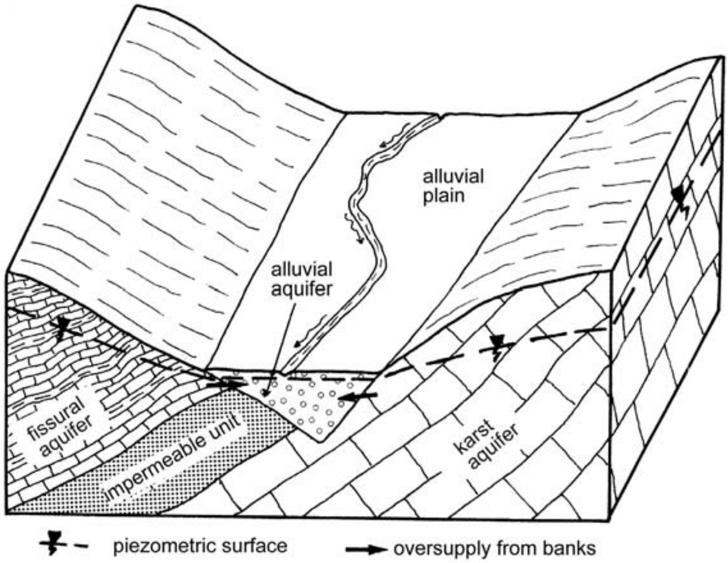


Figure 66 Representative diagram of an alluvial aquifer fed by its banks.

Vertical exchanges can occur as well, when several aquifers are superimposed, due to rock types variations or tectonic offsets locally disturbing the continuity of intermediate impermeable horizons (drainage).

Such arrangements are commonly observed in alluvial aquifers, where the superficial unconfined aquifer can receive upwelling inputs from semi-confined or confined deeper aquifers (Figure 61).

The same is true in large rock masses, where a large reservoir at a higher elevation can contribute to the supplying of underlying aquifers thanks to tectonic discontinuities. For example, in the Dévoluy (north-south subalpine chains), the great karstified Senonian and Eocene series, the framework of the area, is drained by the Grandes Gillardes springs, in a valley cutting into its heart. This relatively suspended aquifer also contributes to the aquifers developed below, through contacts generated by the structural complexity of the area (Barremian, Hauterivian, and Tithonian aquifers).

Groundwater transfers through exchanges between aquifers can occur over great distances and involve several hydrologic basins.

- In the subalpine chains of the Arc of Nice, between Nice and Menton, there are no fewer than fifteen or so small Jurassic limestone units dispersed over a surface on the order of 220 km^2, in the middle of poorly permeable Cretaceous deposits. The structural conditions allow relationships at depth between these karst units, for which the principal drainage occurs, for a total recharge area of around a hundred km^2, through three submarine springs totalling an estimated discharge of 500 $L \cdot s^{-1}$ (Pissarelles, Cabbé, and Mortola), and through coastal springs with a discharge of 100 $L \cdot s^{-1}$ around the borders of Monaco (Gilli, 1999 & 2003).
- To the east of Marseille, the submarine Port Miou spring, which emerges in the calanques of Cassis, appears to have an average discharge on the order of 7 $m^3 \cdot s^{-1}$, which, given the regional specific infiltration modulus, would require the inputs of a basin of over 1000 km^2. The catchment area of this major outlet should therefore extend over a good part of Basse-Provence through various hydraulically interconnected units, thanks to structural complications (Gilli, 2001) (see chap. A9-2.5).

4 PIEZOMETRY OF AQUIFERS

4.1 Definition and methods

Within water-bearing formations, the position of various aquifers can be described by their piezometric surface, which represents the distribution of the aquifer's hydraulic charge. In the case of unconfined aquifers, this surface coincides with the surface of the aquifer. In confined aquifers, the piezometric surface can, however, be located above the surface of the aquifer, which is determined by its impermeable roof.

The piezometric study of an aquifer provides information of great importance on the characteristics of the aquifer. In particular, it allows a global understanding of the groundwater flow conditions, as well as the conditions of inflow and drainage, and the variations in storage.

The collection of piezometric data requires the availability of access points to the water table, which, in some cases, can consist of preexisting wells or boreholes in the study area. Frequently, however, private water wells reveal themselves inadequate for measuring the piezometric level, due to the clutter caused by their equipment (cables and piping), which prevents the passage of a probe. It is also possible for other excavations reaching the water table, whether natural (karst cavities) or artificial (mining wells), can be used for this purpose. Finally, it is important in such an analysis to account for the springs indicating preferential points of contact with, or overflow of the water table. When such control points are too few or even nonexistant, it becomes necessary to create specific access points, called piezometers, which consist of small-diameter boreholes, equipped with perforated casing in the saturated zone. The creation of piezometers in deep aquifers, especially in the presence of confined aquifers, requires particular precautions in order to adequately isolate possible overlying aquifers and to prevent mixing between aquifers.

The measurement of the water level is taken from the surface, with a piezometric probe. It can be automated with the emplacement of a piezograph (following the surface of the water) or a pressure probe (following the water column above a fixed point). In the case of artesian aquifers, the piezometer head must be perfectly waterproofed and equipped with a pressure gauge to measure the hydraulic head in the piezometer.

4.2 Piezometric maps

Piezometric studies require very precise knowledge of the elevation of the measurement points (wells, boreholes, piezometers, springs), which guarantees precision when creating a piezometric map. This map is drawn by interpolating between the measured elevations, based on isohypsal contours (lines of equal altitude of the piezometric surface), the quality and spacing of which will depend on the density of data points and the scale of the study.

The piezometric map of an aquifer allows an instantaneous view of its state at a particular moment. It must therefore be established over a very short time period, in order to be representative, over the entire study area, of identical conditions in terms of local influences and peripheral events (stream discharge and rainfall, in particular).

The piezometric surface can be interpreted, in the same way as a topographic surface, by its morphology, its slope, its detailed variations and its anomalies.

The tracing of contour lines allows the definition, by orthogonal lines following the greatest slope, of the piezometric surface's flow lines, highlighting the aquifer's flow patterns.

The geometry of the contours can sometimes lead to complex representations, resulting from the combination of a few simple basic shapes (Figure 67):

- a linear continuity with parallel and rectilinear flow lines, revealing a relatively uniform flow;
- a concave curve opening downstream, where the flow lines converge towards a favored drainage axis;
- a concave curve opening upstream, and diverging flow lines, revealing a piezometric crest, and often characteristic of a zone of infiltration inflow;
- closed curves with converging flow lines. These piezometric depressions indicate punctures in the aquifer due to pumping or leakage into an underlying aquifer;
- closed curves with diverging flow lines. These are piezometric domes corresponding to preferential areas of infiltration or upwelling.

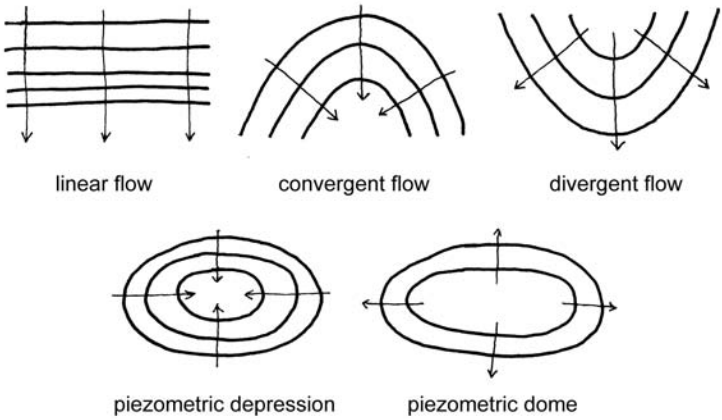


Figure 67 Principal elementary shapes of piezometric contours.

The correlation between the piezometric map of an aquifer and that of the roof of its impermeable cover (see chap. B 2-5 and Figure 60) allows the estimation of the spatial variation in thickness of the aquifer.

The spacing of piezometric contours in the aquifer's drainage direction determines the slope of its piezometric surface, and therefore of its hydraulic gradient, i. This gradient generally varies greatly on piezometric maps. It depends, according to Darcy's Law, on the aquifer's discharge, its cross-sectional area, and its permeability, linked by the following expression:

$$i = Q/A \cdot K,$$

where Q is the discharge of the aquifer (in $m^3 \cdot s^{-1}$), A is its cross-sectional area (in m^2) and K is the coefficient of permeability (in $m \cdot s^{-1}$).

Some of these parameters are defined by geologic and structural studies (geometry of the overlying unit, thickness and cross-section of the aquifer, facies variations of the reservoir), others are determined by specific tests (permeability and transmissivity of water-bearing formations).

It is the combination of all this data that allows the definition, area by area, of the nature of the factors directly governing the observed variations in hydraulic gradient of the aquifer. These factors can, for example, include the cross-section of the aquifer, which, in an alluvial plain, can result in tightening valleys and increasing hydraulic gradients, or instead in widening valleys and decreasing gradients. Similarly, in an area with a constant or well-known cross-section, the variations in piezometric slope can evolve as an inverse function of the aquifer's coefficient of permeability.

Major structural accidents (folds, faults) can also generate important anomalies in the piezometric surface, both in map view and in cross-section, due to the modifications they cause in groundwater flow patterns.

Finally, piezometric maps can provide useful information on the exchanges occurring along the aquifer limit or along distinctive elements in its environment (stream network, irrigation canals, lakes, sea). This information depends on the configuration of piezometric curves in the relevant sector: lack of exchanges, inflow to an alluvial aquifer by the surrounding slopes or by the stream network (Figure 66), drainage of an aquifer by a valley....

These developments can be illustrated by two concrete examples of piezometric maps, established in two different hydrogeologic contexts and at two distinct scales:

1) The piezometric map of a karst aquifer developed in a Triassic gypsum unit in the town of Sospel (Alpes-Maritimes). This document was established in October 1980, based on measurements from 22 piezometers and 4 basal springs (Figure 68). The aquifer is drained to the south by the river bordering the hillside, with an average slope of 0.06 to 0.07. The variations in hydraulic gradient are likely a result of modifications in the drainage cross-sections and in the inflows. For example, the gradient increase in the NW area (0.15 to 0.16) corresponds to a zone with high inflows. Drainage appears generally concentrated into three axes, the two westernmost of which are deeply entrenched and lined with superficial indicators such as slumps and collapses (see chap. D 2.3). These axes illustrate the trace of karst collectors, as otherwise attested to by piezometric monitoring over time, which has shown their high discharge and recharge capacity (piezometric amplitudes of a few meters) within a more homogeneous environment (piezometric amplitudes of a few tens of meters).

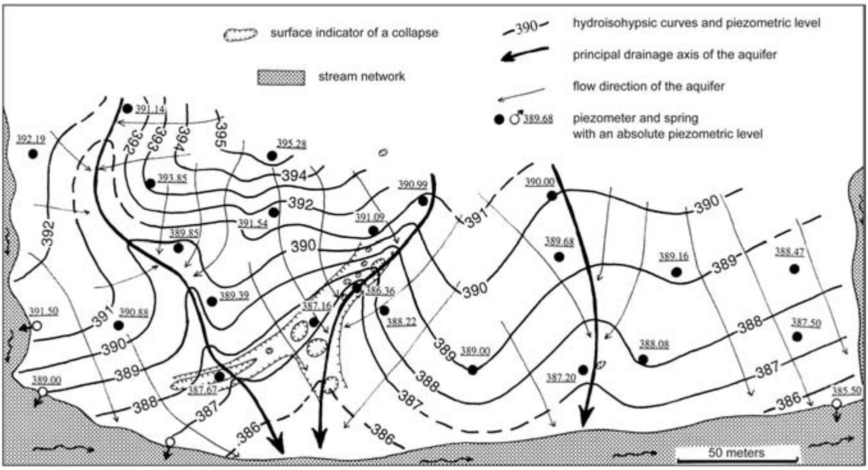


Figure 68 Partial piezometric map of a karst aquifer in a Triassic gypsum unit in Sospel (Alpes-Maritimes), established October 2nd, 1980.

2) The piezometric map of a part of the Siagne alluvial aquifer, in the Frayère and the Béal lower valleys, in the towns of Cannes and Mandelieu (Alpes-Maritimes). This document was created on October 17th and 18th, 2003, based on measurements in 41 wells, water boreholes, and piezometers (Figure 69). The contour lines show a general drainage towards the sea and a preferential collection in several drainage axes. The hydraulic gradient has an average value of 0.003 to 0.005 in the upper regions, and diminishes considerably as it approaches the coastline (0.0005 to 0.001) due to the widening of the plain. It increases, however, towards the western hillside (0.006 to 0.012), in relationship with the decreasing thickness and permeability of the aquifer. The alimentation of the aquifer appears to be sustained by inflows from the Béal and Frayère valleys in the northern part of the sector.

4.3 Piezometric variations

A map of piezometric contours provides a representation of the piezometric surface at a given date. It is therefore often necessary, in order to judge seasonal variations in this surface, to create several piezometric maps at different times, and, particularly during extreme periods (flooding or high-water, and dry season or low-water).

Additionally, a permanent monitoring can be undertaken by equipping representative piezometers in the principal areas of the aquifer with a recording device. The piezograms show water table fluctuations over time,

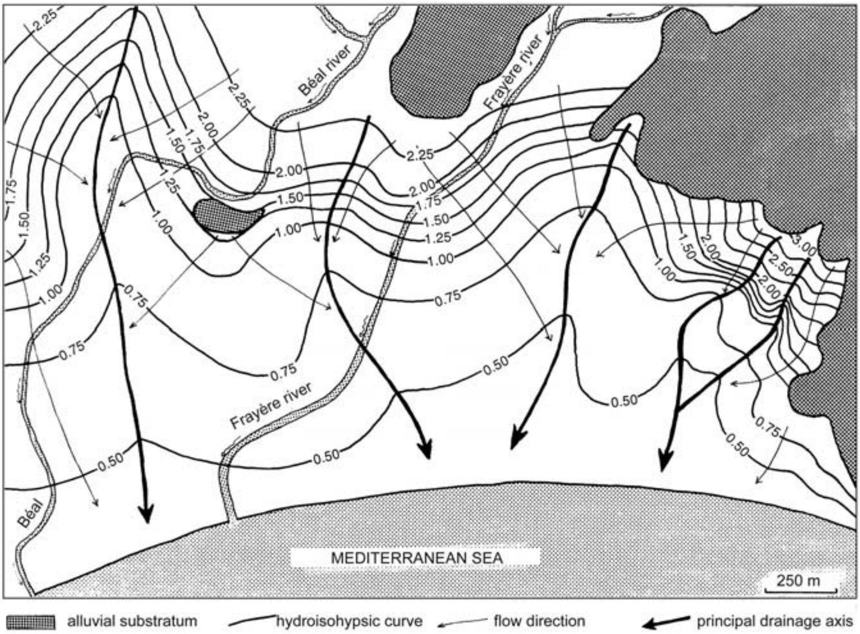


Figure 69 Partial piezometric map of the alluvial aquifer of the Siagne in the Frayère and Béal lower valleys (Cannes and Mandelieu, Alpes-Maritimes), established in October 2003.

and can be correlated with rainfall, or with the discharge of a nearby river when it is responsible for the main inputs to the aquifer (Figure 70).

The analysis of piezometric variations in map, view and in cross-section, allows the determination of maximum and minimum values for the piezometric level, as well as their average annual or inter-annual values. It also provides a good estimate of the natural inputs to the aquifer and the spatio-temporal evolution of its reserves, characterizing in particular homogeneous sectors in terms of recharge and discharge.

Figure 70 presents the piezometric fluctuations of three control wells in the alluvial aquifer of the Var (Alpes-Maritimes) over the course of the years 1989 and 1991, in which the inputs are largely governed by the river flowing out onto the plain. Relatively dampened fluctuations are observed in the downstream piezometers P15 and P35, whereas they are much more marked in the upstream piezometer P41. Such amplitude is explained by the local clogging of the minor Var bed, which then no longer feeds the aquifer during periods of pronounced drought. The aquifer thus distinctly dropped during the extreme drought of 1990, but then rose very rapidly during floods due to losses from the river into its banks.

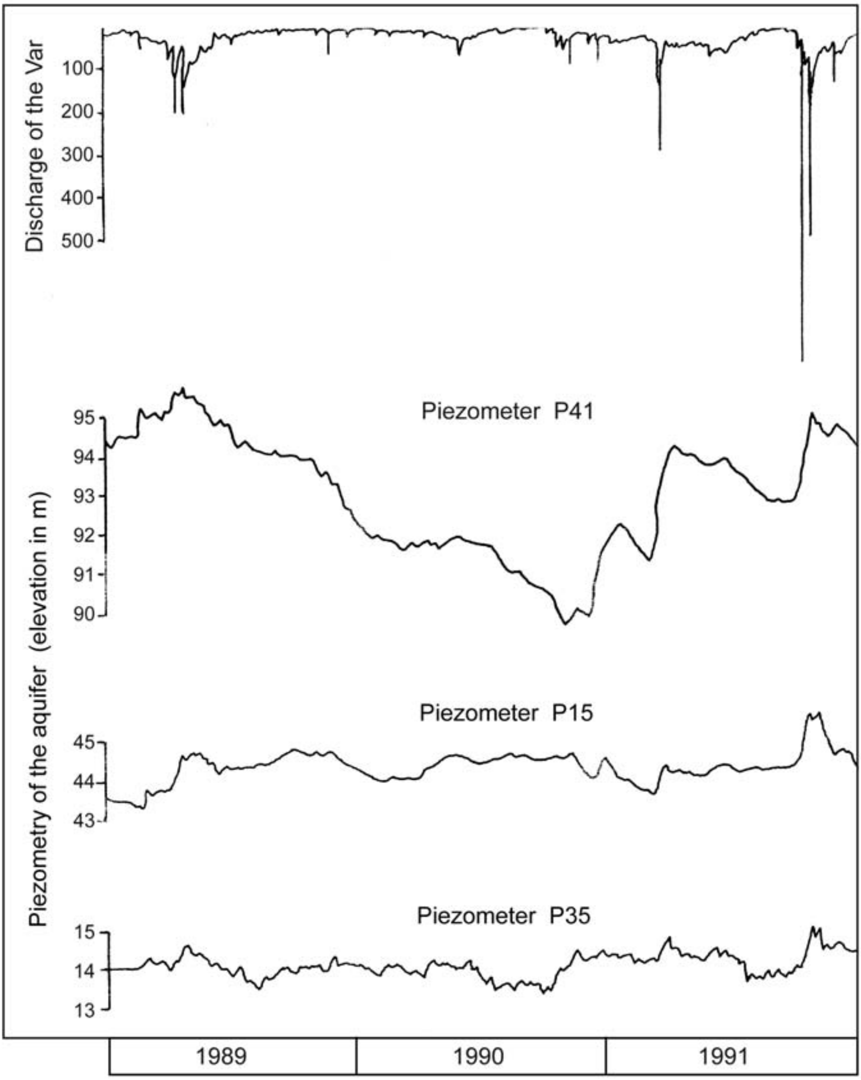


Figure 70 Piezometric fluctuations of three wells in the alluvial Var aquifer (Alpes-Maritimes) from 1989 to 1991 (from Guglielmi, 1991).

5 PERMEABILITY TESTS AND PUMPING TESTS

After the identification of the aquifer's geometric limits and the analysis of its inflows and groundwater circulations, it becomes necessary to acquire specific information on the reservoir's intrinsic properties. These can be obtained by subjecting samples to laboratory testing, through selective tests in boreholes, or through more or less prolonged pumping tests.

5.1 Laboratory measurements

These are measurements of the permeability, K, of the terrain, using samples taken during drilling. They are only cited, as the reworking of the samples causes a more or less marked modification of the terrain's initial structure, and can affect the validity of the results.

Such methods are generally more used in geotechnics (soil mechanics), with the help of permeameters and oedometers (during compressibility tests).

5.2 Selective testing in wells or boreholes

These allow for an understanding of the vertical variations in permeability of the terrain, by taking measurements over successive slices of a well. When the tests are performed in a group of wells, the horizontal permeability variations can also provide a good illustration of the aquifer's general anisotropy.

Different types of tests can be considered, depending on the terrain under consideration and the goals of the study. Their comparison, however, requires total control in order to ensure that the methods used and the well diameters remain constant.

5.2.1 Lefranc tests

The Lefranc method is used in unconsolidated terrain (scree slopes, alluvium, moraines), during the drilling process, over successive slices of the terrain. Each slice is tested, over a height of 0.5 to 2 m, named lantern, where the terrain, exposed at bottom and on the sides of the well, is isolated above the relevant section by tubing or a valve.

The terrain's absorption capacity is determined by pumping or injecting a constant flow of water into the lantern, until the level in the well stabilizes. This is a constant-level test, well-adapted to permeable soils ($K > 10^{-4}\ m{\cdot}s^{-1}$).

One can also extract or inject a given volume of water and then follow the variations in water level over time. This is then a variable-level test, well-adapted to poorly permeable soils ($K < 10^{-4}\ m{\cdot}s^{-1}$).

Calculating the permeability, K, follows from the monitoring of the volume injected or withdrawn, and the resulting variations in level. It also takes into account the geometric characteristics of the slice under consideration (height and diameter).

5.2.2 Lugeon tests

The Lugeon method is used in more or less fractured areas of massive rock (limestone, sandstone, granite), and consists of injecting water under pressure into 2 to 5 m long slices of terrain, isolated from the overlying sections by a valve.

One measures the injected discharge over a given period of time (5 or 10 minutes), while increasing the pressure in a stepwise manner (from 1 to 10 bars), then decreasing it in the same way. The volume of injected water is calculated, and is then used to deduce the terrain's absorption in liters per minute and by linear meters of depth at the different pressure levels. The lugeon is a unit describing this value at a pressure of 10 bars, and it is generally accepted that one lugeon corresponds to a permeability on the order of $1.5 \cdot 10^{-7}$ $m \cdot s^{-1}$.

This method allows for interesting vertical and lateral comparisons in a rock unit. It is frequently used in the context of dam and tunnel studies, and allows for a good approach to injection possibilities.

5.2.3 Micro-turbine flow meter measurements

These measurements, taken in a tubed and perforated borehole, with the help of a small-diameter turbine, allow the detection of vertical water circulation, whether ascending or descending.

It does not truly measure the permeability of the environment, but it determines the positions of the most productive horizons and the current speed, which allows for the calculation of circulation discharges. This method is highly used in determining water drilling diagnostics.

5.3 Pumping tests

Unlike periodic tests, which describe only very limited permeable horizons, pumping tests examine the entire thickness of the aquifer (in complete wells), or a sufficiently representative section (incomplete wells). They provide variable information, depending on the conditions of the test and the nature of the equipment:

- the determination of characteristics particular to the site being tested, in the case of a well test;
- the evaluation of the aquifer's hydrodynamic parameters (K, T, S), in the case of an aquifer test;
- the on-site observation of the peripheral effects of exploiting the aquifer, in the case of a prolonged test.

The implementation of a pumping test requires the preliminary installation of adapted instrumentation in order to monitor the desired parameters:

- in the borehole used for pumping, a piezometric tube, in order to monitor the level of the water table, either with a manual probe or with a piezograph;
- at the end of the backflow pipe, a gate, a meter, and a tap, enabling control of the extracted discharge, measurement of the pumped volume, and sampling of the water;
- peripherally and at various distances dependant on the context and goals of the study, setups designed to monitor the far-reaching effects of pumping (piezometers, spring gauges, staff gages in streams).

In some cases, the extracted water must be evacuated into a specific network, either to avoid reinjection into the same aquifer, or to protect sensitive areas (landslide risks for example) or highly urbanized areas.

Finally, it is crucial that pumping tests remain uninfluenced by pluviometry or by other nearby pumping in the same aquifer, in order to ensure the validity of the results.

5.3.1 Well tests

These allow for relatively rapid testing of a water well's reactions and its production potential.

They are performed by maintaining several discharge levels over a limited time period (from 1 to 3 hours), while measuring the extracted discharge, Q, and the drawdown at the end of the level, s. Each discharge level is followed by a period of no pumping, allowing the stabilized recharge of the aquifer.

During a pumping test in a fractured aquifer in La Trinité (Alpes-Maritimes), four levels were maintained over lengths of 1.5 to 2 hours, with successive discharges of 25, 40, 60, and 88 $m^3 \cdot h^{-1}$, causing respective drawdowns of 12, 25, 52, and 105 cm (Figure 71).

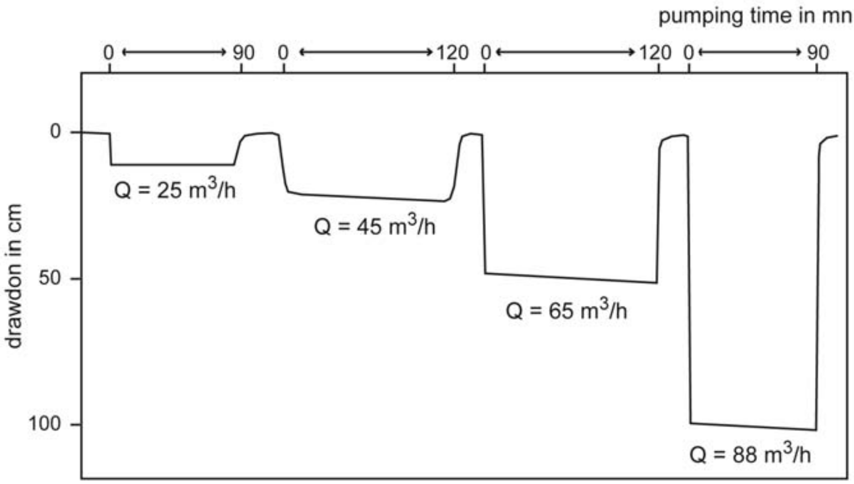


Figure 71 Example of a step-wise pumping test (La Trinité, Alpes-Maritimes).

The drawdown, s, at a given time, t, is given by Jacob's equation:

$$s = B{\cdot}Q + C{\cdot}Q^2.$$

It is the sum of two head losses, characterizing the aquifer/pumping well assemblage (Forkasiewicz, 1972):

- $B{\cdot}Q$ corresponds to a linear loss of head, caused by laminar flow in the aquifer around the well. It is influenced by the aquifer and by the catchment portion of the well;
- $C{\cdot}Q^2$ corresponds to a quadratic, not linear, loss of head, caused by turbulent flow in the well (perforation and tubing) and in the surrounding rock (fractures and conduits). It essentially depends on the pumped discharge, and characterizes the pumping equipment.

The specific discharge/drawdown relationship $s/Q = f(Q)$ is linear, and allows for the direct graphic measurement of the losses of head by the coefficients B and C (Figure 72a).

B is, indeed, given by the intersection of the line with the axis of specific drawdowns, and C is equal to the slope of the line.

The relationship in the preceding example therefore becomes, $s/Q = 2{\cdot}10^{-3} + 1.04{\cdot}10^{-4}{\cdot}Q$.

The well's characteristic curve (Figure 72b) is represented by the function: $s = f(Q)$. It can be plotted with the help of intermediary and extreme points, calculated with Jacob's equation. It allows the definition of a critical exploitation discharge, as a function of the maximum acceptable drawdown (55 $m^3{\cdot}hr^{-1}$ in the preceding example).

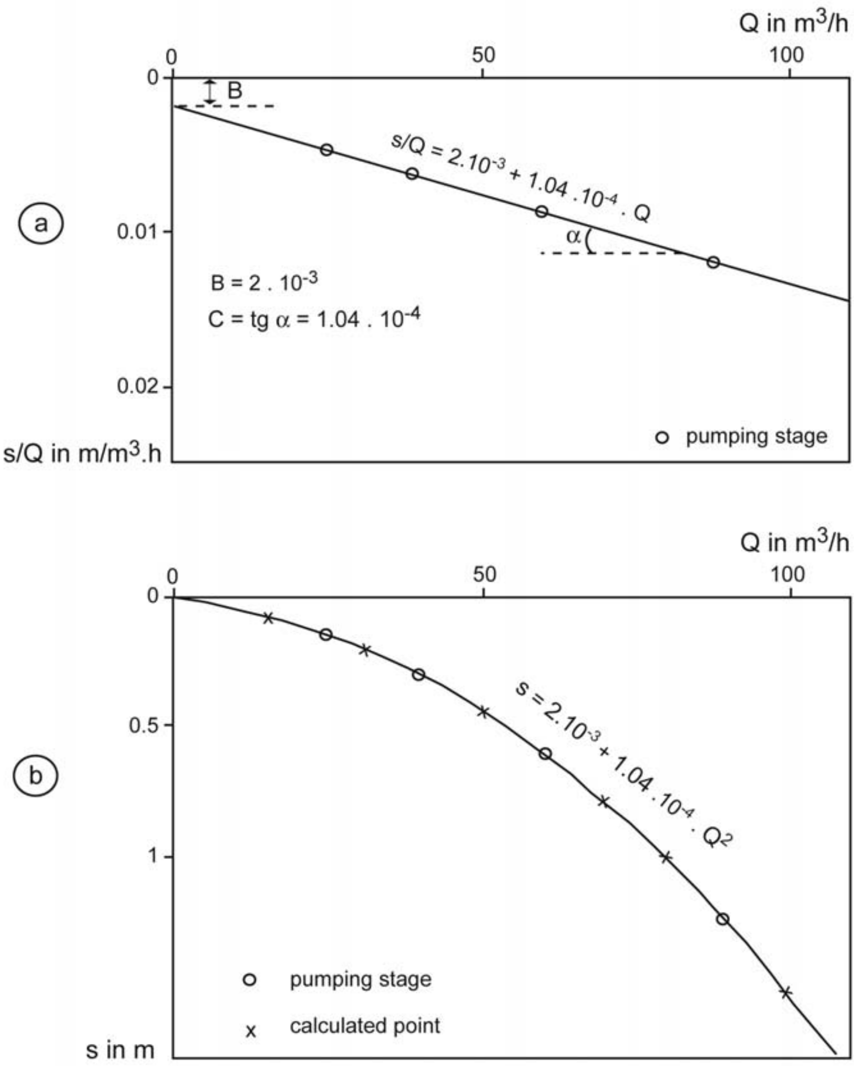


Figure 72 Discharge/drawdown curves. Specific (a) and characteristic (b) (La Trinité, Alpes-Maritimes).

5.3.2 Aquifer tests

These allow the evaluation of an aquifer's hydrodynamic parameters, the specification of its limit conditions and its eventual heterogeneities, and the prediction of drawdown effects as a function of the pumping discharge, as well as possible environmental effects over a varying distance.

They are done with a constant discharge over a period of 1 to 3 days, possibly more for long-term testing, and require the creation of a peripheral piezometer network. Monitored parameters include the pumped discharge and the level of the water table in the pumping well and in the piezometers. One can also observe the rise of the water table in the pumping well and in the piezometers as soon as pumping is stopped (Figure 73).

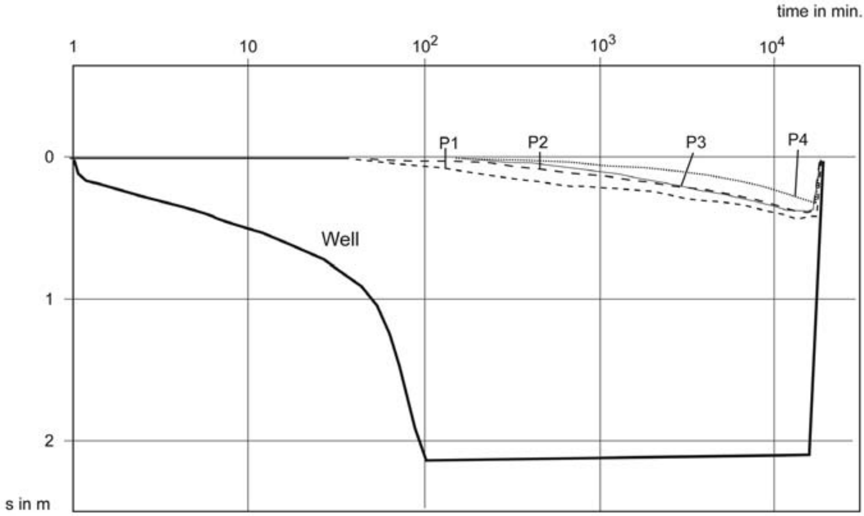


Figure 73 Example of a pumping test. Alluvial aquifer of the Loup River (Alpes-Maritimes).

The pumping data are graphed, with time, t, in logarithmic abcissa (in hours, minutes, or seconds), and the drawdown, s, or the residual drawdown, sr (for the rise), on a linear scale (in meters or centimeters).

The data points create a representative curve for the test, the first part of which shows the well's capacity, and whose alignment along a straight line would represent a test in an unlimited aquifer.

The transmissivity, T, can be calculated with Jacob's logarithmic approximation method:

$$T = 0.183 \cdot Q/c,$$

where Q is the pumping discharge (in $m^3 \cdot h^{-1}$) and c is the slope of the line.

The storativity, S, determined from piezometric curves, is given by the following equation:

$$S = (2.25 \cdot T \cdot t_0)/x^2,$$

where T is transmissivity (in $m^2 \cdot s^{-1}$), t_0 is the time of intersection between the drawdown (or recharge) curve and the initial piezometric level (in s), and x is the distance between the pumping well and the piezometer in question (in m).

This method can be illustrated by a pumping test in the alluvial aquifer of the Loup river (Alpes-Maritimes), over 14 days (Figure 73). The test was performed in a well 9 m deep, with a discharge of 45 $m^3 \cdot h^{-1}$, and the water table height was monitored in the pumping well and in 4 peripheral piezometers, at distances, respectively, of 76 m (P1), 112 m (P2), 107 m (P3), and 260 m (P4).

The curves show the drop in water level of the pumping well during pumping, and the different reactions in each piezometer. The latter are not proportional to their respective distances from the well, and reveal the horizontal heterogeneity of the alluvial aquifer.

The first rectilinear portion of the curves allows the calculation of the aquifer's characteristic parameters, leading to the values in the following table (Table 11).

Table 11 Characteristic Parameters of the Alluvial Loup Aquifer (Alpes-Maritimes).

Point	Transmissivity T ($m^2 \cdot s^{-1}$)	Storativity S (%)
Pumping well	$0.47.10^{-2}$	
P1	$2.32.10^{-2}$	$2.33.10^{-2}$
P2	$2.59.10^{-2}$	$4.93.10^{-2}$
P3	$1.53.10^{-2}$	$7.20.10^{-2}$
P4	$2.36.10^{-2}$	$2.96.10^{-2}$

The curves then present commonly encountered variations for pumping tests, first a doubling of the slope, then stabilisation before the pumping was stopped.

The doubling of the slope (beyond point i on the figure) indicates the existence of an impermeable lateral barrier, probably one of the banks of the filled-in channels within which is established the alluvial reservoir. The image well method allowed an estimate of the limit's distance at between 230 m and 450 m, depending on the point under consideration (well or piezometer), which is totally compatible with the known geologic structure and with the superficial extent of alluvium.

The final stabilization is characteristic of a lateral inflow front at a set level, represented by the Loup River, which is closely linked to its accompanying aquifer.

6 WATER ANALYSES

Natural physical, chemical, isotopic, or microbiological tracers are a powerful tool in understanding groundwater. Indeed, at any observation point (piezometer, cave), natural exit (spring), or artificial outlet (catchment, gallery, well, borehole), groundwater carries a message indicating its origins and the source of its mineralization, the global hydrologic balance of its recharge zone and the different components of the hydrosystem, its residence time in the reservoir, and its natural or artificial sources of contamination. This message can be interpreted if the identifiable chemical components present sufficient contrasts in concentration. Unlike mandatory analyses, the nature and frequency of which are legally mandated, prospecting analyses can consider any relevant tracer, whether natural or anthropogenic (see chap. 11), and any range of time and space.

6.1 Physical and chemical analyses

These analyses, done by various organizations, allow the determination, for example, of sources of mineralization, the evaluation of global hydrologic budgets, and the inputs from different components of the hydrosystem. We will illustrate the value of natural tracers with a few examples.

6.1.1 The role of soil and superficial reservoirs. Example of the Montagne Noire (Guyot, 1983)

Poussarou and Malibert are two karst springs, issuing from Cambrian limestone and dolomite. Their respective contiguous recharge areas have the same surface (19 km^2) and the same altitude; subjected to the same climate, they differ only in their soil and vegetation cover.

The catchment basin with a poor soil cover, Poussarou, has a more abrupt hydrologic response, briefer and more pointed, but the subsequent falling discharge is less sustained (Figure 74). The chloride content tends to decrease during the peak. In Malibert, on the other hand, the soil and the epikarst dampen the peak (delay, attenuation) and sustain the subsequent decrease; the chlorides present a peak followed by a decrease, before returning to the level of background noise. During infiltration episodes, the soil and superficial reservoirs therefore undergo leaching of the solutions that evaporation had concentrated there.

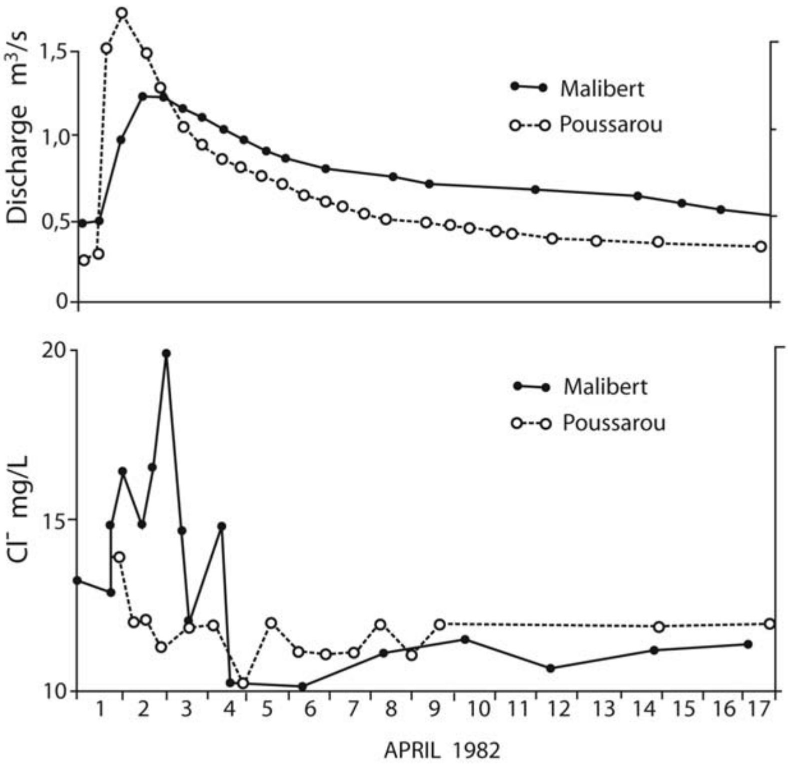


Figure 74 Discharge and chloride content after rainfall.

6.1.2 Effective rainfall signature. Example of the Fontaine de Vaucluse (Mudry, 1987; Emblanch, 1997)

Infiltration following a precipitation event has characteristic meteoric tracers (chlorides) or pedogenic tracers (nitrates, organic carbon), and a characteristic lack of tracers due to a long residence time (silica, magnesium). The Fontaine de Vaucluse clearly shows magnesium dilution concomitant with increasing chloride concentrations (Figure 75). Dissolved organic carbon, or DOC (humic and fulvic acids), is another tracer leached from soil, but one with a non-conservative behavior: it becomes mineralized over time by transforming into CO_2, then into bicarbonates. Its presence at the outlets of a hydrosystem indicates a very brief transit time between soil and emergence. Figure 75 shows the October discharge peak, which includes a series of peaks with very brief residence times (a few days), separated by water having undergone a decrease in its DOC content.

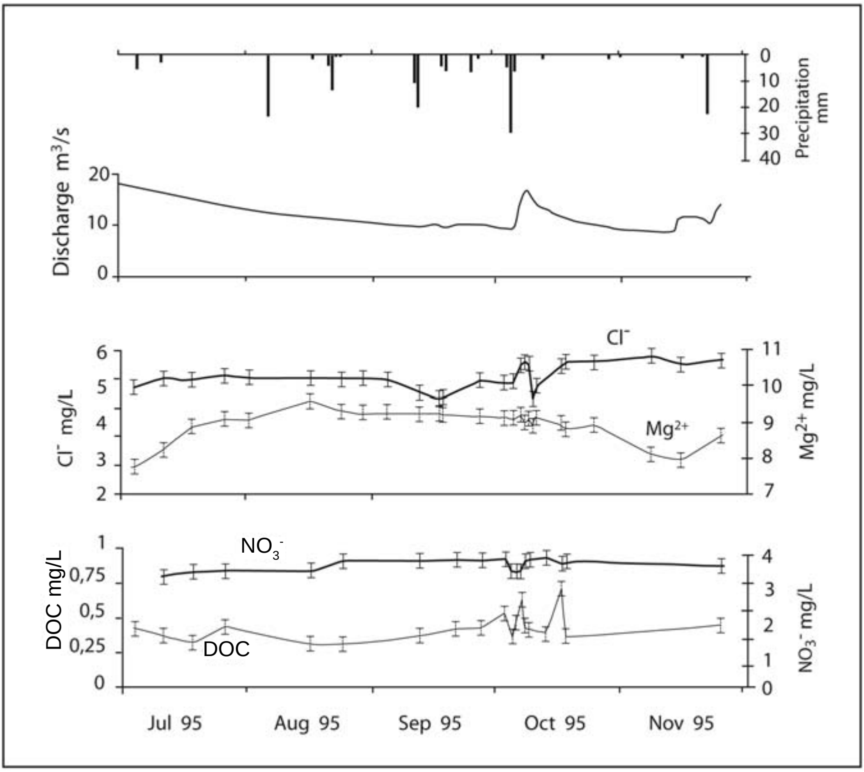


Figure 75 Dilution of reservoir tracers and increase in superficial tracers during a discharge peak.

6.1.3 Recharge components

a) Example of the Souss aquifer (Morocco, Hsissou *et al.*, 1999)

The complex Souss aquifer (Agadir) is in contact with the Ocean, but is also fed by infiltration from the wadis (rivers) issuing from the Western High-Atlas mountains. These wadis drain gypsiferous terrain (Cretaceous) and saliferous terrain (Triassic). Water of marine origin (current salt water intrusion, sedimentary paleosalinity, marine rainy spindrift) is located along the line of "dilution" of seawater (Figure 76).

Water originatin in evaporites (gypsum, halite) or from anthropogenic use (infiltrated wastewater) can be identified by a lower concentration in bromide. This bromide content, compared to the chloride content, thus allows the mapping of recharge zones in the aquifer.

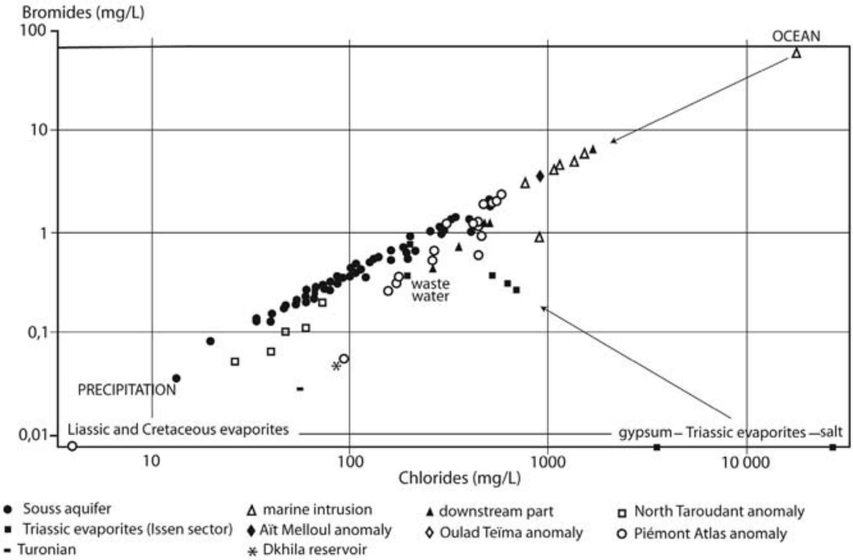


Figure 76 Marine or evaporite origins of water in the Souss aquifer (Maroc).

b) Example of the lower Var valley (Guglielmi & Mudry, 1996)

The alluvial aquifer in the lower Var valley can be fed by the infiltration of river water and by discharge from aquifers in the contiguous hillsides. The chemical characteristics of the two types of water are clearly differentiated: the Var river, which drains the Triassic (gypsiferous) bases of subalpine overthrusts, has a high sulfate content (150 to 200 mg·L^{-1}, compared to 0 to 20 mg·L^{-1} for hillside aquifers). The Pliocene puddingstone of the hills, rich in bedrock silicates, gives water a high silica content (15 to 30 mg·L^{-1}, compared to 5 to 7 mg·L^{-1} for Var water). A simple mixture of the two-component model (aquifer flux = Var flux + Pliocene flux) allows both the evaluation of inflows at a given point over time, and the mapping of each environment zone of contribution (Figure 77).

The Var's high precipitation zones (headwaters, middle segment) have a piezometry diverging downstream, corroborating this recharge. The zones of high hillside contribution have a piezometry converging towards the river, confirming that the hills drain to the river.

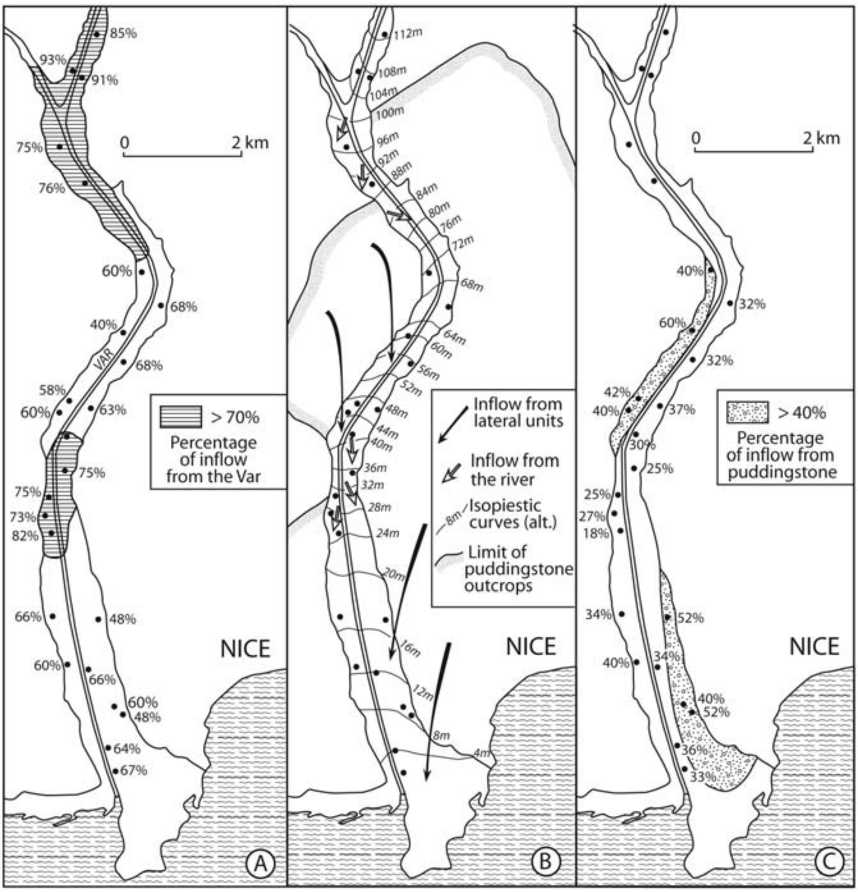


Figure 77 Recharge of an aquifer by a river and by the surrounding hills.

6.1.4 Decline of water quality during exploitation. Example of the Pinchinade graben, (Mouans-Sartoux, Alpes-Maritimes) (Reynaud *et al.*, 1999)

The exploitation of a well in a Jurassic limestone graben within the gypsiferous Provençal Keuper clays demonstrates a decline in quality of the extracted water over time, when drawdown exceeds 30 m (Figure 78). The nitrate content of the water decreases; its sulfate content increases. The inflows to the pumping well change: initially, pumping mobilises recent water, easily infiltrated through limestone. This water has leached the graben's soil (nitrates). The restricted size of the reservoir imposes a lateral realimentation by older water having resided in gypsiferous clays (sulfates), but devoid of shallow tracers (nitrates).

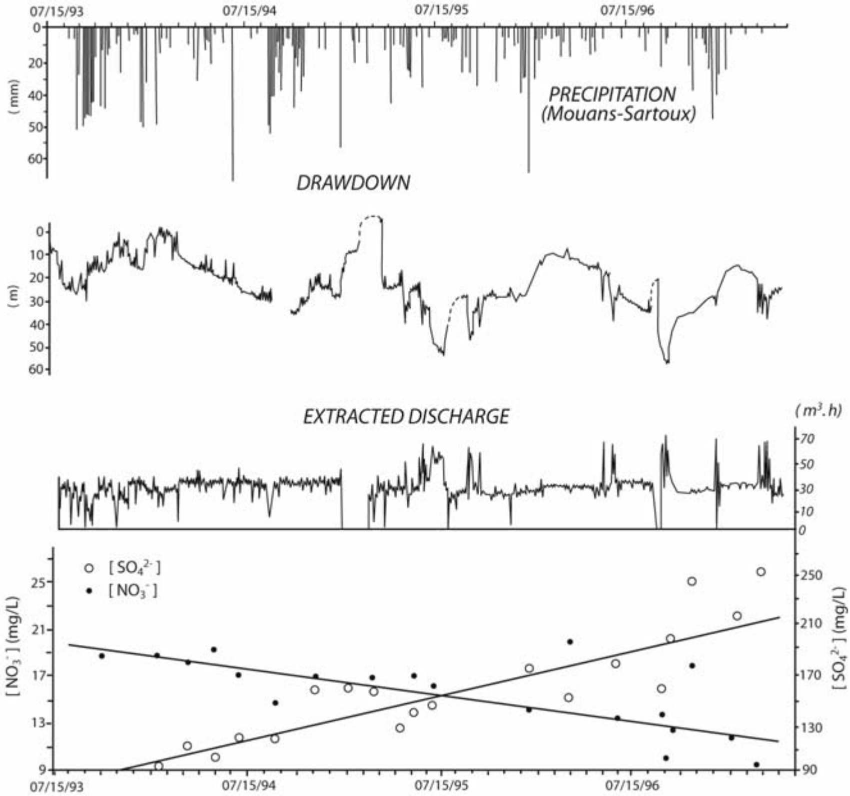


Figure 78 Evolution of the anion content during exploitation of a well.

6.2 Isotopes

6.2.1 Usefulness in hydrogeology

Environmental isotopes are today an invaluable tool in the study of groundwater, as much for prospection as for protection of resources. Isotopes provide fundamental information when data is inadequate and classical methods are inapplicable. Table 12 gives the principal applications of the most common tracers: location, date and magnitude of recharge, water-gas interactions (CO_2, H_2S), and water-rock interactions (silicates, carbonates, sulfides, evaporites), residence time in a saturated or confined zone, origin of pollution….

Table 12 Principal Isotopes Used in Hydrogeological Prospection.

ISOTOPE	Stable	Radioactive
in water	**^{18}O** recharge elevation seasonal dephasing paleorecharge	
	^{2}H + ^{18}O soil evaporation /unsaturated zone/ saturated zone carbonate/silicate exchange H_2S exchange	**^{3}H** dating: < 30 years
	^{13}C nature of vegetation deep/biogenic CO_2 exchange solide carbonate exchange/dating	**^{14}C** dating: < 25,000 years
in solutes	**^{34}S** origin of sulfur: pyrite/evaporite oxidation	**^{36}Cl** dating: < 250,000 years
	^{15}N origin of nitrogen: fertilizers/livestock/sewage	
	^{87}Sr origin of mineralization: bedrock/evaporites/carbonates	

6.2.2 Determining an aquifer's catchment basin: example of the Fontaine de Vaucluse (Blavoux *et al.*, 1992; Malzieu, 1987)

In order to determine the average elevation of a large zone of diffuse recharge for an aquifer (the Vaucluse system), one selects, in the same geologic, geomorphological, and climatic context, springs with a well-known recharge zone (Figure 79). One simultaneously takes samples from these reference springs and from the spring under study, during the dry season (so as to

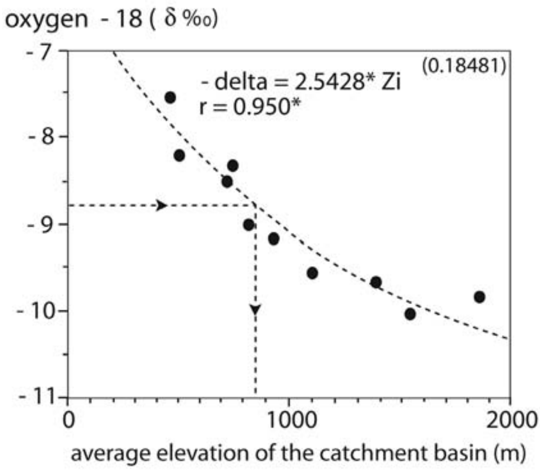


Figure 79 Determination of the average recharge elevation of an aquifer.

obtain water from the system's reserves). The reference springs allow the adjustment (linear, or exponential, in Mediterranean regions with a non-linear relationship between effective rainfall and elevation) of the elevation-^{18}O relationship. $\delta^{18}O$ indeed varies with temperature (low→warm→not very negative, high→cold→highly negative).

This nomogram allows the estimation of the average recharge elevation for the aquifer's reserves.

6.2.3 *Water-soil gas-rock exchanges: example of the Doubs valley deep karst* (Celle-Jeanton *et al.*, 2003; Mudry *et al.*, 2002)

The infiltration caused by a precipitation event dissolves carbon dioxide in the soil, which is indicated in our climate by a $\delta^{13}C$ of –22‰. This CO_2 corrodes solide carbonates, in which the $\delta^{13}C$ is around 0‰. Stoichiometrically, a molecule of CO_2 attacks a molecule of carbonate to give two molecules of HCO_3^-, therefore marked with the average of –11‰. Water transiting rapidly in carbonate rock, isolated from the soil atmosphere (saturated zone), will retain its original mark (Figure 80). Water stored in the unsaturated zone (perched aquifer, epikarst aquifer), will exchange carbon with the soil atmosphere and will therefore be depleted with respect to the initial –11‰. On the other hand, water redissolving carbonate after having precipitated it into the aquifer (very slow transit) will be enriched in ^{13}C. Figure 80 shows these three types of water in the Doubs valley karsts upstream of Besançon.

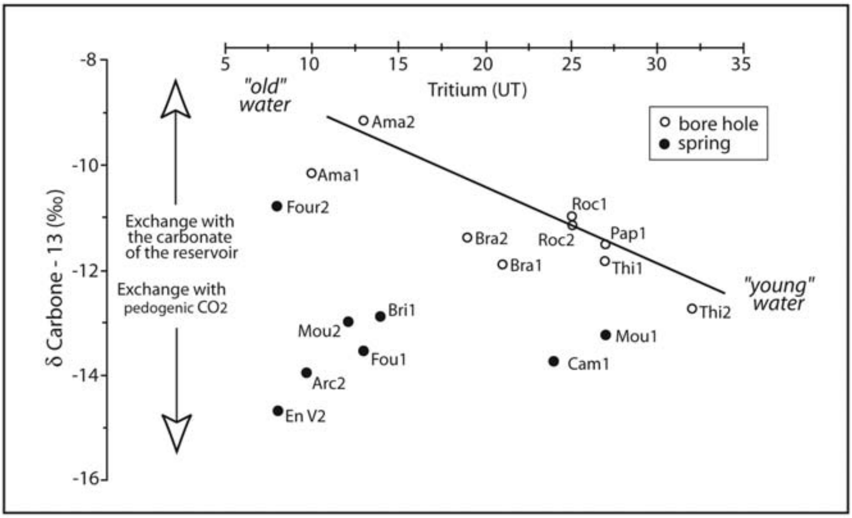


Figure 80 "Deep" karst of the Doubs valley: circulation paths.

6.3 Microbiologic analyses

These analyses concern a wide spectrum of micro-organisms, varying in size depending on the width of the pores or fractures through which water passes. In groundwater analyses, micro-organisms include viruses, bacteria, protozoans, and small multicellular organisms of < 150 µm (Zwahlen, Editor-in-chief, 2004). Their analysis can be done after *in vitro* culture or not.

Micro-organisms living in biofilms play a role in trapping various types of bacteria, which can be released under certain conditions (for example during floods). Biofilms therefore increase microbes' survival. During transport, micro-organisms are affected by their own intrinsic characteristics, but also by their environment (soil, sediment, unsaturated zone, discharge). The transport mechanisms affecting colloids (particles of 0.001 to 1 µm, kept in suspension by Brownian motion) can also apply to viruses and bacteria (Figure 81), which are of similar size. Based on the size of the empty voids in an aquifer, bacteria and protozoans (but not viruses) are likely to be physically filtered out, or subjected to sedimentation, if the flow velocity is low enough.

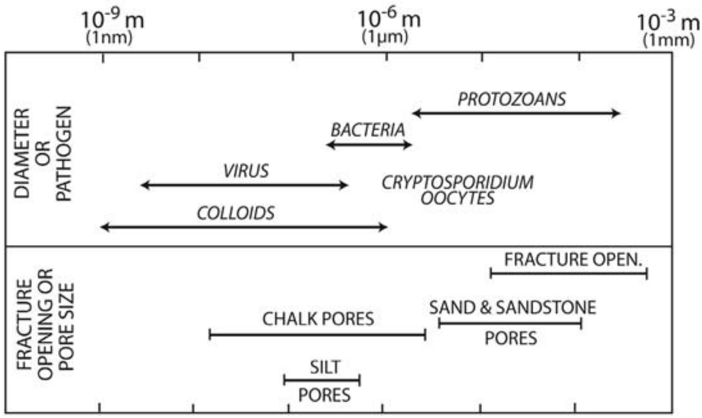


Figure 81 Size of micro-organisms compared to pore size in aquifers (West *et al.*, 1998 in Zwahlen 2004).

The lifespan of micro-organisms (including pathogens) is determined by temperature (cold is favorable), the type of organism, its predators, water chemistry, and particularly, the organic carbon content and shaliness (adsorption). The presence of indigenous bacterial populations can result in a lower survival rate for allogenous microbes.

7 STUDY METHODS FOR KARST AQUIFERS

7.1 Particularities of karst

Unlike porous or fractured aquifers, which obey Darcy's Law and where the study of a small subset of the aquifer (sample, well, borehole) can be extrapolated over a large portion of the reservoir, karst, heterogeneous and hierarchical, requires a more complex approach including on the one hand a global study of the aquifer's mechanics, and on the other hand detailed analyses in the case, for example, of a catchment project or an attempt to fight pollution.

Karst aquifers keep the traces of their different stages of emplacement. A karst system is therefore an often-anarchical-seeming juxtaposition of poorly permeable or even impermeable zones, of cavities filled with water, air, or sediment, or underground rivers or lakes, of water-filled fissures and of submerged drains. The circulation velocity of water in the same aquifer can be slow in fissured zones and very rapid in drains.

Due to this anisotropy, karst systems rely on specifically adapted methods.

7.2 Paleogeographic studies

Karst systems generally being polyphasic, it is important to precisely define their emplacement conditions, in order to evaluate the positions of drainages and reserve zones. Alluvial terraces, benches, perched valleys, temporary outlets, tuff accumulations, etc. are so many geomorphologic clues to understanding the karst system. Analyses can also be done in the endokarst, where the study of the infilling and the staging of galleries will help to explain the evolution of the system.

In coastal environments, bathymetric analyses can help detail the variations in base level linked to eustatism, and indicate submarine valleys linked to the presence of paleosprings (see Port Miou example, chap. A9-2.5).

7.3 Hydrometric, physical, and chemical studies

7.3.1 Discharge

A karst emergence making up the final outlet of a complex capacitative and transmissive system, discharge variations and physical and chemical parameters are so many signals revealing its internal structure, and the analysis of which will provide indications on the internal organization and mechanisms of the aquifer. The following curve (Figure 82), where the smallest rainy period results in a discharge peak, indicates that the system has little storage, as two months are enough to drain it. In addition, the breaks in the slope observed during the emptying of the system following discharge peaks reflect the existence of two compartments, confirming the geologic and structural conditions of the system (Figure 83).

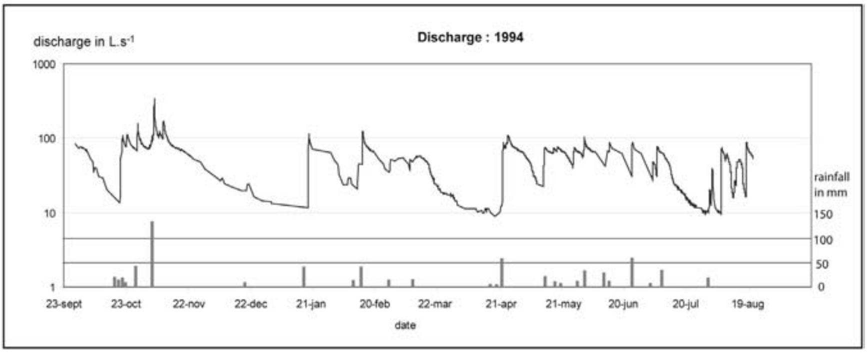


Figure 82 Discharge at the Foux de Lucéram (Alpes-Maritimes). Data from HYDRO, DIREN.

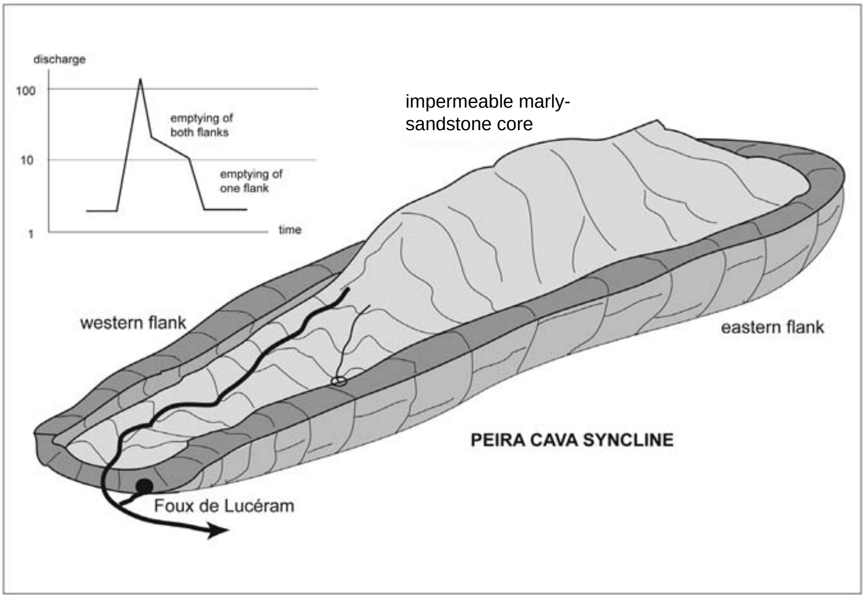


Figure 83 Block diagram of the Peira Cava syncline (Alpes-Maritimes).
The Foux de Lucéram, which drains the limestone, is fed by the two limbs of the syncline.

7.3.2 Physical and chemical parameters

In the same manner, since recharge and discharge reactions are clearly marked and due to the frequency of encountering a single outlet, the study of variations in different physical and chemical parameters can provide information on the deep structure of the aquifer (see chap. B3-6).

7.4 Speleology

This activity was born from hydrogeology, with the engineer Lindner who, in order to ensure a water supply for Trieste (Italy), hoped to find an underground access to the Reka, a river disappearing below ground in the village of Skojcan (current Slovenia) and re-emerging at the spring of Timavo near Trieste. Daring explorations thus led him to the Trebiciano chasm, 327 m below ground, where he finally found the underground river, but remained unable to capture it due to the limits of the available technology. Shortly afterwards, in 1888, E.A. Martel demonstrated in France that it was possible to follow the underground path of the Bonheur brook, which disappears below ground near the village of Camprieu (Gard) and reemerges a few kilometers away at the Bramabiau spring.

In a little over a century, speleology has made immense progress. Prospection methods, the clearing of entryways and underground passageways, and techniques for vertical progression with a single rope have pushed the limits of exploration, enabling the discovery of thousands of kilometers of caves and chasms, which are so many examples of the infiltration and circulation of water in karst aquifers. Over 550 km of passageways have been explored in Mammoth Cave (USA), and over 100 km of wells and galleries in Coume Ouarnède (France). Ever-more daring diving techniques enable the exploration, over kilometers, of major drainages in the very heart of aquifers. Karst systems are therefore beginning to be better understood, from their infiltration surfaces all the way to their outlets. Current speleologic data is in the process of modifying our understanding of the peri-Mediterranean karst hydrogeology (see chap. A9).

Speleology can have several applications in hydrogeology, by enabling:

- knowledge of the geology and geometry of the karst system;
- direct access to karst aquifers and submerged drains;
- access to underground rivers contributing to the alimentation of the saturated zone;
- access to injection points for tracers.

7.4.1 Locating accessible drainages

A karst aquifer and its compartments and annex-to-drain systems are drained by passageways converging towards a major drain feeding the emergence. The resource is generally accessible by drilling over the entirety of the saturated zone, as the distribution of discontinuities, paired with the polyphasage of karst systems, generally allows the interception of productive zones, with the condition that drilling should be expected to extend well below the piezometric surface. Encountering blocks of totally impermeable limestone extending over 100 m is common. The exploitation of a karst aquifer is optimal when it is possible to draw water directly from a drainage passageway. In addition, conduits, perched above the karst aquifers that they contribute to sustaining, can be interesting resources close to the surface in zones with sharp relief.

The detection of submerged or vadose drains from the surface, and their precise mapping in order to place a borehole or a gallery, is therefore an interesting objective, which unfortunately remains problematic, even when the cavities have already been explored by speleologists. Another difficulty is ensuring a perfectly vertical borehole.

a) Topographic surveying

Using classic speleologic techniques, compass, level, and laser range-finder, a topographic survey is done in successive steps, working through the galleries of a cave, and correction by triangulation is impossible. Even though errors generally balance out, it is rarely possible to exceed a precision of 1%, rarely sufficient when attempting to reach, by drilling, a target a few meters across at a depth of 300 to 400 m. When, in 1957, EDF wished to capture the underground river in the Pierre-St-Martin chasm (Pyrénées Atlantiques) by digging a tunnel into the side of a mountain, in order to produce electricity for the valley of Ste. Engrace, the error in the position of the Verna chamber (200 m in diameter), was of 400 m. The work of a geometer with a theodolite and declinometer is necessary, and a precision of 1% is then possible, but at the price of difficulties in the execution.

b) Radiolocation

The best results were obtained by placing an electromagnetic emitter below ground, and detecting the emissions at the surface with a receptor. The emitting coil is placed horizontally, so as to create a vertical magnetic field. It can be installed in an inflatable float on the surface of a lake. The signal is detected at the surface by a vertical receptor coil, for which the signal cancels out when its surface is oriented towards the magnetic axis. Different surface measures therefore intersect above the zone holding the emitter. This method allowed the precise calculation of the lake at the end of the Qattine Azar chasm in Lebanon, below approximately 300 m of rock, the goal being to increase the water resources for the east of Beyrouth (Courbon, 2002).

Several catchments using similar methods have been emplaced, among which can be cited that of the Trou-de-Garde underground river by a borehole 120 m below the Féclaz plateau in Savoy, and that of the Trou-qui-Souffle in Vercors, which supplies the towns of Méaudre and Autran, thanks to a borehole 300 m deep drilled in 1989.

c) Magnetic methods

When the gallery is entirely submerged and accessible only to divers, it is possible to deposit a magnetic bar and to detect it from the surface with a magnetometer. This method enabled the precise mapping of the drain for the Lez spring (see chap. C4-4.2).

7.4.2 Locating unknown drains

Different geophysical methods were defined in chapter B2-2. Although results are generally disappointing, certain methods have sometimes confirmed, from the surface, the presence of cavities, either empty or filled with water or sediment:

- electric surveying,
- microgravimetry,
- MRS (magnetic resonance sounding).

This last method is based on exciting the protons in the hydrogen atoms of the water molecule with an electromagnetic field, and measuring their resonance signals once they are no longer being stimulated. The signal is proportional to the amount of water below ground. It can reveal important volumes of water when they are close to the surface. Tests in the causse de l'Hortus (Hérault) detected the karst conduit, 40 m below the surface, supplying the Lamalou spring (Vouillamoz *et al.*, 2003).

7.5 Tracer tests

They are essential to karst hydrogeology. A substance, not naturally present in the environment, is injected at a certain point, and is then looked for downstream, in the waters of a spring, a river, a chasm, or a well. Depending on the goals of the test and the substances used, detection is done by using the naked eye, by taking samples for analysis, by continuous recording of fluorescence in the field, or by placing packets of activated charcoal in the water to capture certain tracers. Given the cost and the difficulties in execution of such operations, multitracer tests are common, in which several different products are simultaneously injected in different locations.

7.5.1 Qualitative approach

This is a binary test. A tracer injected at a certain point emerges or does not emerge at a spring. This is how the French caver Norbert Casteret proved, in 1931, that the Garonne originated in Spain and disappeared into the Trou du Toro, only to reemerge at the Goueil de Jouéou before flowing into France.

A tracer test can be accidental, as was the case in 1901, when, as the Pernod distillery in Pontarlier caught fire, all the reserves of alcohol and liquor were emptied into the Doubs to prevent the entire town from going up in flames. A few days later, the Loue spring was contaminated by absinthe, proving a link with losses from the Doubs.

7.5.2 Quantitative approach

The restitution of the tracer(s) is examined, based on the discharge of the spring and the precipitation over the catchment area. The arrival time, the shape of the breakthrough curve, and the recovery rate provide information about the aquifer:

- rapid and concentrated restitution indicates an evolved degree of karstification and small reserves. The tracer may have been injected into a conduit in direct communication with the emergence (Figure 84);
- slow, diluted restitution indicates that the tracer passed through a capacitative area, or that karstification is poorly evolved (Figure 84);
- restitution in successive waves correlated with rainy periods indicates that the tracer remains blocked in the epikarst or in an annex compartment;
- the presence of peaks in the absence of discontinuous rainfalls can indicate splitting off and compartmentalization of the aquifer.

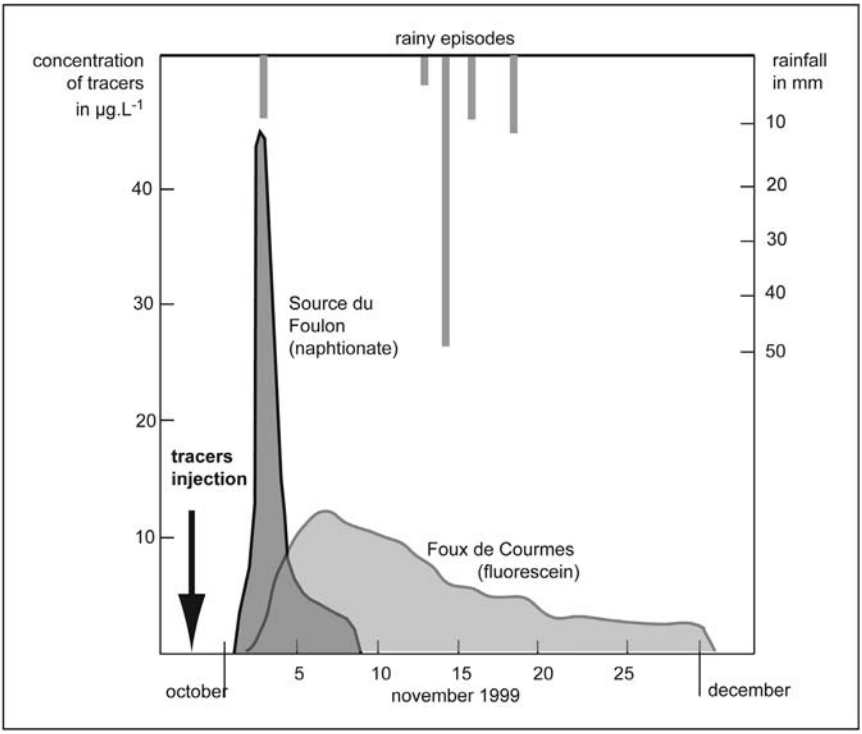


Figure 84 Example of two different restitution curves for two neighboring springs during a multitracer operation (from Mangan, 2000, unpublished).

Tracer tests are always delicate and costly operations, requiring a rigorous operating and interpretation protocol. A few causes of failure should be highlighted:

- quantity of tracer is too small;
- not enough points being monitored;
- tracer is injected into an impermeable compartment;
- monitoring period is too short;
- disappearance of monitoring equipment (theft, flooding);
- erosion of monitoring equipment or clogging by organic material;
- lack of circulation in the compartment (pronounced dry period). (This last cause is very problematic, as the tracer will stay in storage until the next rainfall. It can then modify the results of other tracer tests);
- contamination of samples by the tracing substance still present on hands, injection equipment, car,….

The most commonly used tracers are fluorescent ones, as spectrofluorimetric analysis is not costly and can detect very low concentrations. Furthermore, field devices enable now to perform continuous measurements.

Table 13 A Few Tracers Used in Karst Hydrogeology.

Product	Color	Analysis methods	Detection threshold	Fixes to activated charcoal	Drawbacks
fluorescein	green	fluorescence	a few μg·L^{-1}	yes	can be mistaken for natural fluorescence and vice-versa
rhodamines	red	fluorescence	a few μg·L^{-1}	yes	adsorbs easily
eosin	pink	fluorescence	a few μg·L^{-1}	yes	spectral signature is similar to that of fluorescein
duasyn	blue	fluorescence	a few μg·L^{-1}	yes	not sold yet commercially in Europe
naphthol	no color	fluorescence	a few μg·L^{-1}	somewhat	can be mistaken for natural fluorescence and vice-versa
K iodide	no color	ionic chromatography	10 μg·L^{-1}	no	costly analysis
lithium chloride	no color	atomic absorption	10 μg·L^{-1}	no	costly analysis
Na Cl	no color	conductiviy	1 g·L^{-1}	no	requires large quantities
radioactive substances	no color	number of particles	_	no	delicate procedure
bacteria	no color	microscope	_	no	delicate procedure
bacteriophage viruses	no color	microscope	_		deteriorate in pumping
colored spores	variable	microscope	_	no	labor-intensive detection

When illuminated by a monochromatic beam of light at a specific wavelength in order to excite them, these substances emit a specific emission radiation.

The substance is not directly proportioned; instead the intensity of the fluorescing signal is measured. There is therefore the risk of confusion with pollutants or with naturally present substances in the water. A number of organic substances are fluorescent, with a maximum of around 250 nm (humic and fulvic acids). The dosing of tracers should therefore always be verified with qualitative research, a high concentration being capable of indicating only a natural fluorescence peak (Figure 85). Values that are too low are therefore not reliable, and a number of older tracer tests, once deemed positive, are now being questioned.

Qualitative monitoring of tracers is done with excitation spectra. Generally, natural fluorescence shows peaks with very elongated wavelengths (many fluorescent substances), whereas injected tracers show narrow, intense peaks. Nevertheless, a weak peak can in some cases be masked by a high background of natural fluorescence.

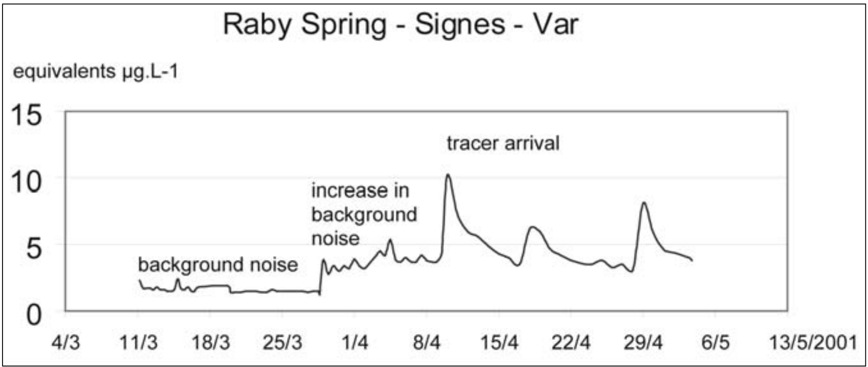


Figure 85 Fluorescence measurements characteristic of naphtionate restitution. The values preceding the april 8th peak are due to natural fluorescence.

When fluororeceptors are used, the activated charcoal they contain offers a large specific surface and, when left for a continuous period of time in running water, they adsorb the tracers that are present. The receptors therefore function as integrators of the flux of tracer that reappeared, and allow a semi-quantitative evaluation. The concentrations measured in the eluates are generally 10 times higher than in water; the sensitivity of the measurement is therefore improved. Unfortunately, the receptor also accumulates natural background fluorescence, making the information more difficult to use. Fluorescence monitoring equipment now enables continuous measurement of the passage of tracers, but requires qualitative confirmation.

7.6 Prolonged emptying tests

This method, developed in Algeria by Collignon (1986 and 1988), enables the rapid, simple, and precise evaluation of the water reserves stored in karst aquifers.

It relies on prolonged pumping, accompanied by rigorous monitoring of the extracted discharge and of the piezometric surface in the pumping well. It also must be done during a period without any influence from precipitation, and requires a very significant volume of extracted water (a few hundreds of thousands or a few million m^3).

Based on a large number of tests, Collignon demonstrated that, during high-discharge pumping in a well relying on a karst aquifer, the curve showing the evolution of the piezometric level as a function of the extracted discharge was reproducible, and marked by three distinct phases (Figure 86):

- instantaneous drawdown at the start of pumping and at each restart following a pause, with a magnitude of a few meters to a few tens of meters. This rapid decrease in the water level of the pumping well (generally over a time period of less than a day) corresponds to the establishment of a new permanent drainage pattern for the aquifer through the well, and represents the capacitative effect of the well and the losses of head in the perforated tubing and the fractures connecting the well with the karst conduit;
- a period of slow, regular decrease in the water level (from 1 to 20 cm per day), resulting from the slow emptying of the aquifer in the absence of any pluviometric influence;
- a more or less rapid rise in the piezometric surface once pumping is stopped. The residual drawdown represents the portion of the aquifer extracted by the test.

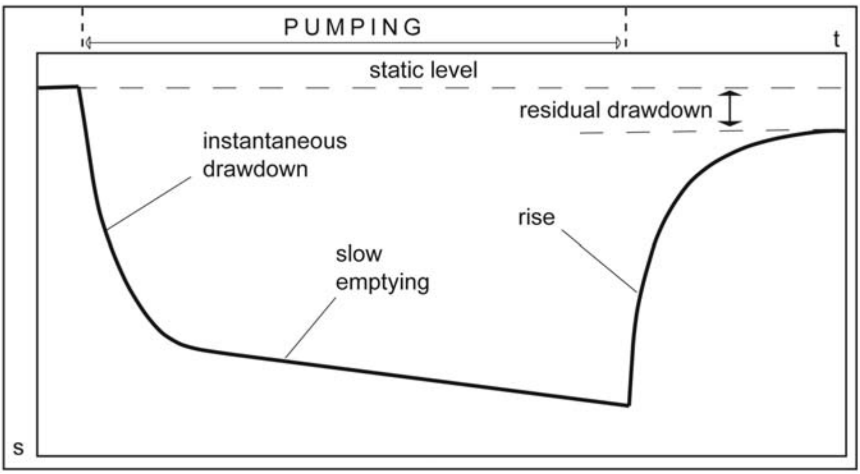


Figure 86 Typical curve for an emptying test (from Collignon, 1986).

The slow emptying phase is linear, indicating that the karst unit under consideration has the same behavior as a cylindrical reservoir perfectly connected to the well, with an impermeable envelope and constant capacitative properties over depth (at least in the slice of terrain affected by the test). The proportional relationship between the drawdown and the extracted volume enables an easy calculation of the specific volume Vs of the aquifer, which is equal to the volume of water extracted per meter of drawdown. In the example of Figure 87, the specific volume Vs is given by the relationship $\Delta V/\Delta s$ and has a value of 220,000 $m^3 \cdot m^{-1}$.

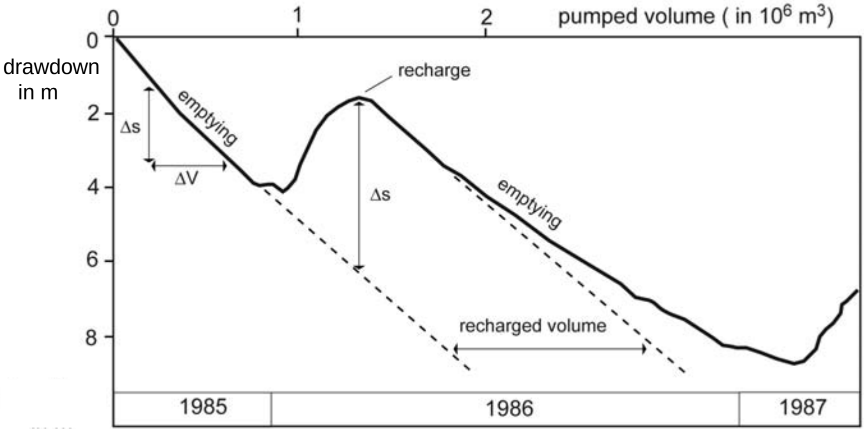


Figure 87 Example of long-term monitoring of a pumping well (from Collignon, 1988).

This test also enables the estimation of the permanent available reserve (equal to the volume of water stored in the aquifer at average low water), by taking the product of the specific volume and the usable height of the pumping well.

The emptying of the aquifer by pumping, in non influenced periods, is compensated by recharge of the aquifer by effective rainfall. The quantification of this recharge is represented graphically by the distance along the abscissa between two emptying lines, or by taking the product of the specific volume Vs and the recharge height on the Δs ordinate. In the example of Figure 87, the recharge volume for 1986 reached 1.1 million m^3.

In addition, the alternation over time of induced discharge and pluviometric recharge allows the evaluation of the renewable reserve, which is equal to the volume of water flowing into the aquifer over the course of one year, due to direct and indirect precipitation effects.

Finally, this type of test can reveal changes in the emptying curve over time, indicating variations within the aquifer or distant environmental effects. A steepening slope, for example, characteristic of a specific volume limit, can result from decreased permeability of the reservoir at a certain depth, or from loss of a lateral influx (stream losses, exchanges with a neighboring aquifer). Conversely, a decreasing slope indicates an increase in the specific volume and can be explained by a more permeable section of the aquifer, by a connection with a lateral reservoir, or by a decrease in losses due to leakage (drying of a spring).

This method is of primary interest to the exploitant of a water well, as it enables a direct evaluation of the reserve in the part of the aquifer directly connected to the pumping well. It can be complemented by appropriate research (tracer tests and physical and chemical monitoring), enabling a very good optimisation of our knowledge of karst aquifers, with the goal of actually managing their groundwater resources over both time and space. Two different examples of this method's applications are presented in chapter C5 (Mangan, 2000).

8 MODELLING GROUNDWATER FLOW

Porous environments, in which the three-dimensional distribution of properties is the most easily predicted, were the first type of aquifer examined through numerical modelling.

Depending on the quality and amount of quantitative data gathered for an aquifer, several types of models can be created.

8.1 Deterministic models

These use the hydraulic equation describing a porous medium, and consider the intergranular medium to be continuous. Their goal is to mimic the functioning of the aquifer: knowing its geometric parameters, its porosity, its transmissivity, its permeability, and its storativity, the model can simulate the impact of recharge (precipitation, stream losses) on the piezometry of the aquifer. The different phases of model construction are:

- the vertical and spatial discretisation of parameters in space (geographic gridding, Figure 89);
- the referencing of piezometric data (correlation between observed and calculated values)—this operation requires back-and-forthing between the results obtained and the hypotheses made based on the parameters;
- the predictive simulation of natural or artificial scenarios (flooding, drought, climate change, pumping, artificial recharge). They rely on three basic principles: conservation of mass from one grid square to another, flow according to Darcy's Law, and the elastic behavior of water. Deterministic models solve the diffusivity equation:

$$\mathrm{div}(K^* \,\mathrm{grad}h) = S_s \partial h/\partial t + q$$

where S_s is storativity, $\partial h/\partial t$ is the variation in hydraulic head, and q is discharge

In addition to this equation governing the flow of water, other equations describing the movement of pollutants can be used. The models then take into account a substance's molecular diffusion in water (independent of flow) and kinematic dispersion in pores (which depends on flow). Diffusion and dispersion are actually combined in the general term dispersion. Dispersion therefore has transversal and longitudinal components. Within the rock, water circulates at a velocity that varies from the edges to the center of a pore according to a parabolic curve, due to friction. Figure 88 shows a point source of pollution evolving as a dispersion front. Convection (or advection) is the transport of material by flow.

It is also necessary to take into account the interactions between the pollutant and the solid grains of the aquifer. One can compare conserved (or conservative) pollutants to evolving (or non-conservative) pollutants.

Deterministic models present both a cognitive value in terms of the behavior of the hydrosystem (confirmation of the parameters used and of their spatial distribution), and management value. MODFLOW is a very common model distributed by Waterloo.

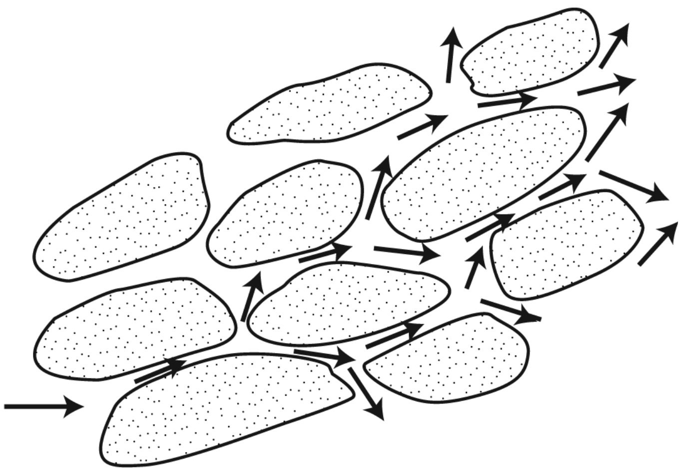


Figure 88 Dispersion of a tracer (or a pollutant) in intergranular spaces.

Figure 89 shows an example of piezometric reconstruction in the fluvioglacial cone of Pontarlier (Doubs), based on the given grid.

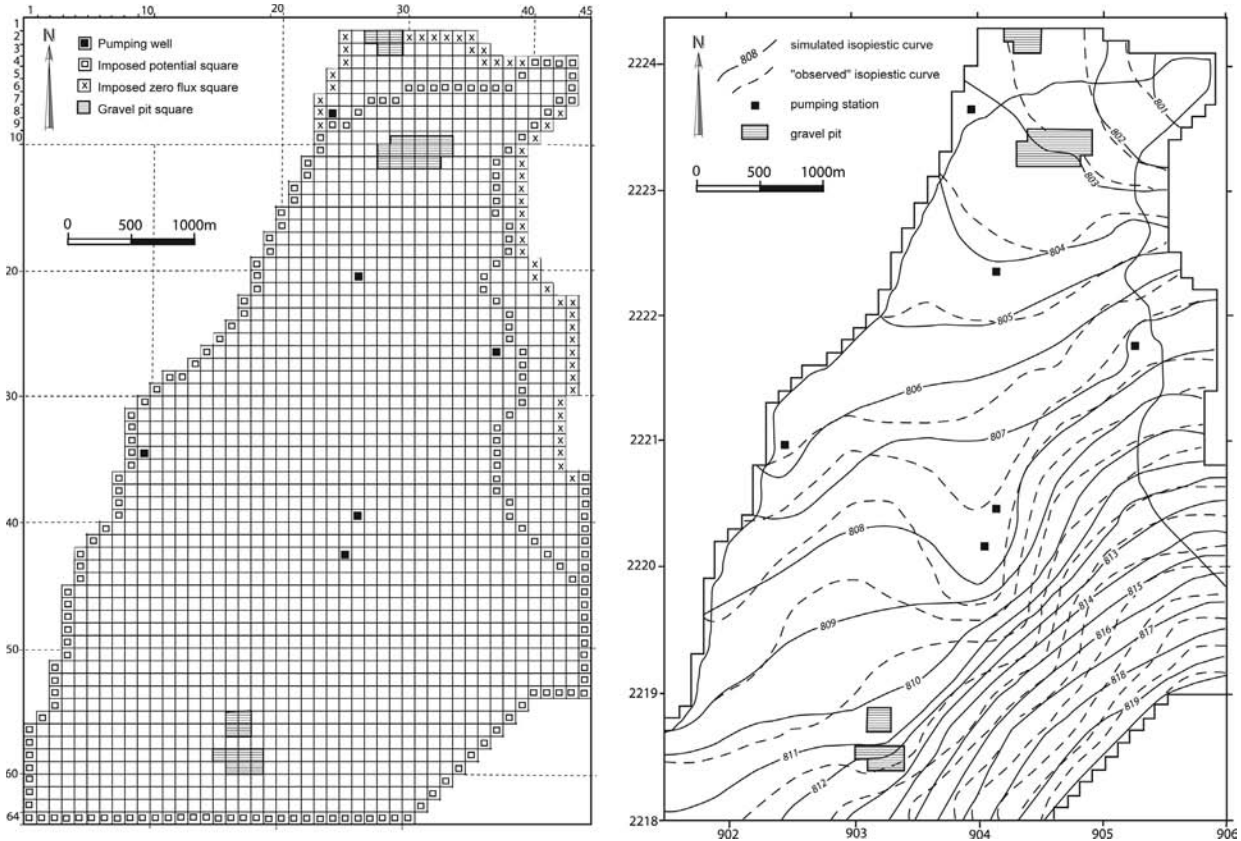


Figure 89 Gridding of the Pontarlier plain model (left), and reconstruction of high-water piezometry (right) (from Gaubi, 1993).

8.2 Stochastic or global models

These determine the transfer function linking the input variable (effective rainfall, for example) to an output variable (spring discharge, for example). These *black box* models do not take into account the actual properties of the environment. Their value is purely in terms of management, they do not confirm any parameters. Compartmentalized models, derivatives of the MERO model, use successive reservoirs. GARDENIA is a commonly used model (BRGM).

Chapter B4

Hydrogeologic Syntheses and Budgets

The final report produced for a study often relies heavily on structural and hydrogeologic maps detailing the general conditions in the study area, on interpreted cross-sections or block diagrams illustrating the limits of aquifers, and on schematic figures outlining the exchanges betwen reservoirs (see chap. B 2-5).

When the natural conditions are complex, it may also be necessary to illustrate certain situations with simplified figures, intended to make the presentation of problems that directly interest the reader more accessible.

1 DRAINAGE OF THE JURASSIC KARST UNITS ON THE EASTERN SIDE OF THE SUBALPINE CASTELLANE ARC, IN THE ALPES-MARITIMES

The drainage is principally through the Loup and Cagne valleys, whose deep gorges cut into the water-bearing units all the way down to its impermeable Triassic base. Other outlets, of lesser magnitude, line the aquifer's southern edge, at the contact with the underlying impermeable Triassic and Miocene units.

Figure 90 illustrates, in a simplified manner, the most probable extent of the catchment basins for the principal aquifers, based on the multiple arguments which guided the study as it progressed, notably:

- the impermeable limits of the reservoir, made up of basal Triassic units (at the bottom of the gorges, in anticlinal upwarps, and on the southwestern front), frontal Miocene units (inserted beneath the southeastern front's overthrust), and capping Cretaceous units (preserved in the centers of synclines to the northwest);
- the rough outlines of the structure of the aquifer formation, including the frontal overthrust, the main anticlinal axes, and the collecting faults;

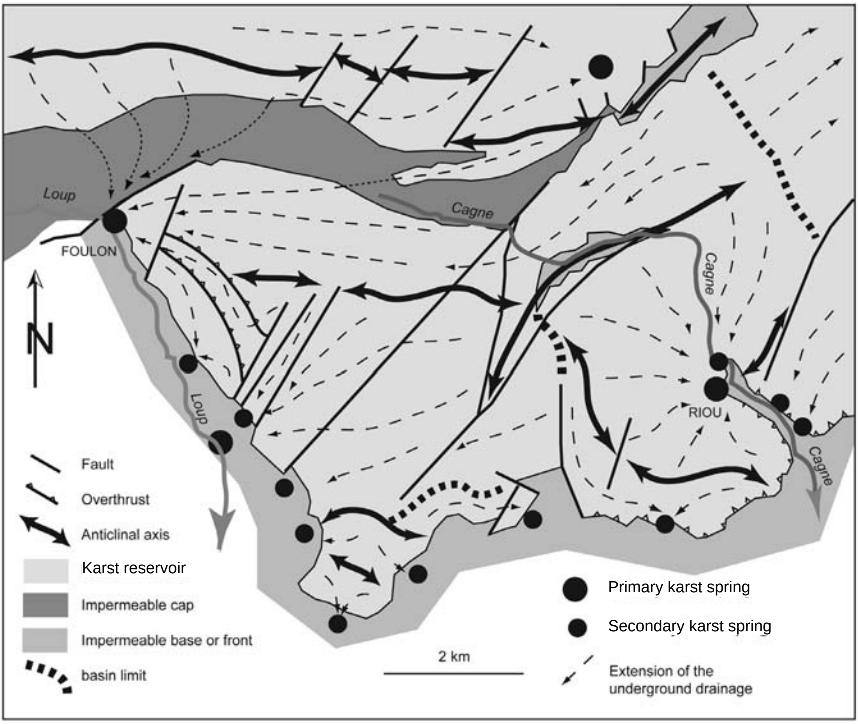


Figure 90 Catchment basins for karst units in the front of the subalpine arc drained by the Loup and Cagnes rivers (Alpes-Maritimes).

- the precise pinpointing of groundwater flow patterns based on the results of multi-tracer tests;
- the general analysis of the relationship between discharge at the outlets and the surface of the catchment basin, based on a specific infiltration module, locally placed at 18 $L{\cdot}s^{1}{\cdot}km^{-2}$;

2 DRAINAGE OF THE JURASSIC KARST MASS IN THE BRAGUE BASIN, IN THE PROVENÇAL FORELANDS OF THE ALPES-MARITIMES

The drainage is complicated by the vertical division of the area into two units on either side of an impermeable horizon, by multiple exchanges with its surroundings, and with largely hidden outlets.

The simplified presentation of known mechanisms appears in Figure 91, which provides a broad view of exchanges between the two karst aquifers (upper and lower), the hydrographic network (the Brague river and its tributaries, the Bouillide and the Valmasque), and the alluvial aquifer in

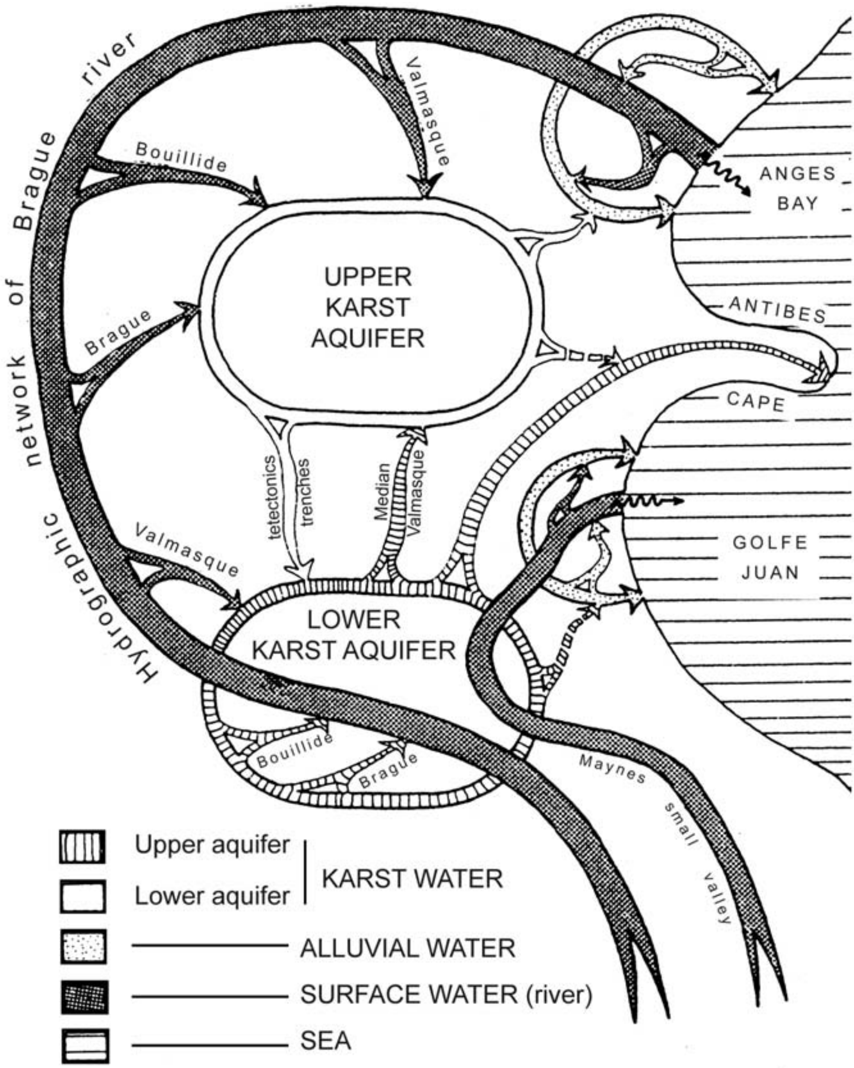


Figure 91 Brague Basin (Alpes-Maritimes). Schematic diagram of exchanges between the karst aquifers and their environment.

the lower valley and the sea (Mangan, 1986). Groundwater circulation in this system includes the following particularities:

- exchanges between the two aquifers, enabled by brittle deformation (grabens and transverse faults);
- partial drainage of the lower aquifer, in the upper part of the basin, by springs located at the contact with the intermediate impermeable layer (Brague and Bouillide);
- inflows to the upper aquifer from more or less pronounced stream losses;
- inflow to the alluvial aquifer from the upper aquifer in the lower Brague valley;
- outlets from the karst and alluvial aquifers hidden out at sea.

One should also note the following differentiation with respect to relationships between the surface and subterranean flow of water:

- at the base of the lower aquifer, the infiltration coefficient reaches only 32%, despite a much greater karst absorption, which is later partially returned to the stream network near the outcropping intermediate impermeable unit;
- at the base of the upper aquifer, infiltration is largely predominant, with an average value of 63%, and even reaching 80% in the lower Valmasque basin. This aquifer's outlets are nevertheless very small, due to the large, unseen outflow in the alluvial fill of the lower valley and out to sea.

3 DRAINAGE OF THE ALLUVIAL AQUIFER IN THE LOWER VAR VALLEY (ALPES-MARITIMES)

The alluvial aquifer accompanying the river is also highly dependent on inflows from the hillsides, both from the Jurassic karst aquifer and from the Pliocene puddingstone aquifer (Guglielmi, 1993) (see chap. B3-6.1.3b).

The schematic diagram in Figure 92 illustrates the drainage conditions of these different aquifers, determined by the local structure and mutual exchanges.

The hydrologic budget for the alluvial aquifer in 1991, with an upstream influx of 0.5 $m^3 \cdot s^{-1}$, compares 3.4 $m^3 \cdot s^{-1}$ of inputs (2.2 from the Var and 1.2 from the banks) to 3.6 $m^3 \cdot s^{-1}$ of losses (1.85 to the Var and 1.75 to pumping for drinking water). The positive remainder of 0.3 $m^3 \cdot s^{-1}$ reemerges at sea.

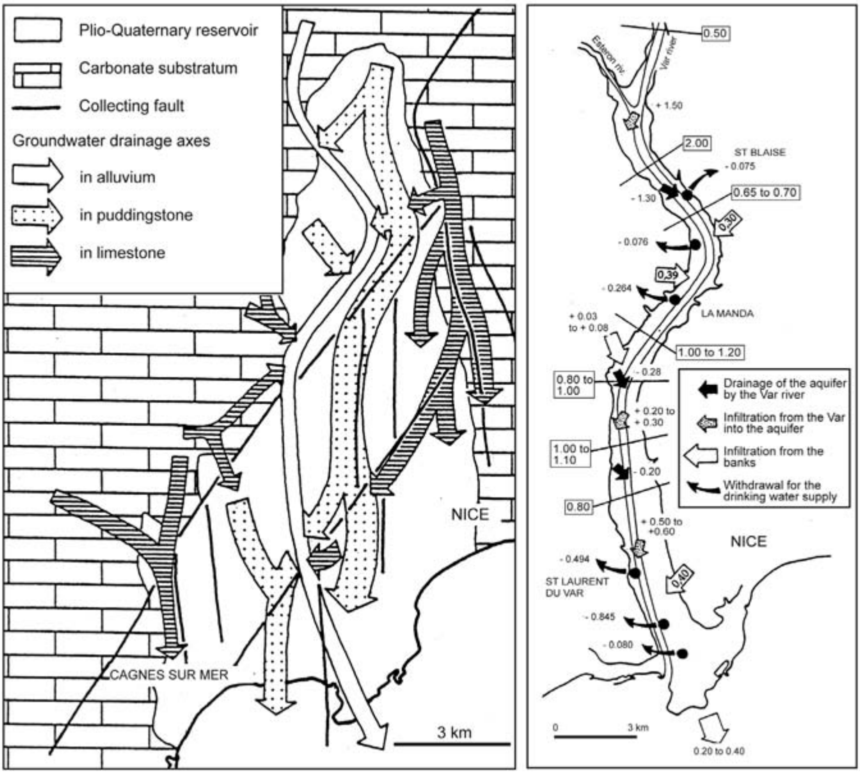


Figure 92 Schematic diagram of groundwater flow towards the Var aquifer through Plio-Quaternary structures, and hydrologic budget of the alluvial aquifer for the year 1991 (Guglielmi, 1993).

Chapter B5

Diviners and Divining

The diviner is to the hydrogeologist as the medicine man is to the doctor. No one can deny that diviners have been finding water since the dawn of time, and some will even point out that there are multiple examples of hydrogeologists whose studies have not found results. However, water being highly present below ground, totally dry wells are rare. It therefore remains to be seen whether diviners' successes are simply a matter of chance, particularly since a very weak discharge is often considered a success for a diviner where a hydrogeologist would see a failure. A team consisting of a diviner and a driller, searching at shallow depths (<100 m) in areas where many productive wells are already known, can easily rely on chance. Failures are ignored, or blamed on negative vibrations, and successes are common enough to establish a positive local reputation. The low cost of failure is largely compensated by the benefits of success, enabling the survival of such a commercial operation.

Diviners use various instruments, forked metal or wooden wands, pair of L-shaped rods, pendulum, etc., which become animated when the bearer passes over a productive area. Diviners often speak of water veins, which can be several tens of kilometers long, and can sometimes originate in distant mountains. The diviner then determines the depth to be drilled and the probable discharge based on the pendulum's oscillations, the tilt of the wand, or the number of pebbles falling from his or her hand.

The power of divining has been the subject of studies varying in the rigor of their experimental protocol. It was easily shown that the diviner's various tools did not move of their own volition, but instead amplified imperceptible motions in the operator's arms. The hypothesis generally retained by those who are least skeptical is that groundwater circulation modifies the magnetic field, and that certain individuals can sense these modifications. In France, Rocard (1997), a physicist, proposed that magnetic receptors existed in the forearms of diviners, but was unable to find experimental proof of his idea. Statistical approaches have been attempted. The BRGM, for example, had asked diviners to survey a certain area, and found their results to be purely a result of chance. A similar result was obtained by the University of Nice zetetics lab, which, using an experimental site with a network of pipes and sluice gates, was able to prove that the diviners willing to participate in the experiment did not have the ability to detect water circulations (Charpak & Broch, 2002). Additionally, the authors would like to highlight that the quantitative aspect of divining studies does not take into account units of measurement. However, although the procedures are identical in France and in England, the French use the metric system while the British count in feet. The largest study was done in Germany on 500 diviners, among which 43 individuals appearing to possess unusual capacities were the subjects of a further study seeming to reveal some sort of power (Köning & Betz, 1989). However, further analysis of the raw data *a posteriori* did not confirm this conclusion (Enright, 1995).

Diviners' powers therefore seem to originate more from empiricism, from the unconscious integration of visual *stimuli*, or from a solid analysis of the natural environment, than from any extrasensory perception.

C

WATER RESOURCES

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Chapter C1

Water Needs and Their Evolution

1 WATER CONSUMPTION

The annual consumption in France is approximately 35 billion cubic meters, 6 billion of which are for domestic needs. 7 billion are provided by groundwater, 50% of which is for the drinking water supply.

The all-purpose per capita consumption varies greatly by country, between 6,000 m^3 per year for the United States and 7 m^3 per year for countries in the Sahel. The average is around 600 m^3 per year per person.

The global consumption doubles every twenty years. In 2025 the world population is projected to reach 8 billion people, yet today around 25% of the planet's inhabitants do not have access to potable water. The medium-term outlook is therefore highly worrisome.

The main uses of water, and in part of groundwater, are as follow:

- domestic uses:
  - dietary needs: drinking, washing and cooking of food;
  - household needs: sanitation, toilet flushing, heating, washing of laundry and dishes;
  - amenities: watering gardens, washing cars, filling pools;
- collective and public uses:
  - fire protection;
  - street cleaning;
  - filling of pools and decorative basins;
  - watering public parks, athletic fields, and golf courses;
- agricultural uses:
  - irrigation of fields,
  - livestock farming and drinking water for animals;

- industrial uses:
  - hydroelectric production;
  - use in the production, conservation, and functioning of many manufactured products;
  - cooling of production equipment (thermoelectric plants, refrigerated plants, various factories);
  - energy production for heating and air conditioning (heat pumps, cooling towers);
  - washing of material (quarries, gravel pits), of laundry (industrial operations), or vehicles.

2 DOMESTIC USES AND AGRICULTURE

2.1 Drinking water supply

The minimum vital needs of a human, drinking, cooking, sanitation are approximately 10 L per day per person. Domestic consumption today is around 140 L per day per person in France. The addition of urban cleaning water brings that number up to 250 L per day per person. This consumption varies with cultural habits and with wealth. It can reach 400 L per day per person in some large cities in the United States; conversely, it is below 30 L per day per person in many African cities. Increasing quality of life is thus accompanied by a considerable increase in water consumption.

In France, the water extracted for the drinking water supply is 60% from groundwater and 40% from surface water.

Thankfully, the increase in consumption in developed countries is now slowing. For example, in France, an increase of almost 2% per year from 1950 to 1970 went to 0.8% per year from 1970 to 1985, to reach 0.4% per year since 1985. The increasing price of water, which has reached the equivalent of one month of a minimum wage salary for a French household, and an increased awareness of environmental problems explain this trend. The next predictable step will therefore be the search for better quality. The situation becomes dramatic in developing countries, where an increase in untreated wastewater is accompanied by the decrease in quality of potable resources.

2.2 Urban uses

Aside from purely domestic uses, city-dwellers also use water for street cleaning, commerce, craftsmanship, and sewer maintenance. This

Table 14 Volumes Extracted in 2001 for Water Uses in France (in millions of m³) (from the Réseau National des Données sur l'Eau, 2004).

Type of use	Type of resource	Rhône-Méditerranée-Corse	Rhin-Meuse	Loire-Bretagne	Seine-Normandie	Adour-Garonne	Artois-Picardie	FRANCE
Drinking water supply	Surface water	474	53	466	788	456	17	**2,253**
	Groundwater	1,288	328	542	938	287	330	**3,713**
Industrial uses	Surface water	494	482	135	492	386	181	**2,170**
	Groundwater	568	413	76	209	103	111	**1,480**
Irrigation	Surface water	2,814	9	154	9	670	1	**3,658**
	Groundwater	196	70	351	107	361	24	**1,110**
Energy	Surface water	12,705	3,706	1,909	539	281	1	**19,141**
	Groundwater	18	< 1	< 1	< 1	< 1	<1	**19**

Table 15 Examples of Units of Consumption.

Use	Consumption in L
watering a garden	from 100 to 1,000 per household
toilet flush	6 to 12
bath	150 to 200
shower	40 to 80
car wash	200
washing machine	70 to 100 per wash
dishwasher	25 to 60 per wash

Table 16 Distribution of Uses.

house cleaning and watering	8 %
drinking and cooking	4%
dishes	7%
hygiene	32%
toilet flush	36 %
washing machine	13%

Table 17 Comparison of Domestic Consumption in L per Day per Person (Sources: Eurostat, 2001; IFEN, 2002).

Canada	326	United States	295
Japan	278	Australia	268
Switzerland	252	Finland	213
Italy	213	Spain	200
Portugal	194	Greece	175
Sweden	164	United Kingdom	153
France	137	Germany	129
Belgium	112	Poland	98

consumption reaches approximately 100 L per day per person in Paris. Although some cities have a parallel pipe network for untreated water, in most cases, street cleaning and the watering of gardens use treated drinking water. These needs are difficult to reduce, and as cities continue to increase in size, this portion of water use will increase in the future.

2.3 Agriculture

Agricultural uses make up the largest portion of the global water consumption. The production of 1 kg of flour requires 500 L of water.

It is difficult to know the proportion of water used for agriculture as part of the water returns back to the aquifers by infiltration, but an estimate is that agricultural needs make up 70% of the water consumption in France, and 90% of that goes to irrigation. Approximately 20% comes from groundwater.

In arid countries, more efficient irrigation techniques (drip irrigation in Israel) decrease the percentage of water used for agriculture. Studies are done in order to encourage the development of cultures with a greater added value, such as greenhouse tomatoes instead of wheat (Morocco).

2.4 Bottled water

In France, an individual national survey on nutritional habits (Institut de veille sanitaire and AFSSA. Inca1-1999 report) over a sample size of 3,000 people, showed that 6% of the population does not use tap water for cold or hot (tea, coffee, infusions) beverages, and that 31% of the population never chooses cold tap water over bottled water. This suggests increasing distrust of tap water.

This phenomenon is not limited only to rich countries (Figure 93); in poorer countries, where the distribution network does not allow a qualitatively and quantitatively adequate tap connection, an explosion in bottled water consumption is being observed, facilitated by the low cost of packaging.

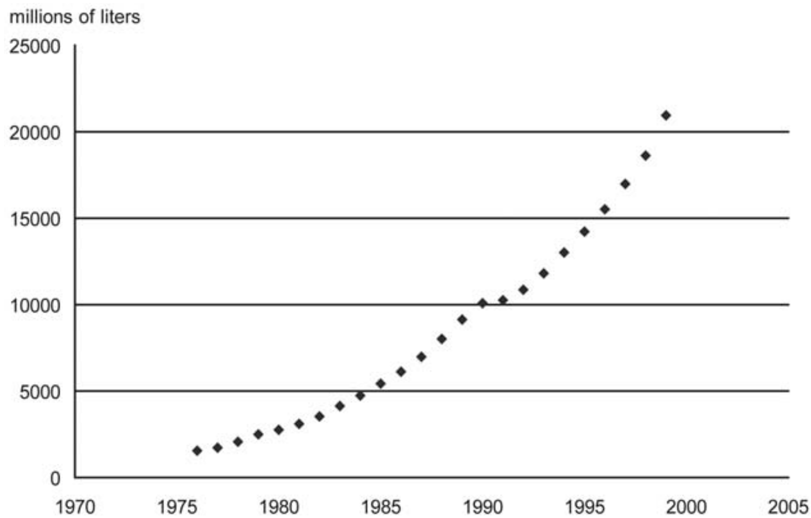

Figure 93 Evolution of bottled water consumption in the United States (from the International Bottled Water Association USA © 2002).

3 TECHNICAL USES OF GROUNDWATER

3.1 Hydraulic energy and hydroelectricity

The transfer of mechanical energy from groundwater into usable energy is rare. However, a few examples can be cited, in France, in China, and in Croatia.

The Eylies (Ariège) hydroelectric plant is powered by the capture of karst groundwater in the Cigalère cave. The Miégebat plant in the Ossau valley diverts the underground river in the Eaux Chaudes cave through a 514 m long gallery feeding a waterfall 400 m high. There was an unsuccessful attempt to harness the underground river of the Pierre Saint Martin (Atlantic Pyrenees) in the 1960s.

A few examples of underground dams harnessing karst rivers for hydroelectric production are known in China, including the dam in Luota (Hunan), in a Permo-Triassic limestone syncline perched above impermeable coal beds, where an underground excavation created a 3 million cubic meter reserve powering a 10 MWe facility. In France, a dam was built in the entryway to the Bournillon cave (Vercors), in order to power the plant with the same name in the Bourne gorges.

In order to take advantage of abrupt topography with a number of levelled poljes, many hydroelectric installations were built in Croatia, intercepting the water circulating in Dinaric poljes before it disappears below ground into sinkholes. The water is then carried through subterranean galleries over several kilometers towards poljes or rivers at a lower elevation, where it passes through turbines. These installations do not directly use groundwater, but, by intercepting the water before its natural descent into the endokarst, they greatly modify the behavior of the different karst systems in the region. Figure 94 illustrates the hydroelectric infrastructure on the Trebisnjica River, north of Dubrovnik. Part of the water in the Nevensinje, Dabar, and Fatnicko poljes, which contributes to the dicharge in the Buna and Bregava springs, is diverted from the system. Forty or so peripheral springs were monitored regularly over the course of several years. The average spring discharge underwent a general decrease. The Ombla spring, for example, went from an average discharge of 34 to 24 $m^3 \cdot s^{-1}$ after the construction. The dry season discharge, however, is sometimes greater, thanks to leakage from the dammed lakes and the subterranean reservoirs maintaining underground circulation (Milanovic, 2001).

Such projects can, however, exist only in very particular geologic environments.

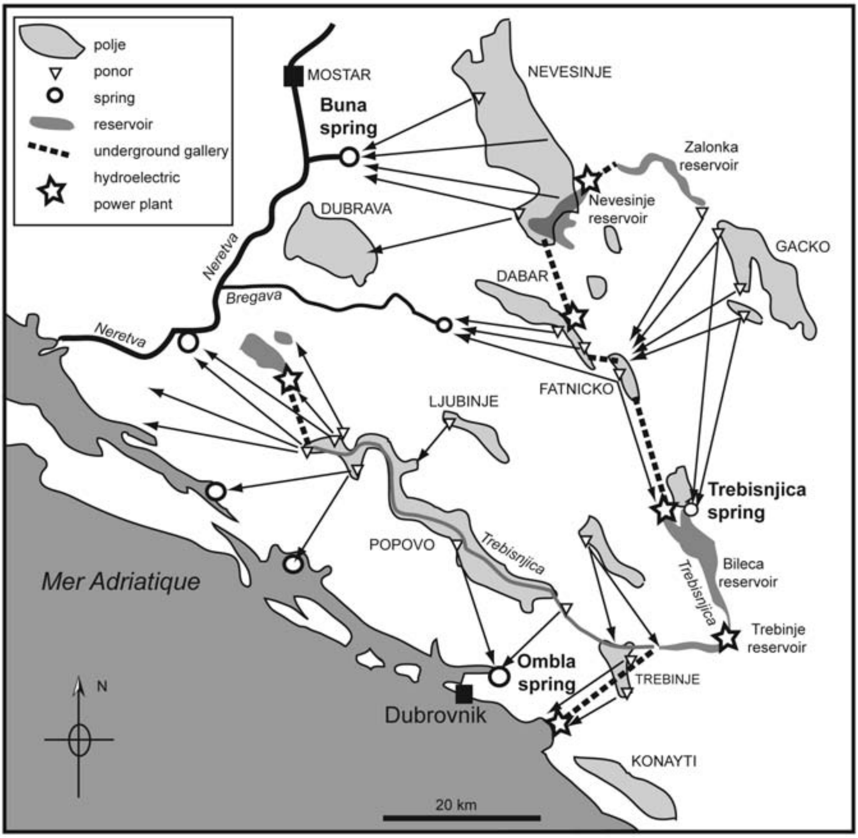

Figure 94 Hydroelectric infrastructure in Trebisnjicka (Croatia) (from Milanovic, 2001).

3.2 Cooling thermal and nuclear power plants

Groundwater is not greatly used in energy production (see table 14).

3.3 Heat pumps and geothermal energy

Geothermal energy currently accounts for only a small percentage of the global electricity production. It is probable that, due to pressure from anti-nuclear environmental groups and to the continuous increase in oil prices, this energy source will be more widely used once certain technical difficulties are resolved (see chap. A10).

The use of groundwater for heat pumps can produce 3 kWh of thermal energy for every 1 kWh of electricity used. This heating method is becoming more widespread, and should therefore prompt more research on shallow aquifers, important sources of calories.

3.4 Industry

The production of raw material and equipment requires water (Table 18). Industry derives approximately 25% of its consumption from groundwater. As in agriculture, the current trend is towards the search for procedures enabling a more efficient use of water.

Table 18 Water Used in Industry per Ton of Resulting Product (Newson, 1994).

Product	Water used in m^3
aluminum	120
automobiles	200
paper	1,000
steel	2,500
tires	2,600

Chapter C2

The Exploitation of Aquifers

1 PRELIMINARY RESEARCH

- Any search for a new water resource must take into account the desired use, the stated demand, and the spatial limits of search area.
  Water to be used as a potable resource must conform to the physical and chemical standards required by sanitary regulation. Other uses hold less stringent standards, but often have their own quality criteria. For industrial uses, water must be neither corrosive, abrasive, nor too likely to create mineral deposits; its use in heating or air conditioning systems requires that its temperature allows heat transfers; in agriculture, its electrical conductivity, sulfate and chloride contents, must not be too high.
  Water demand can be highly variable, depending on the use: from a few $m^3 \cdot day^{-1}$ for a single residence to several hundreds or thousands of m^3 per hour for collective supplies or for industrial or agricultural uses. Demand can also vary greatly over time, with peak consumption sometimes 5 to 10 times greater than the average.
  The size of the area under investigation also influences the options to be considered. While the search is often limited to a single possibility when the area is constrained, it can, on the other hand, offer multiple opportunities and allow the choice of an optimal aquifer and exploitation site when there is a vast territory to be explored.
- The hydrogeologic study is undertaken based on the given objectives, in order to identify appropriate aquifers, to allow an objective comparison between the various potential solutions, and to propose the most favorable site.
  Specific investigations then allow the determination of the most effective catchment system, and the evaluation of the project's productivity and its possible environmental impacts.

- The choice is also influenced by other constraints, on the one hand the ascertaining that the resource can be adequately protected if it is intended for domestic use, and on the other the acceptability of the proposed degree of pumping with respect to regulations and potential impacts on sensitive environments (minimum flow release for rivers, risk of influencing other water sources).

2 CATCHMENT SYSTEMS

Exploitation methods for water have greatly evolved over time. Initially, gravity-driven networks were favored, and relied on the direct diversion of springs located at an elevation above that of the destination, or on gallery and trench systems draining superficial aquifers (scree slopes, alluvium). Wells were principally used for local supply, raising water manually or hydraulically, or even with the help of suction pumps at the surface, in the case of shallow aquifers. The development of drilling methods and pumping equipment subsequently enabled the tapping of deeper and deeper aquifers, and access to more and more complex hydrogeologic structures.

Diversions at the emergence point have almost no effect on aquifers. When catchment systems are more complex, however, involving conduits and galleries tapping the initial source of the water, they can cause changes in the elevation of the emergence point, which will also affect nearby drainage conditions.

Catchments directly within an aquifer, through pumping, result in significant perturbation of the groundwater system, and can affect sites over a range of distances and for a variable length of time.

Each catchment has its particularities, depending on the topographic and hydrogeologic characteristics of its environment. Their description of catchment systems therefore remains simplified and relatively general.

2.1 Diverting springs

In the case of a karst outlet issuing from a cave in a very concentrated manner, the catchment system can simply consist of a concrete extension of the underground riverbed, often combined with a small dam to create a moderating reservoir, where a diversion to a canal or a perforated extraction tube can be inserted.

When the emergence originates in a fracture or a localized fracture zone (karst and fractured reservoirs), the production site is covered by a catchment system with a geometry directly dependent on the local geometry. The construction is generally set well into the rock, after the latter has been cleared of any unconsolidated covering and of its weathering mantle, in order to limit the risk of contamination by lower quality surface or shallow water (Figure 95a).

If the water is emerging from a heterogeneous material, for example within a paleovalley filled with rock debris and scree (porous reservoir), the catchment system will be completely closed and equipped with drainage channels at the base of its uphill wall. It is dug down to the impermeable substratum, in order to avoid leakage below the floor. (Figure 95b).

In all situations, the catchment system also includes a stabilization chamber for the water, revealing its natural piezometric level, and a header chamber, fed by the stabilization chamber.

The stabilization chamber also plays the role of decanter, and should be equipped with a basal drain.

The header chamber is equipped with a lateral flood drain, and a submerged section of perforated tubing at the head of the outgoing pipe.

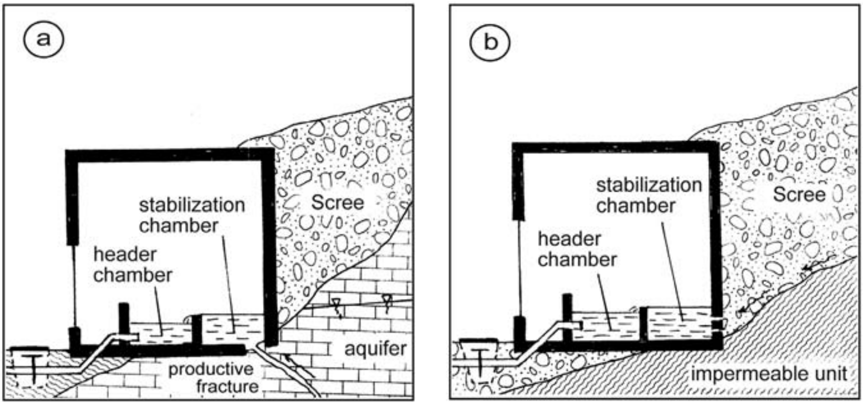

Figure 95 Typical diagrams of point-source catchment systems directly touching the water-bearing formation (a) and at the base of a relay reservoir (b).

2.2 Drainage galleries and trenches

When the emergence is diffuse and extends along the contact between the aquifer and its impermeable substratum over a given length, it becomes necessary to reconcentrate the discharge by cutting across the maximum number of small outflows.

This objective can be attained only through the emplacement of drainage trenches or galleries.

- Trenches are levelled, with a high longitudinal slope, then filled with clean, draining material, after the emplacement of a gutter and of perforated tubing in the lower section,

- Galleries require a greater initial investment, but remain accessible later on. They collect water through a system of drainage channels opening at the base of the uphill wall.

The collection basin is set into the impermeable terrain, parallel to the slope, over a segment long enough to prevent lateral leakage (Figure 96a). When water emerges from a relay reservoir, the catchment system can also extend into the hillside in order to reach the initial reservoir, which can increase productivity, but can also lead to very complex networks (a few hundreds of meters of galleries). Drainage of the aquifer can finally be complemented by rings of subhorizontal drains, drilled from a terminal chamber in the gallery (Figure 96b).

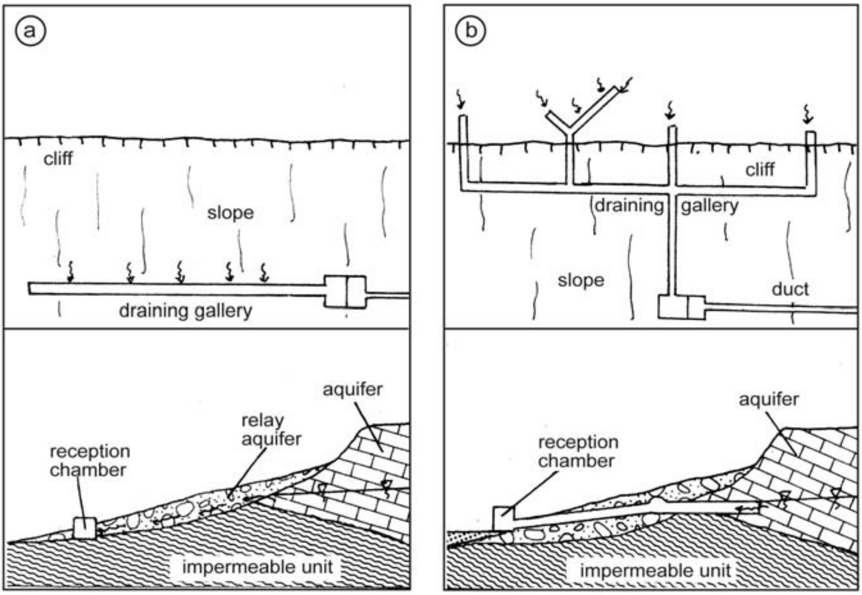

Figure 96 Typical map and cross-section diagrams of drainage galleries, at the foot of a relay aquifer (a) and extended to the original source (b).

Whatever the catchment system put in place (drainage gallery or trench), the collected water is led to a reception area containing, as in the previous case, a decanting basin and a header chamber, as well as a basal drain, a flood drain, and a perforated segment of intake piping.

This method is also sometimes used in the upper part of the saturated zone of an aquifer, either by herringbone-pattern trenches, or by a network of galleries (for hillside and alluvial aquifers). Excavations are done in the upstream direction, maintaining a high longitudinal slope in order to enable graviationl flow. In the case of galleries, it is also possible to use extraction pumping, and construction is facilitated by intermediary vertical wells enabling a better long-term maintenance.

2.3 Wells and wells with radial collectors

A well is a catchment construction penetrating vertically into an aquifer. It generally has a large diameter (from 1 to 5–6 m) and a depth no greater than a few meters to a few tens of meters, although certain wells can reach a hundred meters in rocky terrain.

The main construction difficulty originates from the need to evacuate water as soon as the well reaches the water table. This is why the oldest wells did not extend far below the water table, and collected water only through their base.

Today, well construction favors the opening of drainage channels in the walls of the well below the water table, and continued excavation all the way to the impermeable substratum in order to draw from the entire cross-section of the aquifer and thereby increase productivity (Figure 97a).

In such cases, and when conditions permit it, care must be taken to surround the well with a layer of gravel, which serves as a sand filter, around the walls in the permeable zone, and to protect the upper part of the well against surface water infiltration, by ringing it with cement.

When the permeable zone is not very thick, wells are frequently dug with an impermeable shaft lining until they reach the impermeable substratum, and then completed with horizontal drains radiating into the most productive section. Each drain is equipped with a sluice gate as soon as it is completed, which facilitates drainage during construction (Figure 97b). This method results in a noticeable increase in the well's productivity.

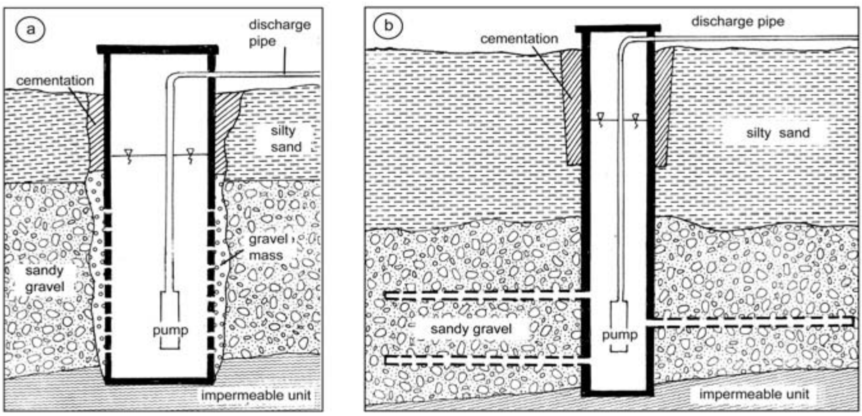

Figure 97 Typical diagrams of a well (a) and a well with radial collectors (b).

2.4 Water drilling

Boreholes (also commonly termed wells) are characterised by their small diameter (under 1 m and usually between 0.2 and 0.5 m), in comparison with their depth, which can reach several hundreds of meters, but rarely extends further than 1,000 meters (with the exception of geothermal and oil drilling projects).

Boreholes therefore can provide access to all underlying aquifers, both confined and unconfined. They can tap very specific horizons by using perforated tubing, and isolating the undesirable horizons with filled tubing and cement. Similarly, a ring of cement is put in place around their upper portions in order to prevent contamination by surface water (Figure 98).

3 MAINTENANCE OF CATCHMENT SYSTEMS

Catchment systems often present a decreased productivity over time. This degradation is caused by deposits cloggin waterways and/or by corrosion of the draining elements of a borehole. It depends on the construction conditions of the catchment system, the chemical composition of the water, and the mode of exploitation of the catchment.

- In the case of spring diversions and drainage galleries, decreased discharge is usually caused by clogging, which can have various origins:
  - mechanical, when fine soil particles carried by the water settle out and reduce the cross-sectional area of the drainage channels or the empty volume of the drainage material;
  - physico-chemical, when the obstruction is caused by deposits precipitated from the water, such as calcium or magnesium carbonates or sulfates, or even iron hydroxides;
  - biochemical, when the clogging is caused by gelatinous ooze produced by the biologic cycling of certain microorganisms, particularly when the water contains iron salts (iron bacteria).

Noticeable improvements are generally possible through regular maintenance, when the catchment systems are accessible. If they are in large part made up of drained masses without access points, intervention options are limited. It is therefore essential that maintenance be considered during the design and construction of a catchment system. Similarly, it is advisable to avoid planting on a catchment area, and to regularly remove shrubs or trees that may appear, as their root systems are capable of extending all the way down to the drainage channels and to the aquifer, where they can also facilitate the precipitation of chemical deposits.

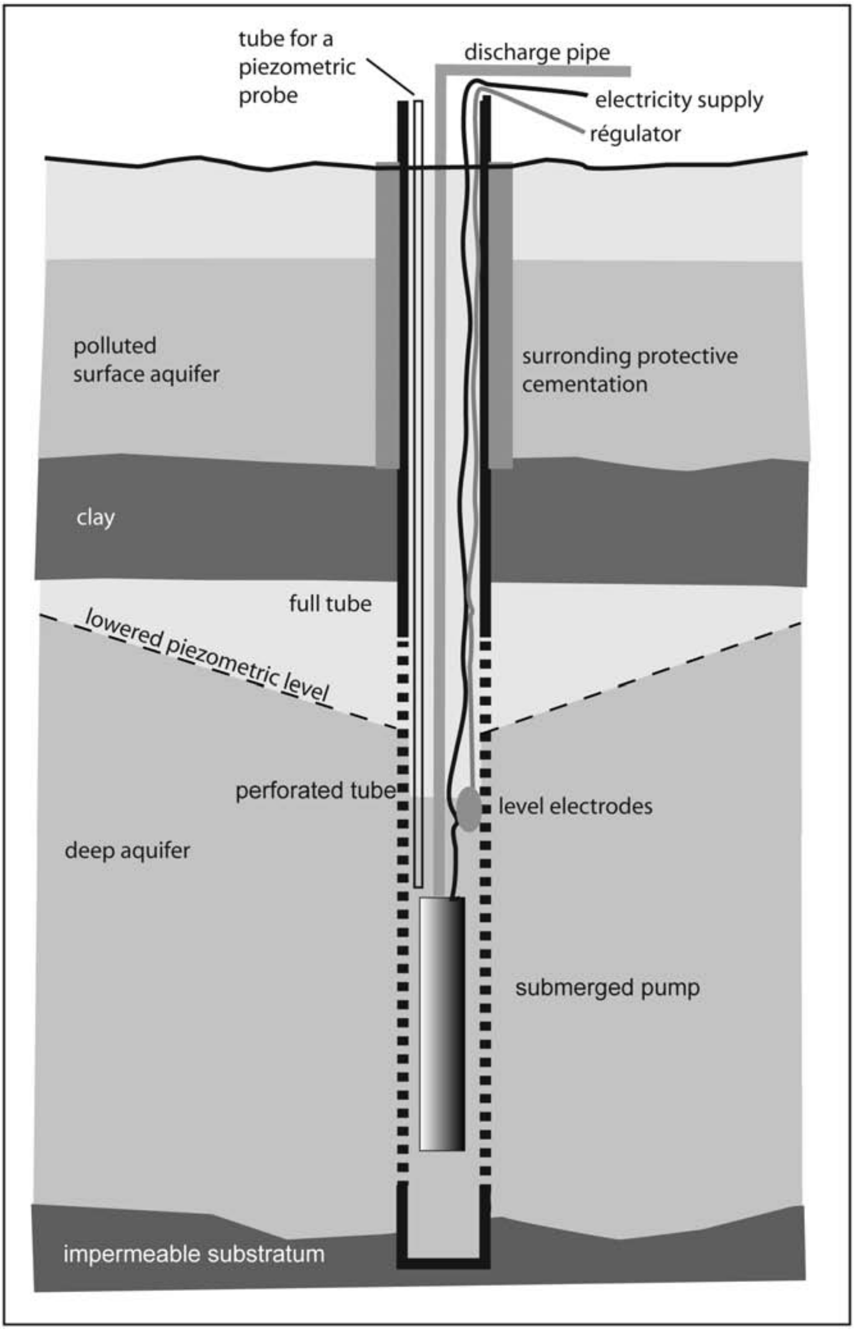

Figure 98 Typical diagram of a water-seeking borehole.

- In the case of wells and boreholes, the same processes apply, and can be aggravated by pumping conditions, particularly the transport of fine particles into the zone of pronounced drawdown, and the formation of precipitates generated by this depression.

Wells, due to the open drainage channels in their draining section, are subject to the risk of silting up in their lower portion or in their enveloping gravel filter.

The sensitivity of boreholes is also due to the corrosion risk for their metallic portions (support tubing, backflow tubing, pumping mechanism), when the water passing through is chemically or bacterially aggressive, or due to electrolytic reactions if there are multiple components.

The only means of preventing or attenuating such effects consists of taking them into account during the construction and exploitation of the catchment system: choice of equipment (construction material, isolating joints, cathodic protection or surface coating of tubing), choice of perforation type and gravel sheath, prolonged development phase prior to exploitation, adaptation of the pumping rates.

Reclamation procedures are numerous, but of varying effectiveness: mechanical scraping of surfaces, drainage channels, and perforated tubing, alternating pumping or injection of compressed air or pressurized water, injection of selected chemical substances (hydrochloric or muriatic acid, sulfamic acid, polyphosphates, chlorine).

4 EXPLOITATION OF COASTAL AQUIFERS

4.1 General cases

4.1.1 Study of the saltwater intrusion

Study of the aquifer should permit the identification of sectors in which contamination is possible; a structural and paleogeographic analysis is therefore essential. Electric surveying, which, on the one hand, can help clarify the geometry of the aquifer (depth to bedrock, permeability), on the other hand highlight the interface, characterized by an abrupt drop in resistivity, and such surveys are a well-adapted tool. For example, in a sandy aquifer, the resistivity for freshwater is on the order of 100 to 200 $\Omega \cdot m$, whereas it drops to 2 to 3 $\Omega \cdot m$ once salt water is reached (Figure 99).

Since contamination occurs from downslope to upslope and from bottom to top, aquifers must be equipped with sensors so as to enable the 3D dynamic monitoring of the intrusion, with a network of piezometers with

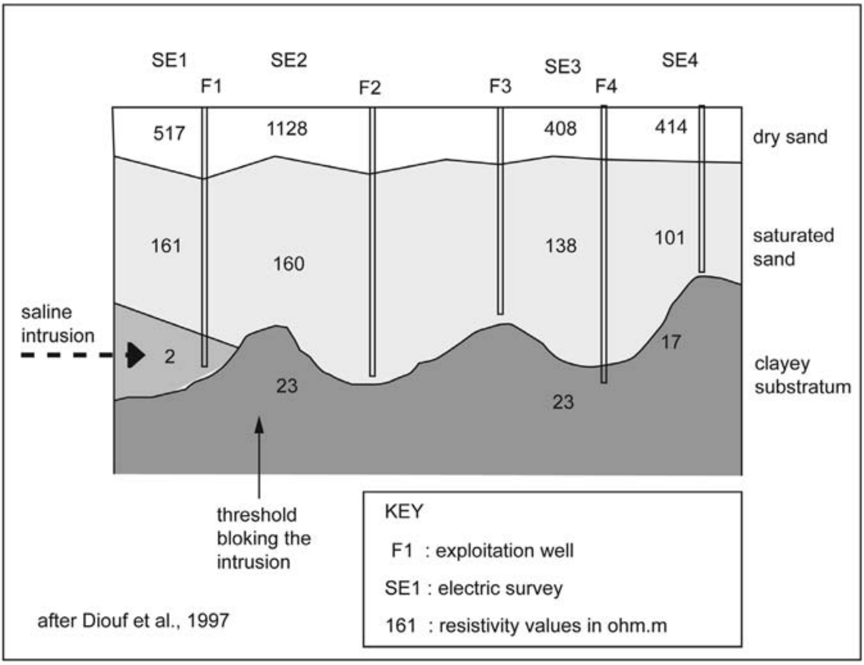

Figure 99 Conductimetry study of the saltwater intrustions in the coastal dunes of Dakar (Senegal) (from Diouf *et al.*, 1997).

conductivity probes enabling the regular acquisition of vertical profiles. This enables the drawing up of isoconcentration maps allowing the monitoring of an eventual marine intrusion's evolution.

Salinity is not, however, always linked to a marine intrusion. The leaching of continental evaporites can also increase the NaCl concentration of water. The bromine content can differentiate the two types of water. Indeed, the Br^-/Cl^- ratio (in 10^3 $meq{\cdot}L^{-1}$) is near 1.53 for sea water, and between 0.7 and 1. 2 for evaporites (Edmunds, 1996) (see chap. B3-6.1.3a).

4.1.2 Treatment

The intrusion of sea water can be limited by artificially raising the piezometric surface downslope of the pumping zone, either through damming or grout curtains, or by returning water to the aquifer (Figure 100). The town of Orange (California, USA) relies on 28 wells used to inject treated wastewater and water from deeper reservoirs, in order to create a hydraulic barrier protecting the Fountain Valley aquifer from marine intrusions.

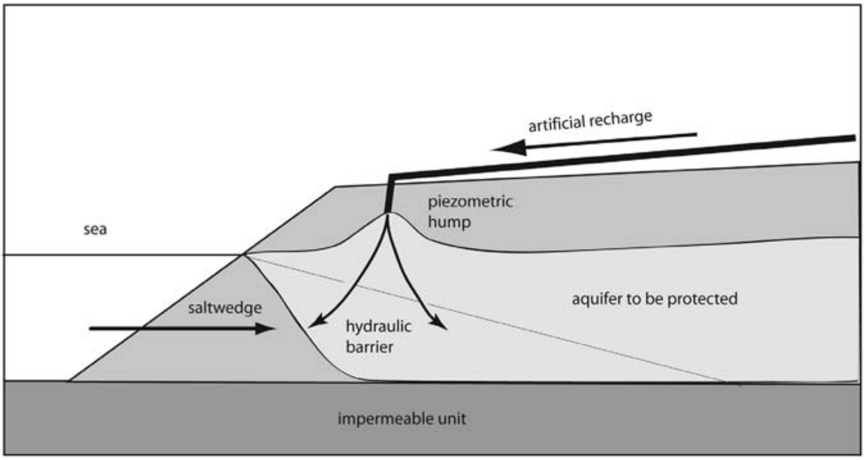

Figure 100 Hydraulic barrier created by injection in a coastal aquifer.

4.2 Coastal karst aquifers

4.2.1 Detection of sub-marine emergences

Springs large enough to be of economic value are clearly visible at the surface, where they form rings. They are therefore known to the locals, and inquiries with fishermen enable the finding of their location. For the smaller springs, various detection methods are in use:

- temperature: during the summer, sea water heats up rapidly at the surface, while karst waters remain at a constant temperature. They can therefore seem very cold and can be felt by swimmers. In the winter, the reverse is the case. *In situ* temperature measurements, or a thermal imaging survey from the air, allow the detection of freshwater emergences during the summer or winter, when the thermal contrast between the two waters is the greatest;
- salinity: salinity differences can easily be found using conductimetry;
- coastal geomorphology: a notch (visor) cutting into limestone at the edge of the water is almost always associated with a nearby spring.

4.2.2 Exploitation

a) Diversion at the outlet

Direct exploitation at the outlet is rarely possible due to the salinity. Attempts to cap the emergence with a resin bell were undertaken at the Galeso spring in Mar Piccolo (Tarente, Italy) in the 1970s (Stefanon, 1972). A continuous measurement setup monitoring the position of the interface enabled the adjustment of diversions. This system was nevertheless abandoned, as it did not solve contamination problems further upstream. A similar setup was developed for the Mortola spring (Menton, France & Italy), where first a flexible tarp, then a steel bell capped the spring, but there too the remaining salinity of 1.4 $g{\cdot}L^{-1}$ is too high to make exploitation worthwhile.

Some springs, however, have zero salinity, when the aquifer is well-protected from the marine environment by impermeable formations, or when the pressure is high enough in the passageways to prevent the intrusion of salt water. The outlet must then be isolated from the sea by a circular dam (Aurisiana, Italy).

Exploitation by increasing the hydraulic charge has been attempted, in order to lower the fresh water/salt water interface. A subterranean dam was thus built in the submerged gallery of the Port Miou spring, but it did not yield the hoped-for results (see chap. A9-2.5). Several attempts to raise the level of the Almyros of Heraklion pool also failed to lower the salinity to a satisfactory level. An attempt to increase piezometric level by totally blocking the conduit was unsuccessfully attempted on the Cabbé spring (France). A circular dam around the Anavalos spring (Greece) was, however, successful. The idea was to create a column of fresh water above the emergence, so that the resulting pressure would counteract that of the sea water and prevent it from contaminating the spring. Water is drawn off so as to not cause a drop in the level. If the level of the dam is too high, the discharge of the spring decreases; if its is too low or the freshwater level is lowered through pumping, saltwater contamination occurs.

b) Diversion in the aquifer

Given the emplacement mechanisms of coastal karst systems, which enable deep contamination, it is generally preferable to draw on the resource through wells upstream of the emergences, but for aquifers with large karst conduits, drawdown provokes the migration of the saltwater intrusion, in all three spatial dimensions, with a very irregular shape. Salt water can reach and contaminate the catchment in an unpredictable manner. If the aquifer is large, compartments isolated from the marine environment can be sought out.

One solution consists of drawing only upon the upper layer of the aquifer, using several shallow wells, in order to induce only minimal drawdown.

Subhorizontal drainage galleries can also be used, at the top of the aquifer. Increases in discharge must then be obtained by lengthening the

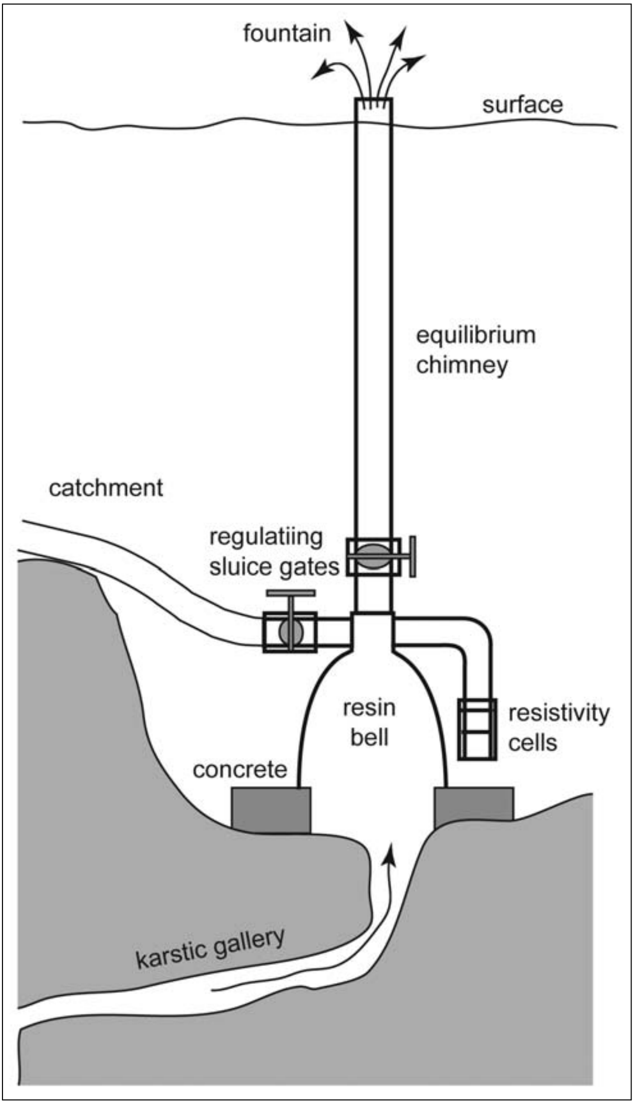

Figure 101 Tarente catchment system (from Stefanon, 1984).

galleries. Numerous examples of such catchments have been indicated in Croatia, in Cuba, and in Malta. These drains have the advantage of allowing the blockage of active fractures when their salinity becomes too high (Figure 102).

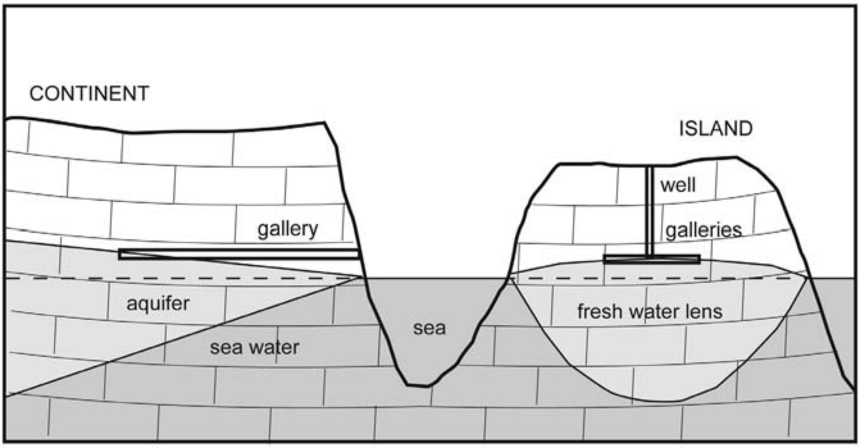

Figure 102 Catchment systems for coastal waters using drainage galleries.

Finally, if the hypothesis of saline contamination through deep paleodrains is considered, according to mechanisms visible in the Bay of Bali or in Argostoli (see chap. A9), an attempt could be made to locate and block the drains.

CHAPTER C3

Protection of Aquifers

1 EUROPEAN REGULATIONS

The October 23rd, 2000 Water Framework Directive from the European Commissions goes beyond the current efforts, by asking member states to develop and put in place plans to maintain and better the aquatic environment.

The Directive has, as its goal, the establishment of a union-wide framework for regulatory actions affecting water. It stipulates that the sustainable use of water be founded on the long-term protection of water resources. The directive states that water is not a commodity, but an inheritance that must be protected, defended, and treated as such.

2 SANITARY CONTROL OF DRINKING WATER

Analyses by the mandatory state regulating organization (DDASS) have the final say in sanitation: water must meet certain criteria for potability (for distributed tap water) or capacity to be made potable (for potential resources).

The sampling sites for these sanitary analyses are:

- the resource being exploited, in order to its protection by managing its catchment basin;
- the exit of the treatment plant, in order to measure the modifications with respect to the original composition (change in pH, change in nitrogen oxidation, remineralization with hydrogenocarbonate and calcium, reduction in carbonate, iron, phosphorus, fluorine, arsenic contents, oxidation of organic carbon, of pesticides);
- the distribution network, in order to judge the consumer's protection. At this point in the network, in addition to the basic composition of the water, the impact of additives is measured: residual chlorine, the concentration of which must be high enough to protect the consumer

once water reaches the tap, treatment residues: trihalomethanes (chloroform, bromoform), bromates....

The nature and frequency of sanitary analyses are determined by the December 20th, 2001 2001–1220 decree, which is the translation in French legal terms of the October 23rd, 2000 European Union Parliament and Council's European Framework Directive 2000/60/CE.

Table 19 Water Quality Limits.

Escherichia coli	0	per 100 ml
Enterococci	0	per 100 ml
Acrylamide	0.1	$\mu g \cdot L^{-1}$
Antimony	5	$\mu g \cdot L^{-1}$
Arsenic	10	$\mu g \cdot L^{-1}$
Barium	0.7	$mg \cdot L^{-1}$
Benzene	1	$\mu g \cdot L^{-1}$
Benzo(a)pyrene	0.01	$\mu g \cdot L^{-1}$
Borium	1	$mg \cdot L^{-1}$
Bromates	10	$\mu g \cdot L^{-1}$
Cadmium	5	$\mu g \cdot L^{-1}$
Chromium	50	$\mu g \cdot L^{-1}$
Vinyl chloride	0.5	$\mu g \cdot L^{-1}$
Copper	2	$mg \cdot L^{-1}$
Total cyanides	50	$\mu g \cdot L^{-1}$
1-2-dichloroethane	3	$\mu g \cdot L^{-1}$
Epichlorhydrin	0.1	$\mu g \cdot L^{-1}$
Fluorides	1.5	$mg \cdot L^{-1}$
Polycyclic aromatic hydrocarbons (PAHs)	0.1	$\mu g \cdot L^{-1}$
Total mercury	1	$\mu g \cdot L^{-1}$
Mycrocystin-LR	1	$\mu g \cdot L^{-1}$
Nickel	20	$\mu g \cdot L^{-1}$
Nitrates	50	$mg \cdot L^{-1}$
Nitrites	0.5	$mg \cdot L^{-1}$
Aldrin, dieldrin, heptachlor, heptachlor epoxide	0.03	$\mu g \cdot L^{-1}$
Other pesticides	0.1	$\mu g \cdot L^{-1}$
Total pesticides	0.5	$\mu g \cdot L^{-1}$
Lead	10	$\mu g \cdot L^{-1}$
Selenium	10	$\mu g \cdot L^{-1}$
Tetrachloroethylene, trichloroethylene	10	$\mu g \cdot L^{-1}$
Total trihalomethanes (THM)	100	$\mu g \cdot L^{-1}$
Turbidity	1	NFU
Radioactivity: total indicative dose	0.1	mSv per year
Tritium	100	$Bq \cdot L^{-1}$

These standards concern physical parameters, toxic and undesirable substances, polycyclic aromatic hydrocarbons (PAHs), benzene toluene ethylbenzene xylene (BTEX), volatile organic compounds (VOCs). They do not yet take into account new contaminants (hormones, endocrine disruptors, drugs).

Bacteriological analyses on water have a regulatory finality in terms of respecting potable water standards. The regulatory sanitary analyses focuse on a small number of bacteria, such as *Escherichia coli*, Enterococci, and sulfur-reducing bacteria. The tests are concerned with common micro-organisms, which serve as quality indicators. Their presence in excessive amounts indicates the possibility that pathogenic organisms could also survive in the same environment. These pathogens are looked for only when a problem arises.

In the same way as chemical analyses, bacteriological analyses are done at various points along the distribution network, from the resource all the way to the consumer.

Table 20 Quality marker parameters, indicating the functioning of water production and distribution systems.

Total aluminum	200	$\mu g \cdot L^{-1}$
Ammonium	0.1	$mg \cdot L^{-1}$
Total coliform bacteria	0	per 100 ml
Free and total chlorine	no smell or taste	
Copper	1	$mg \cdot L^{-1}$
Chlorites	0.2	$mg \cdot L^{-1}$
Chlorides	250	$mg \cdot L^{-1}$
Sulfur-reducing bacteria (including spores)	0	per 100 ml
Color	15	$mg \cdot L^{-1}$ (Pt/Co)
Conductivity	180 à 1,000	$\mu S \cdot cm^{-1}$ at 20°C
Concentration of hydrogen ions	6.5 à 9	pH units
Total organic carbon (TOC)	2	$mg \cdot L^{-1}$
Calco-carbonic equilibrium	no aggressivity	
Total iron	200	$\mu g \cdot L^{-1}$
Manganese	50	$\mu g \cdot L^{-1}$
Number of aerobic germs revivable at 22 and 37°C	Can't exceed 10 times the usual value	
KMnO4 oxidability	5	$mg \cdot L^{-1}$ O2
Smell	acceptable	
Taste	acceptable	
Sodium	200	$mg \cdot L^{-1}$
Sulfates	250	$mg \cdot L^{-1}$
Temperature	25	°C
Turbidity	0.5	NFU

Analyses at the catchment point measure the "health" of the water resource to be potabilized. This quality at the source is a function of the potential risks over the catchment basin, as well as of the natural "filtration" conditions of the aquifer. The aquifer filters through two principal processes: mechanical filtering of particles too large to pass through the pore spaces (Figure 81); filtering of bacteria as they die if the transit time is long enough. Environments with small pore spaces and slow circulation velocities (silt, clayey sand) retain bacteria. In addition, advection takes enough time (months) that it is longer than micro-organisms' half-life (DT_{50}), resulting in their death. In open environments (gravel channels, fractures in hard rock, karst conduits) however, the transit time (hours or days) is not enough for the microorganisms to die off, and the fracture "porosity" is too large to filter them out.

However, other analyses are performed after disinfection, and these then serve to measure the treatment effectiveness. Finally, analyses are done on the water reaching consumers (bars, communities, individuals), serving to minimize the risk of contamination in the distribution network.

These three analysis locations are important; the one at the resource helping to manage activity in the recharge area, the one after treatment guaranteeing the distributed product's innocuity, and the one at the final destination helping to determine the appropriate management of public and private infrastructure (reservoir cleaning, sewage leaks). Treatment accidents can cause catastrophes, as in the cryptosporidiosis outbreak in Milwaukee (USA), which resulted in 104 deaths among the 403,000 people contaminated in 1993. That was a case involving surface water, but 7 groundwater contaminations were reported between 1984 and 1997 in Great-Britain, in the USA, and in Japan.

Certain bacterial contaminations, such as *Legionella*, are a result of unsafe use of hot water (aerosols in showers, cooling towers), which results in bacteria proliferating in the less used branches of household piping.

3 VULNERABILITY, HAZARDS, RISKS

3.1 Vulnerability

The vulnerability of aquifers is by definition (Zwahlen *et al.*, 2003) a relative property, non-measurable and adimensional, based on the supposition that the environment can provide protection for groundwater against anthropogenic impacts, particularly those caused by pollutants entering the subterranean environment. Vulnerability is therefore an evaluation of the lack of this natural protection.

There is a distinction between intrinsic vulnerability, which is inherent to the geologic environment and to the local climatic conditions, and specific vulnerability, which is linked to the properties of the contaminant.

Intrinsic vulnerability is therefore the extreme case of specific vulnerability for a tracer that is entirely conserved (for example a chloride) between its entry point and its target (aquifer or catchment point). In the opposite case, an organic substance with low mobility and a high ease of adsorption or degradation will not pass all the way from entry to exit.

Specific vulnerability is, in the great majority of cases, smaller than intrinsic vulnerability.

3.2 Hazards and risks

An environmental hazard is defined as an instantaneous event or a continuous process which, when it occurs, results in the possibility of degradation in the quality of the environment, directly or indirectly.

A risk is the combination of a hazard and a vulnerable environment; as a result, a hazard only presents a risk if it is likely to affect something valuable (the target), in this case, groundwater (Figure 103). The risk over an aquifer is the effect of a hazard, for example, leakage of an industrial pollutant, on the vulnerability of the environment, without overlooking the flow of the aquifer, which can displace impacts.

The origin-path-target conceptual model depicts the transfer of a hazard towards the aquifer (vulnerability of the resource), then towards its catchment points (springs, wells, boreholes).

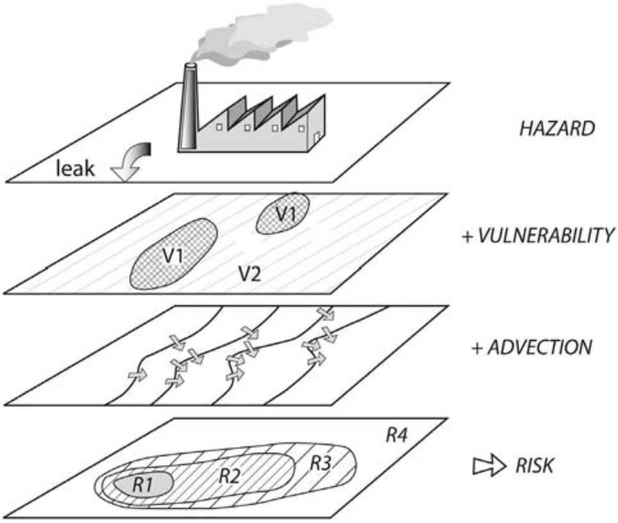

Figure 103 Aquifer pollution risk factors (Zwahlen, editor-in-chief, 2004).

4 PROTECTION ZONES

In France, groundwater protection falls under two legal frameworks: that of the National Parks, or that of drinking water catchments. No easements can currently be applied to patrimonial groundwater resources.

Protection zones in France have four principal functions: to protect the catchment system itself, to control potential sources of non-potability, to control degradations in quality over time, and/or to control the risk of accidental pollution.

Protection zones for catchment areas are nested zones in which human activities are controlled, and therefore regulated. The general principle is to decrease constraints as a function of distance from the catchment point, but the distance is in transit time and not in spatial length, which can result in non-concentric zones.

There are three defined zones: immediate, close, and distant protection. The area outside the zones is not supposed to influence the water quality at the catchment, but only to cause acceptable risks. It is therefore generally not useful to place an aquifer's entire catchment basin in a distant protection zone.

The emplacement of protection zones can be useful only if the expert responsible for the file can draw on an in-depth understanding of the resource being exploited. The mode of inflows to the catchment, in particular, must be perfectly understood in order to zone the zones wisely (Figure 104).

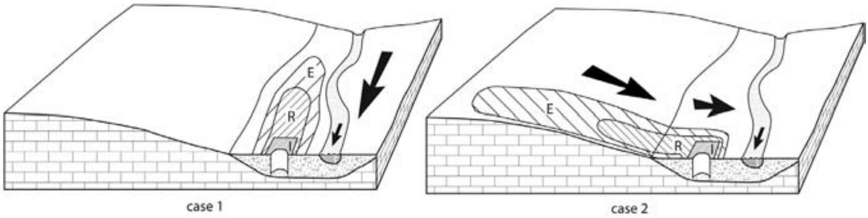

Figure 104 Difference in the design of a catchment area protection, according to its recharge mode.

The definition of protection zones is therefore currently a large source of work for specialized hydrogeologic and environmental consulting firms. For example, in a porous environment, the expert must have data on the geometry of the aquifer (limits, thickness, storativity), on its piezometry, on its hydrodynamic characteristics (transmissivity, permeability), on its physico-chemistry over time. The expert therefore requires geophysical surveys, exploration drilling, piezometric surveys, pumping tests, and dating and analyses of the water. In heterogeneous (fractured or karst) environments, there is the additional requirement of tracer or multi-tracer tests in order to determine the residence times for water infiltrated in various zones of the catchment basin.

4.1 Immediate protection zone

The immediate protection zone (or immediate zone) is a limited area intended to protect the catchment system itself, within which all activities aside from water extraction are forbidden. The land parcel must be entirely owned by the community. An immediate zone must not be a storage area for streetlights, firewood, sewer-cleaning vehicles, or rabbits being breeded for hunting! (all examples encountered in Southern France).

This zone does not not exempt from construction standards: tubing cemented to the non-water-bearing cover and the impermeable units separating aquifers, impermeable slab foundation, surrounding rim higher than the ten-year flood level….

The constructed catchment system (gallery, tank, borehole, well) must prevent public access with a building closed by a locking metal door. The size of the immediate zone is a function of the nature of the aquifer: a zone of a few m^2 for an artesian well, or of 10 m x 10 m for a superficial unconfined aquifer. The size is generally dictated by the size of the catchment construction: a classic point-source catchment requires only a 10 m x 10 m zone, a small spring catchment with an access gallery of 20 m might have a perrimeter measuring 10 m x 40 m, and a large catchment field such as the city of Avignon's catchment system for the Durance aquifer, which relies on several wells and twenty boreholes, occupies an area of 500 m x 300 m.

The immediate zone and its borders (a radius of 15 m around the catchment construction) must be deforested, as tree roots damage the masonry work in catchment galleries, well shaft linings, etc., and therefore allow the infiltration of parasitic surface or shallow water. The area must be maintained: cleared of undergrowth and mowed mechanically (no herbicides!) every year, and organic debris must be removed.

As much as is possible and necessary, the zone should be fenced off with an impassable barrier and a locked door. However, catchments at the foot of a cliff or in the middle of a forest, for example, do not require fences; in the case of a well in a zone of flooding risk with strong currents, it is preferable to use only barbed wire, as a fence would be likely to obstruct floodwater and be torn down.

4.2 Close protection zone

This zone is defined as the zone of significant drawdown in the aquifer.

In France, it is recommended that the zone be drawn to take into account a residence time of 40 days, supposedly long enough to get rid of any bacterial contamination.

The close protection zone (or close zone) corresponds, in a continuous medium and under conditions of mechanical extraction, to the cone of depression associated with a catchment. In a discontinous environment, this zone corresponds to the portion of the aquifer within a short mass transfer time (hours, days).

The close zone has a double protection function: quantitative protection of the resource, and protection of its quality.

With respect to the quantitative aspect, it requires that any new search for water within the zone be not recommended: a private entity or a community should not compete with the community exploiting the same resource. The community itself can of course increase its production capacity (reconstruction of catchment systems, drilling of new wells).

With respect to the qualitative function, numerous restrictions and regulations can be cited. The extraction of material from the ground (quarries), which modifies the infiltration conditions of precipitation, the creation of new installations classified as environmentally hazardous, the issuing of building permits with individual sewage treatment, the installation of open-air livestock housing, of industrial poultry farms, or of hog farms, are forbidden. The construction of stormwater or wastewater injection wells, of wastewater or hydrocarbon pipelines, the storage of radioactive or chemical waste, of flammable material and petroleum, of motor oil, of wastewater treatment plant residues, or of manure is also forbidden, as is the disposal of household waste, filth, industrial waste, and silage.

Prairies and agricultural fields must receive only biological fertilizers in reasonable amounts: the correct proportioning and the timing of biological fertilizers (livestock farming byproducts, wastewater treatment residual sludge) and chemical fertilizers (ammonium nitrate, potassium, synthesized urea) must be defined as a function of the soil grade, texture, and thickness. Fertilizer spreading must take place only over dry soil, during the vegetative period, which requires a storage capacity large enough to last the winter. Intensive culture, which consumes large amounts of fertilizers and herbicides, and cultures leaving bare soil during the winter, are forbidden in the close zone, and if possible replaced by natural prairie. Land use in extensive forested or pastoral zones may remain the same.

4.3 Distant protection zone

The distant protection zone (or distant zone), which encloses the close protection zone, is meant to enable land management practices that will consider both development and water protection. It is a tool meant to direct agricultural land use and the control of community development projects in the area. Activities considered hazardous are therefore not recommended in vulnerable zones, and the creation of quarries, factories, major construction projects, storages, pipelines, or wastewater dumping points can be considered only after further study. In local urbanisation plans (PLU), forest and prairie zones must be maintained as much as possible in order to guarantee the long-term quality of the water being extracted.

4.4 Satellite protection zones

In a close zone (for example), certain faraway points can be closer to the catchment in terms of time than other points that are closer in distance. If one of these temporally close points is highly vulnerable, for example if it is a swallow hole (ponor), a satellite immediate zone can be created around this point. Similarly, if this ponor was within the distant zone, a satellite immediate zone could be created around the point, and a satellite close zone around its drainage basin.

This is the case for the Arcier spring, which has supplied water for part of Besançon since Roman times. There is one zone around the catchment and there are four satellite immediate zones (Figure 105), three of which protect ponors located downslope from villages (particularly the large

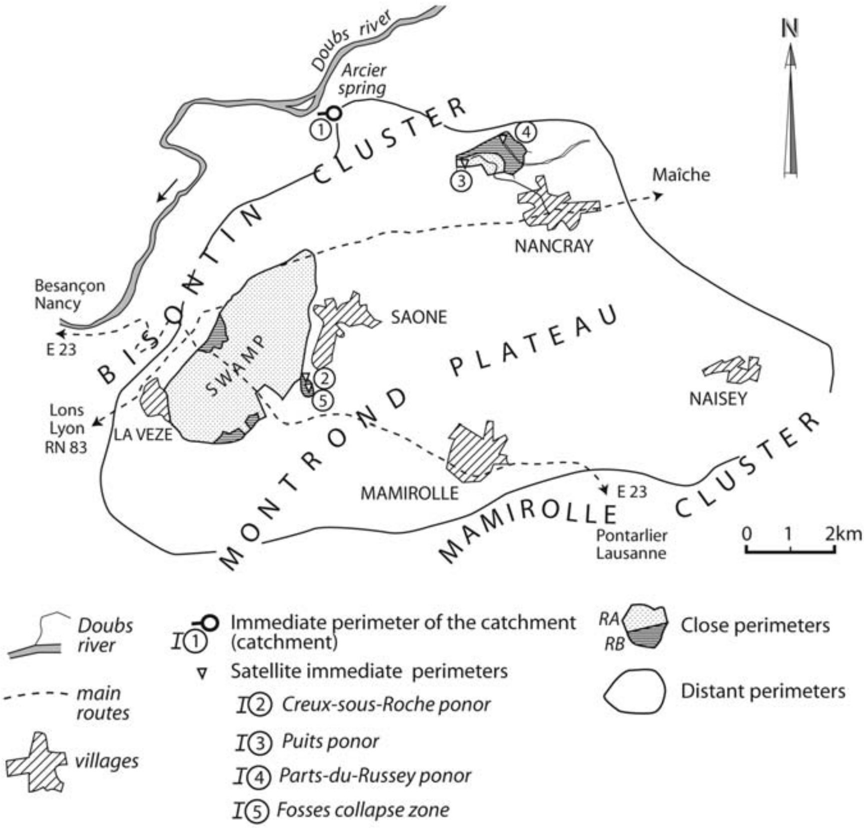

Figure 105 Satellite immediate zones around the Arcier catchment supplying Besançon.

ponor in Creux-sous-Roche), and one of which encompasses an active collapse zone located above subterranean circulations. The close zones are totally disconnected from the spring, but they protect the drainage basins of the streams disappearing into the ponors, which water reaches Arcier's catchment within few hours.

5 THE PROBLEM OF NITRATES

Nitrates are the common oxidized form of nitrogen gas. Naturally present in the water cycle due to the mineralization of nitrogenous organic material in the soil, their natural background level does not exceed 5 mg·L^{-1} in our climate.

When subjected to effective rainfall episodes, the soil is leached (Figure 106), and these nitrates migrate into the groundwater. Springs and wells can, as a result, present small spikes in their nitrate content.

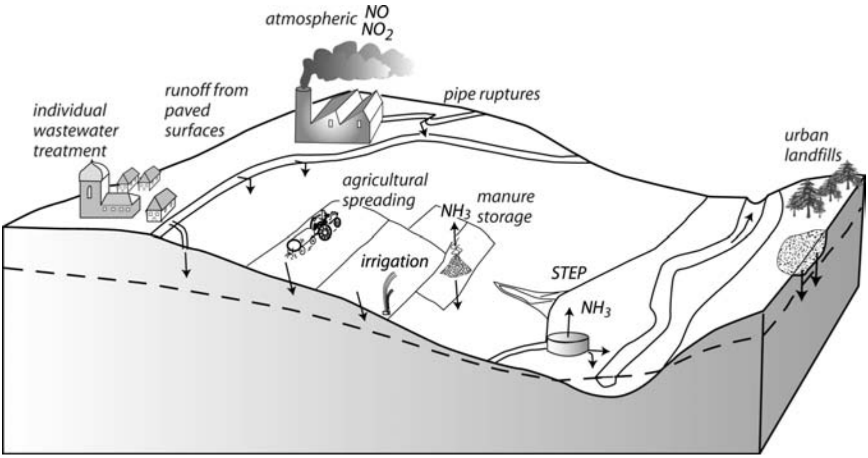

Figure 106 Anthropogenic nitrogen in water resources.

Three major anthropogenic sources of nitrates have increased the nitrate concentration in groundwater: organic nitrogen from domestic wastewater (sewage), organic nitrogen from livestock farming operations (liquid excrement, slurries, manure), and mineral nitrogen from nitrogen-based fertilizers (ammonium nitrate).

Today, a significant percentage of domestic wastewater is treated in wastewater treatment plants, in some cases equipped with a tertiary treatment setup, and point-source nitrogen pollution from domestic sources is decreasing. The same cannot be said for agricultural sources, from which diffuse nitrogen surpluses flow into surface waters and/or infiltrate into groundwater. In regions with irrigated agriculture (Figure 107), the soil produces two nitrate pulses per year (bottom line), one during the natural infiltration of spring rains, and the other during the summer, during the peak of irrigation. The natural signal is no longer perceptible once the minimum anthropogenic nitrogen content is greater than the maximum natural nitrogen content (upper line).

The density of livestock (pigs, poulty) in certain farming regions (Brittany in France) causes regional "structural" organic nitrogen surpluses, as the spreading of manure is too intense over the surface of the plots in question. As a result, in certain drainage basins, the concentration of organic nitrogen being spread is greater than 300 $Kg{\cdot}ha^{-1}$, when it is not meant to exceed 170 $Kg{\cdot}ha^{-1}$. This legal limit, the maximum allowance, does not, however, take into account the agronomic particularities of each plot (soil grade, thickness, and texture).

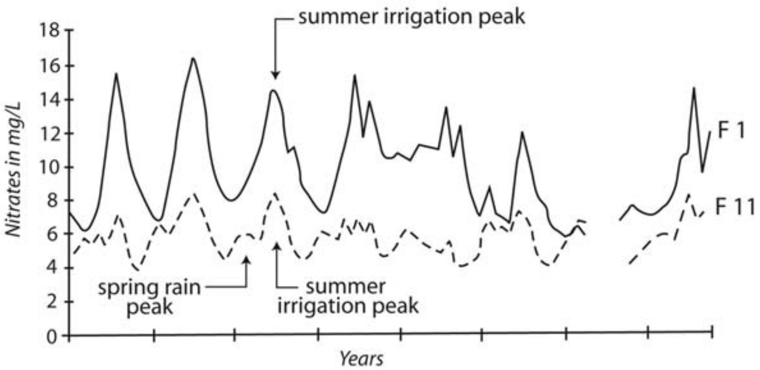

Figure 107 Seasonal variation in nitrate concentration in the Avignon alluvial plain (data from the Société Avignonaise des Eaux).

The only solutions are to export the excess byproducts of livestock farming into watersheds with a nitrogen deficit, or, in the frequent case of an entire region having a surplus, to incinerate the excess manure.

In areas of intensive farming, the spreading of ammonium nitrate, a highly soluble fertilizer, causes increases in both nitrate and reduced nitrogen likely to nitrify under aerobic conditions. Another problem is that this input of mineral nitrogen occurs in addition to the inputs of organic nitrogen in the major, already excedentary livestock farming regions, without taking into account the doses already present due to this organic nitrogen. This useless added nitrogen then serves only to contaminate water resources even more.

Groundwater in every intensively farmed area is affected by this pollution, which shuts down catchments or requires costly treatments (nanofiltration, reverse osmosis). In France, the aquifers of the Paris, Aquitaine basins, of the Alsacian vinyards, and of the Saone or Valence plains regions, are subject to this intense diffuse pollution.

6 DOMESTIC SEWAGE AND SANITATION

There are two collection methods for domestic pollution: on-site septic systems, where sewage ends up being treated by an individual treatment system, and town sewers, where sewage is brought to a treatment plant that can be several kilometers away from the collection point. The hazards to groundwater are different for each method: individual septic systems present only a local pollution hazard from the sewage being treated, whereas town sewer systems often have leaks, resulting in hazards due to the leakage of untreated sewage as well as from the water exiting the treatment plant.

Industrial pollution is generally treated on-site where it is produced, but as some installations are very large, internal pipelines are a source of leakage and the underlying aquifers receive sometimes-enormous influxes (for example tens of $Kg \cdot day^{-1}$ of polycyclic aromatic hydrocarbons towards an alluvial aquifer being exploited for drinking water). The majority of sewer networks are combined, meaning that they collect sanitary sewage and stormwater runoff (from roads and car parks). If the quantity of wastewater depends only on consuption, the quantity of runoff depends on rainfall. High precipitation can therefore cause high water levels in sewers, thereby "cleaning" them.

7 WASTEWATER TREATMENT

Wastewater treatment systems are diverse and adapted to the nature of the pollution to be treated: urban sewage, having a fairly standard composition, is subjected to treatment processes based on a small number of basic principles. Industrial wastewater, however, has a highly varied composition, and treatment is accomplished with procedures specific to the nature of the pollutants to be treated (organic material, hydrocarbons, solvents, toxic substances, heavy metals).

The treatment is also adapted to the number of inhabitant-equivalents to be treated, and therefore to the size of the community being served, as well as to its seasonal variability (tourist destinations).

7.1 Independent wastewater treatment

Independent treatment systems are the solution chosen for industry, small communities (hamlets far from the nearest agglomeration), or a single residence far from the collection network. The type of system depends on the soil permeability: lagoons require impermeable, easy-to-excavate soils (clay, marl), whereas such an environment would not be conducive to mechanical filtration through the soil, which requires a certain minimum soil permeability ($0.3\ mm.mn^{-1}$).

Lagoons and all other "surface water" treatment systems must let their treated product out into the hydrographic network. Mechanical filtration systems use either the soil in place (if the permeability is appropriate), or a substitution soil in order to treat effluent from a septic tank or a decanter-digestor. The role of the soil porosity is to absorb the hourly variations in hydraulic charge coming from the residence, and to allow a long enough residence time for the effluent, with a large contact surface area between the effluent, the solid particles, and the soil atmosphere. Mechanical filtration allows the physical filtration of bacteria through the material, but not the treatment of nitrogen. There are two variants of this method: if the soil is impermeable, if the unsaturated zone is nonexistent (almost-exposed aquifer), or if the soil is hydromorphic, filtration occurs over a slab and the treated water goes out into a ditch or a stream; if the soil has a permeability between 0.3 and 2.5 $mm.mn^{-1}$, the effluent is filtered through the unsaturated zone.

Independent wastewater treatment systems are an interesting solution for residents far from collection networks, but as they are the financial and technical responsibility of the owners, it is difficult to ensure that the installation is done according to adequate standards. The only solution would be for the community to manage independent systems in the same manner as shared systems (construction, diagnostic). Small lagoon units, installed in rural zones, lack qualified personnel, and local communities have put SATESE (Technical Assistance Service for Wastewater treatment Plant Operators) in place, in order to improve the inconvenient situation.

7.2 Urban sewer systems

Town sewer systems use biological or physco-chemical processes depending on the regularity of the discharge being treated, the price of land, and the winter temperature.

Physico-chemical systems, based on the principle of adding reactive substances (ferric chloride, quicklime), can eliminate phosphorus, but not nitrogen. Adjusting the dosage of the reactants enables the treatment of variable quantities characteristic of industry and of tourist destinations (coastlines, ski resorts). The treatment occurs in a reactor; the facility therefore has a small footprint, which makes it easier to integrate into areas with high land prices (cities, tourist destinations: ski and coastal resorts). In addition, the closed facility allows for containment of unpleasant odors. The inconveniences are the high cost of reactants, the resulting sludge mass, and the technical complexity of the treatment, which is incompatible with the lack of qualified operators in small communities. In addition, the resulting water may require additional treatment downstream in order to control bacterial contamination.

Originally designed to decant suspended material and to oxidize organic material, the activated sludge system requires a larger surface of oxygenation basins. This treatment is now being completed by the tertiary physico-chemical treatment of phosphorus and nitrogen.

Spatially extensive treatment systems (macrophyte lagoons, infiltration beds) require a high surface area per inhabitant, and are therefore used only in small, rural communities (hamlets, isolated areas).

The specific drawback of biological systems is their low tolerance of variations in quantity: they are therefore well-adapted to communities with little seasonal population variation (rural areas and agglomerations). The large masses of sludge produced must absolutely not return to the hydrographic network. This sludge, which has a high agronomic value, generally has a poor image with farmers who might benefit from it, and the surplus must therefore be incinerated.

In combined sewers, the stormwater runoff has a composition that varies over the course of a period of rainfall: the first water to reach the ground washes the pavement, picking up suspended material, heavy metals, and automobile lubricants. After this washing, the stormwater is of better quality. The inability of treatment plants to handle the peak discharge of combined sewers during rainstorms was long solved by creating "storm sanitary sewer bypass", which bypassed the treatment plant and dumped the combined sewage and runoff into the environment (river or aquifer). Today, treatment plants are being equipped with holding basins with capacities of several thousands of m^3, capable of holding at least the beginning of flood peaks, in order to treat them later along with normal urban effluents, after the peak.

CHAPTER C4

Management of Aquifers

1 DEFINITION

In traditional societies where water is scarce, its management generally follows strict rules. In oases in the Sahara, foggara systems have traditionally enabled exploitation of the aquifer with the help of gravity, thanks to drainage galleries feeding irrigation ditches equipped with a distribution system allowing each individual the amount of water allotted by customary rights. Management of the resource occurs in this case at the exit from the system. It is impossible to take more than what the system can provide. The appearance of wells and boreholes where the quantity of water extracted is determined by the nature and power of the material poses the problem of managing the resource itself. Water must be taken in accordance with the capacity of the pumping system and of the aquifer, but also with the needs of society. Otherwise, it puts an entire social system at risk.

The same is true in France, where advances in exploitation technology combined with increases in extraction and dumping are prompting the emergence of qualitative or quantitative problems that can affect all or part of society. For example in Bretagne, the spreading of liquid pig manure produces more than 200,000 tons of nitrogen per year, and agricultors add another 200,000 tons of nitrified mineral fertilizers. The nitrate concentrations in groundwater often exceeds 50 $mg \cdot L^{-1}$ and the water is therefore no longer potable.

The management of aquifers includes all of the actions enabling the optimal use of the resource they contain, in order to answer to socitey's needs. Management can be both quantitative and qualitative.

Water management can therefore be studied on several levels:

- at the level of the catchment system (see chap. C2): what must the system's characteristics (well, borehole, gallery, well) be in order to adapt to the possibilities of the resource?
- at the level of the aquifer: how to manage exploitation in order to most benefit from the resource?

- at the level of the hydrologic system: what will the effect of pumping in the aquifer be on the systems on which it depends or which are dependent on it?
- at the level of a basin including several hydrologic systems.

One could compare surface waters, easily accessible yet vulnerable, to groundwater, protected but difficult to use, but surface water and groundwater cannot be dissociated as they belong to one continuous cycle. Groundwater contributes to the feeding of watercourses and rivers, and therefore plays a primary role in the quantitative and qualitative maintenance of surface water resources and the preservation of humid areas. Inversely, rivers participate in infiltration and in recharge of aquifers. Their respective interactions must be correctly understood in order to enable the effective management of the resource in its entirety. In France, SDAGE (Organisational Systems for the Development and Management of Water) have been defined for every great basin as a function of the current state and the development, conservation, or rehabilitation goals for aquatic environments. The SDAGE have legal status, and are taken into account by the State and by local communities, in the context of decisions to be made with respect to water. Aquifers were classified based on their strategic interest and their potential, and action plans were defined in order to acquire a better understanding of groundwater resources.

Aquifer management must obey several constraints:

- technical: what are the currently available solutions for a given problem?
- economic: are the solutions economically justifiable?
- social: is the chosen procedure acceptable to society?
- environmental: are the solutions compatible with protection of the environment?

Management can be passive if the exploiter just considers regulating extraction as a function of the aquifer's capacities. It can be active if the aquifer is considered to be a complex entity, including three functions (Detay, 1997):

- capacitative: the aquifer allows storage of a certain quantity of water;
- conductive: between the entry and exit points, water flows, transmits pressure and transports elements;
- reactive: the water seeping into the ground undergoes a series of physico-chemical and biological reactions that modify its composition and participate in its purification.

Humans can act on all three of these functions, and, particularly on transfers, by artificially recharging the aquifer through infiltration or injection in order to benefit from the naturally purifying environment and to use its storage capacities. Reasonable actions enable the management of the system, but they require a deep understanding of the three functions.

Table 21 Properties of Water Resources.

Surface water	Groundwater
rapid acquisition of characteristics	difficult-to-grasp characteristics
immediate availability	study and construction necessary
rapid flow	slow flow
rarely good in quality	often excellent quality
high vulnerability	natural protection
rapid return to initial state after pollution	risk of long-term contamination

2 STUDIES

2.1 Data collection, controls, and monitoring of basins

Good management is dependent on the effectiveness of these. The goal being to understand the characteristics of the environment, it is essential to have access to reliable, homogeneous, and accessible data, conserved over a length of time sufficient to allow study and comparison.

2.1.1 Data networks

The European Union adopted, in September 2,000, a water framework directive (WFD). It aims for a general goal of "good status" for the different types of aquatic environments, in under fifteen years, over the entire European territory, and including groundwater. The strategy adopted to accomplish this task includes the definition of the current state and long-term monitoring projects, in order to define the actions to be taken in the future. In France, hydrological and hydrogeological knowledge is shared amongst the BRGM (Geological survey), the DREAL (Regional environment administration), other delegated administrations, Water Agencies, departmental councils, water exploitants, the national meteorological society, and numerous stakeholders such as universities, consulting firms, associations, etc. The stakeholders are therefore varied, and information is dispersed. The State and public establishments manage patrimonial information networks that ensure the following of the general evolution of aquatic environments on a qualitative and quantitative level, but local management networks also exist, at the scale of an aquifer, a river, or a watershed. In order to respond to the needs of the WFD and to make information accessible to largest number of people, a considerable data integration effort is under way. The data is included in the RNDE (National Network of Data on Water) and is also taken up by the new National Water Information System. On the watershed scale, the Water Agency takes ownership of the quality monitoring for surface water and groundwater, while the quantitative monitoring is done by the DREAL for surface water and by the BRGM for groundwater.

A few sites are worth noting:

- INFOTERRE, bedrock data from the BRGM, which is available online (www.infoterre.brgm.fr) but is difficult to use, and is interesting to compare to the USGS site (United State Geological Service; http://water.usgs.gov/)
- ADES (access to Ground Water Data) (http://ades.rnde.tm.fr/ades.asp)
- HYDRO, hydrologic and hydrogeologic database from the National Water Data Network and from RNDE also accessible online (http://hydro.rnde.tm.fr/)

2.1.2 Current state of knowledge in France

The goals set by the WFD restarted studies. But the funds allocated to data collection remain very inadequate. Budget cuts, decentralization, reorganization, and service restructuring, which are frequent in France, are a considerable hindrance to long-term research. Numerous portions of the territory are therefore underdeveloped in terms of hydrogeologic knowledge, which does not enable the management of groundwater or of surface water, as can be seen in the recurrence of flooding in the last few years, which is too easily attributed to natural disasters.

"Governing is to anticipating" (*Emile de Girardin*), and if there is a domain in which long-term planning is essential, water management is it. However, a typically French bad habit is that of making political decisions *ad hoc*, as a function of too-frequent events or elections. Elected officials and scientists do not exist on the same time scale. After a year of drought, credits are released in order to mobilize new resources, only to be eliminated the following year if flooding occurs ! But naturalists' studies are long (see part B), and therefore require an investment over several years.

Research funding is distributed sparingly, and financing a hydrogeology thesis on regional topics, such as the study of an alluvial aquifer or of a karst spring, becomes a real headache. And yet, if the financial consequences of a dry year or of great flooding events are added up, the sums in play are considerable, and could finance thousands of theses! The cost of the Nîmes disaster (destructive flood) in 1998, tied to urban development projects undertaken without a proper understanding of the thalwegs crossing the city and the aquifers that feed them, adds up to 600 million euros. As a PhD costs around 100,000 euros (salary and expenses), that would have been enough money to finance 6,000 researchers.

2.2 Acquisition of knowledge on the scale of the aquifer

2.2.1 Goals

This must enable the definition of the three functions of the aquifer:

- capacitative function: characteristics of the materials, geometry, and limits of the aquifer;
- conductive function: definition of the natural and artificial influxes, definition of hydrodynamic characteristics, inventory of extraction points, estimation of exchanges with superficial hydrosystems and other aquifers;
- reactive function: definition of physico-chemical and biological parameters of the water, monitoring of their evolution, inventory of pollutions.

This knowledge is very unequal across regions, aquifers of different natures, and resources in use for varying lengths of time.

2.2.2 Study and monitoring tools

Aquifer study methods were described in part B. Advances in electronics and new technology now enable the possibility of placing low-cost remote autonomous measuring stations, transmitting information through a GSM communication network or a landline. Inflows and outflows to karst systems can be understood, as can the characteristics of groundwater (Figure 108).

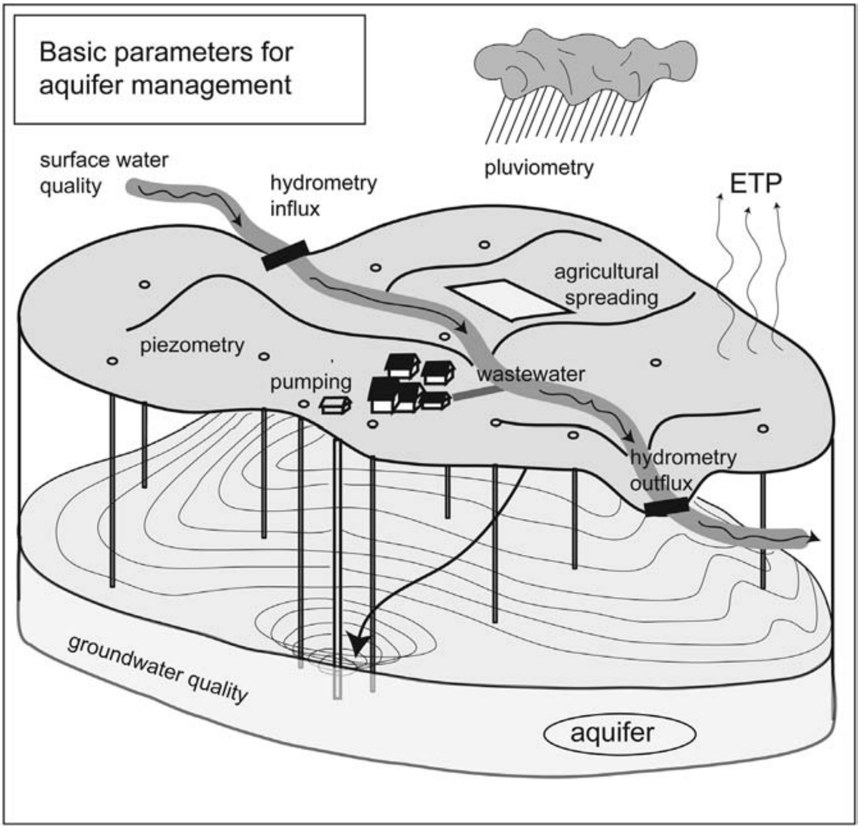

Figure 108 Data to be aquired in order to enable management of aquifers.

Probes with a diameter of a few centimeters can be placed in boreholes and can provide piezometric and physico-chemical data. The most complex probes can simultaneously acquire data on 20 different parameters. Thanks to the data collected, numeric models allow the simulation of an aquifer's behavior (see chap. B8).

Geographic Information Systems (GIS) can synthesize this information and combine it with other data on the environment and on land use, in order to automatically produce thematic maps which can help in decision-making.

All the necessary tools exist to enable an effective management system. The only limits are on the political and administrative level. Management implies action extending largely outside of the town level; it should therefore, in France, be under the charge of departmental and regional councils.

3 ACTIONS ON AQUIFERS

3.1 Quantitative action

These are meant to restore equilibrium in an aquifer or to counter effects induced by exploitation. An aquifer is, indeed, in a state of equilibrium defined by the intrinsic characteristics of the aquifer system and by the inflows and outflows of water. This equilibrium oscillates between extremes linked to climatic variations. Exploitation provokes an additional constraint which defines a new equilibrium. The effects can be as follow:

- lowering of the piezometric level;
- drying of superficial terrain;
- reduction in the discharge of peripheral springs;
- subsidence settling;
- brutal collapses, particularly in gypsic terrain;
- saltwater intrusions in coastal zones;
- withdrawal of poor quality surface water.

In order to restore a satisfactory level to the aquifer, possible interventions include assisting infiltration, artifically recharging the aquifer, or blocking natural outlets in the case of karst systems (see chap. C4).

Due to the effects of withdrawals from a confined aquifer below Shanghai, the city underwent significant settling. The subsidence recorded since 1921 reached 1 cm per year in the years 1956–1959. In 1964, river water injection projects began in the aquifer. In 1966, a hundred or so injection wells allowed recharge directly into the confined aquifer. This stopped the subsidence, and in 1976 the city had risen back up by 34 mm (Detay, 1997). Nevertheless, due to its runaway urbanisation, the city of Shanghai is still subsiding today. Mexico City, built on drained marshland, is experiencing the same phenomenon, accentuated by earthquakes, which liquefy the soil.

In the United States, 18 major sites are affected by subsidence, and for 6 of these, the decision has been taken to stop pumping of groundwater and to use surface water instead. Re-injection is, indeed, not always possible. In addition, the terrain has been disorganized by settling, and a return to initial conditions is rarely possible.

3.1.1 Aquifer recharge methods

a) Assisted autochthonous infiltration

One frequently employed method is the construction of small dams along a river in order to regulate surface water flow and to encourage infiltration in the basins thus created. Examples are numerous in desert zones, such as in southern Tunisia, where a massive development campaign along the path of wadis has been under way for several years. This technique offers the additional advantage of supplying water to arable land, and therefore of allowing cultivation. On the Island of Malta, hillside retaining walls were emplaced on wadis in order to encourage infiltration, with the goal of limiting the saltwater intrusion caused by pumping.

The lowering of the level of the Var (Alpes-Maritimes) alluvial aquifer, which forced truck farmers and water exploiters to lower the level of their wells, was limited by the construction of several retaining basins along the length of the river. Nevertheless, these basins were progressively silted up, limiting the infiltration possibilities. Silting up is the principal problem in recharge systems. The creation of a sinuous path can be considered in order to slow circulation and favor infiltration along riverbanks.

Agriculture can also play a role in the recharge of aquifers. In Spain, in the Alpujara, irrigation channels from Roman times (Sabovik, 1973) divert water from rivers in order to feed the aquifer. In France, Lacroix & Blavoux (1994) thus highlighted the beneficial role of irrigation on the Lower Durance aquifer, the level of which peaks in July-August. Inversely, studies can be undertaken to favor infiltration in agricultural zones, in order to limit the harmful effects of runoff: soil erosion, transport of solids, and contribution to flood discharge.

Stormwater runoff from urban impermeable surfaces can also be directed towards infiltration setups. This system offers the double advantage of relieving the infiltration deficit caused by the impermeabilisation of surfaces and of avoiding the negative effects of runoff. 80% of the runoff from Valence-Lautegne (Drome) are directed in such a manner towards three infiltration basins with a total volume of 70,000 m^3 over a surface of 4.1 ha. In karst zones, runoff can be directed into natural cavities, as long as it is of acceptable quality, since the environment provides only a reduced level of natural purification.

b) Allochthonous input from river diversions

Surface water from rivers can be diverted in order to recharge an aquifer. karst environments, thanks to their rapid recharge properties, can give rise to interesting situations, as is the case in the West Bank of Jordan, where the Yarqon-Taninim aquifer (Cenomano-Turonian carbonate formation), exploited at a rate of $400 \cdot 10^6$ m^3 per year, receives a complement of approximately $100 \cdot 10^6$ m^3 per year through infiltration of surface water from the Jordan river.

But quantitative action can also be taken by using the aquifer as a capacitative regulatory system. The discharge of certain rivers can thus be regulated by injecting their water into the neighboring aquifers. Water from the Oise, for example, is withdrawn during flooding periods, infiltrated through the chalk aquifer, and restored through pumping in dry periods in order to increase the dry season discharge of the Oise by approximately 1 $m^3 \cdot s^{-1}$ (Detay, 1997).

c) Artificial recharge of aquifers (from Detay, 1997)

The artifical recharge of an aquifer implies the availability of a surface water resource (river or lake), of a high enough quality to avoid costly preliminary treatment, and with a discharge compatible with the recharge goals. The aquifer must also obey several constraints:

- large thickness of unsaturated soil above the aquifer in order to enable storage and autopurification;
- favorable transmissivity;
- high vertical hyraulic conductivity in order to facilitate the formation of a reserve;
- moderate horizontal hydraulic conductivity in order to enable the conservation of the reserve created.

These parameters can be found in chalk and in porous formations (sand, gravel). Fractured aquifers and karst, within which water circulates too quickly and is only porly filtered, are generally not favorable to artificial recharge, but other methods of active management can be developed (see chap. C4-4).

Artificial Groundwater Recharge (AGR) is highly developed in the USA, particularly in California. The city of Los Angeles obtains 40% of its drinking water from artificially recharged groundwater. AGR is used varyingly in Europe.

In France, the principal AGR sites are located in the Paris region (Croissy/Seine and Flins-Aubergenville), in Dunkirk, Dijon, and Lyons. They account for approximately 200 million m^3 per year of infiltrated water. Different methods described below are used (Figure 109).

d) AGR through infiltration

Artificial groundwater recharge is generally done through infiltration basins or ditches (Figure 110), often equipped with a bed of sand. The infiltration rate varies from 15 to 0.1 $m \cdot day^{-1}$ depending on the setup. It is generally

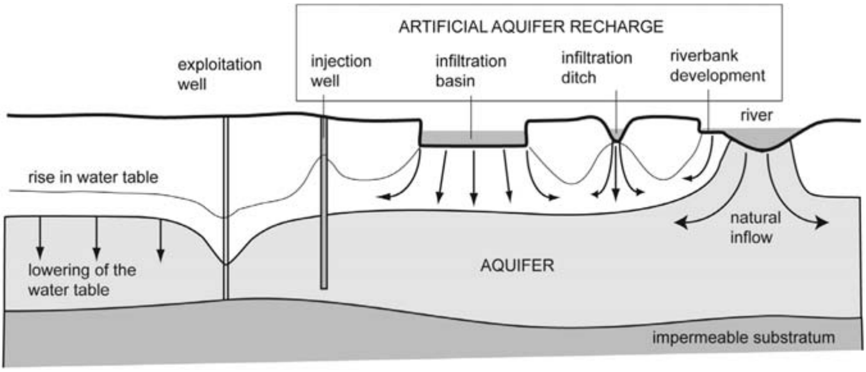

Figure 109 Different AGR methods.

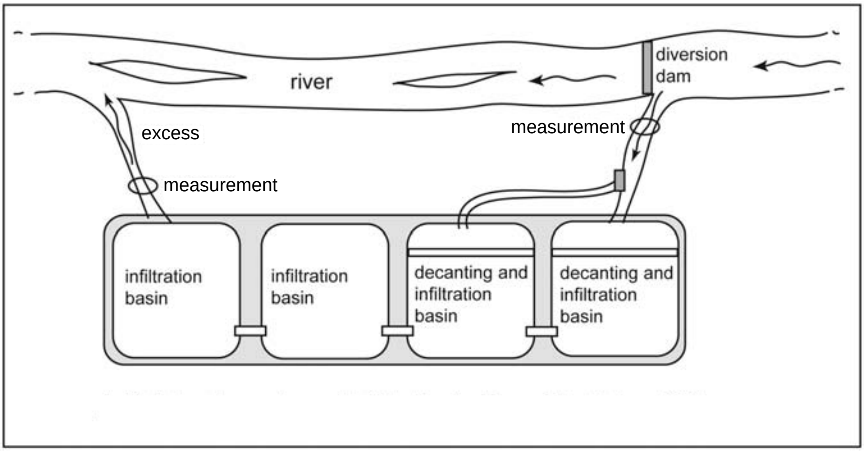

Figure 110 AGR through infiltration basins (from Detay, 1997).

around 1 m·day^{-1}. Modifications to riverbanks can also increase the surface area in contact with the aquifer formation. Diversion dams can direct the river water towards infiltration basins. Inflatable rubber dams are used in California (USA), in order to divert water from the Santa Ana river into infiltration basins, artificially recharging an aquifer supplying 2 million inhabitants. 70% of the water pumped comes from this setup. The dams are inflated or deflated at will, depending on the discharge and turbidity of the river, in order to collect only clear water and avoid the silting up of the basins (Detay, 1997).

e) AGR through injection

Boreholes or wells reaching the surface of the water table can be used to inject water into the aquifer one wishes to sustain. However, the wells silt up rapidly; so a method was developed in the USA, ASR (aquifer storage recovery), where the same well is used for pumping and for injection. These alternating uses prevent blockage. This method offers the advantage of requiring a reduced surface area in comparison to infiltration basins or ditches.

3.1.2 Underflow dams

The preceding methods concern conductive functions at the entry to a system, but actions can also be taken within the aquifer, by locally altering transfer conditions. Impermeable barriers can be built within the aquifer in order to store water and to locally raise the level of the water table (Figure 111). This method is used in the Sahel, as well as in Brazil in agricultural zones. The water stored in this way is protected from evaporation.

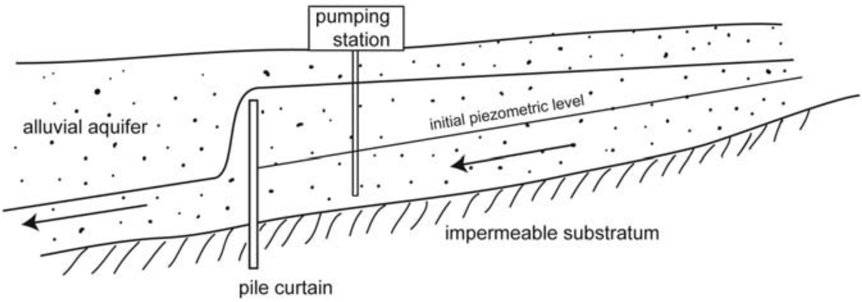

Figure 111 Water storage with an underflow dam.

3.1.3 The problem of clogging

This is the major problem in artificial groundwater recharge. Clogging is caused by the influx, in infiltrated water, of fine-grained particles that silt up the pores in the soil, but also by physico-chemical or biological reactions in the soil causing, for example, swelling of clays or proliferations of bacteria or algae, creating a biological film that cannot be totally eliminated, as it participates in the purification of infiltrated water. In deep basins, water pressure can also compact the terrain and reduce its permeability, encouraging clogging.

Basins must therefore be regularly maintained. In order to limit clogging, water is generally decanted and filtered, and chemicals are added to encourage flocculation of clay particles or discourage the proliferation of algae and bacteria. Finally, the oxygenation of water, through waterfalls, helps the elimination of suspended organic material by bacteria. Infiltration basins can also be equipped with liners or geotextiles which are then regularly cleaned and changed. In some cases, a lawn can be planted at the bottom of the basin, but this solution allows only short recharge times, under a thin layer of water.

In infiltration basins, the alternation of aquifer recharge phases with dry phases generally limits clogging effects (Figure 112).

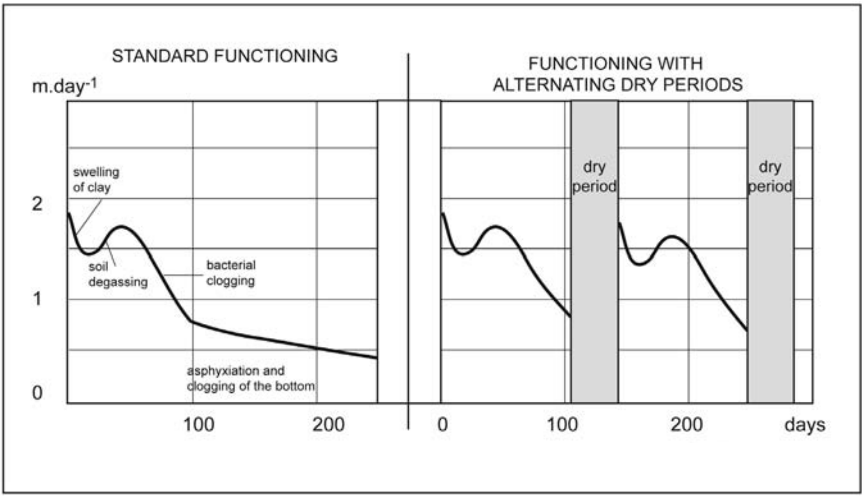

Figure 112 Clogging avoidance by alternating wet and dry phases (from Detay, 1997).

3.2 Qualitative action

The first step is to avoid contaminating the aquifer. French regulations require the emplacement of protection zones around water catchment points (see chap. C3-4) and the law passed in 1992 clearly details the prohibitions and restrictions intended to protect surface and groundwater quality.

As in coastal aquifers, contamination through intrusion of polluted water can be limited with the emplacement of a hydrauic barrier with artificial groundwater recharge (Figure 113).

The aquifer can nevertheless be accidentally contaminated or, due to the age of its contamination, require processing. Humans can also intervene in the quality control of an aquifer by acting on the reactive properties of the

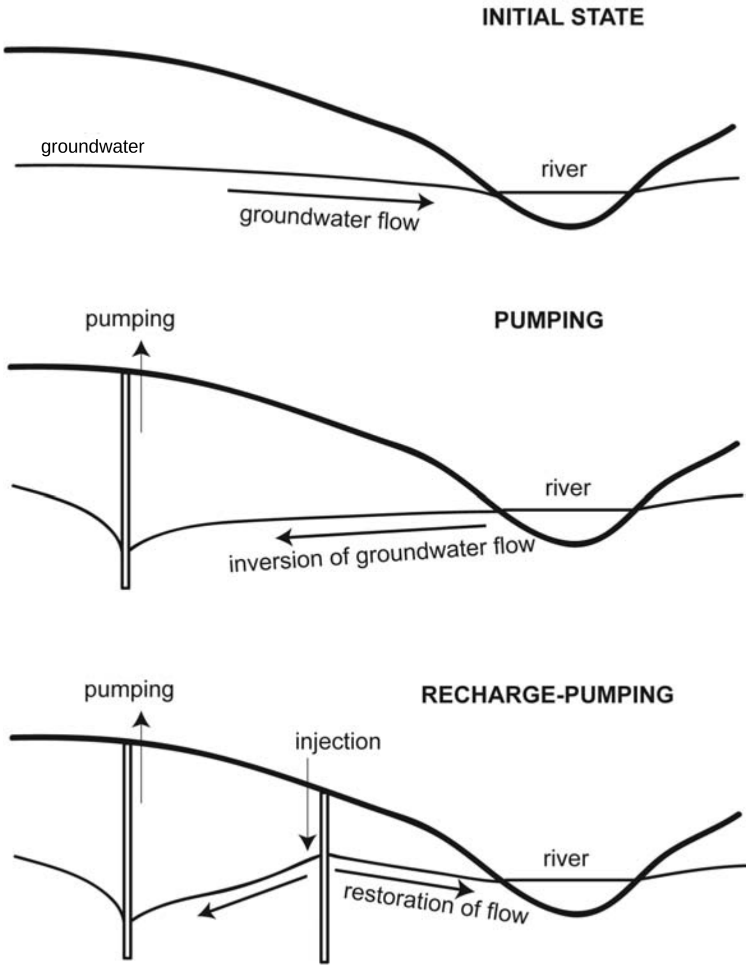

Figure 113 Restriction of a surface water intrusion into an aquifer with a hydraulic barrier.

environment. Action can be directed towards preserving an existing quality, or the improvement of a degraded aquifer, but the natural properties of the environment can also ensure the treatment of surface water. Indeed, the aquifer includes several physical, chemical, and biological reactants that interact with the fluids passing through it. For example, the ammonium present in the Seine's waters, downstream of Paris, is oxidized into nitrates in the Croissy-sur-Seine site, thanks to an aeration waterfall placed upstream of the basins, as well as the aerobic soil atmosphere of the unsaturated zone that exists between the bottom of the basins and the surface of the water table.

3.2.1 Fight against point-source pollution

Two types of action are possible. If water circulates rapidly in the aquifer, as is the case in karst systems, qualitative monitoring can predict when the pollution plume will reach catchment areas. Pumping can then be stopped as the wave of pollution passes through.

If circulation is slow, the aquifer must be cleaned-up. Procedures are varied, depending on whether the pollutant is floating at the surface of the aquifer or is spreading throughout it entire cross-section. One can, for example, create a hydraulic barrier by injecting water into the aquifer around the contaminant, and then pump the polluted water. The injection of reactants or solvents may be necessary. Volatile pollutants can be mobilized by injecting air into the aquifer. One can also, for pollutants less dense than water, skim the surface of the aquifer by creating a cone of depression through pumping, at the surface of which a second pump can recover the substance to be eliminated (Figure 114). Biodegradation processes are used for certain organic products, by injecting bacteria and favoring their development in the aquifer through the addition of nitrates.

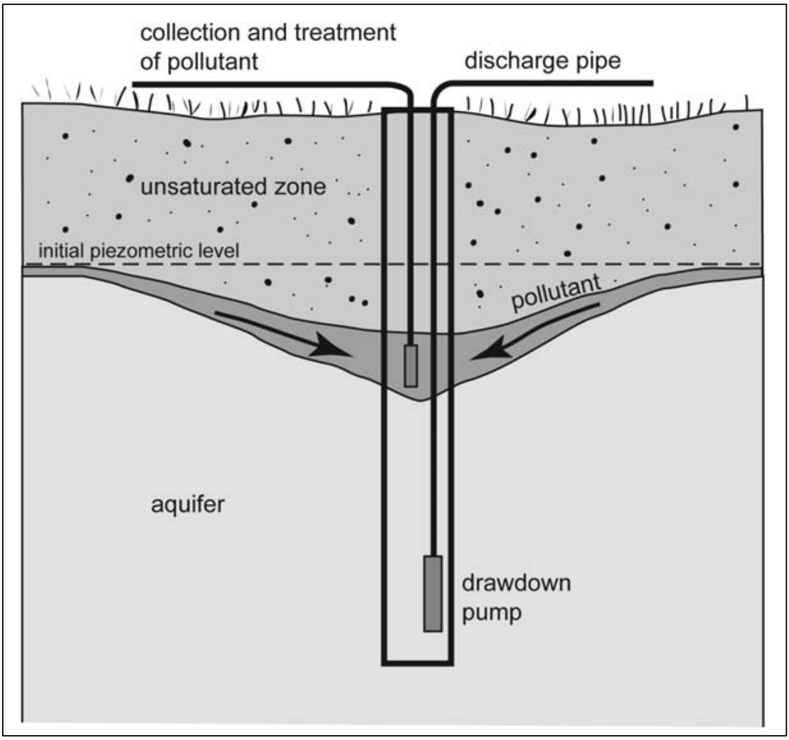

Figure 114 Example of aquifer cleaning-up through skimming.

3.2.2 Fight against bottom contamination

a) Denitrification

Denitrification occurs naturally in the soil thanks to carbon. It can nevertheless be insufficient, and liquid organic carbon (methanol, ethanol, acetic acid) can then be injected into the aquifer. Various procedures are used, but a major problem is the clogging that these methods induce.

Another procedure consists of pumping water, treating it at the surface by circulating it through organic material (chopped straw), and then reinjecting it into the ground.

b) Deferrization and demanganization

Iron and manganese are undesirable in water. Well injection of water enriched in oxygen through aeration provokes the precipitation of iron, then of manganese in the aquifer.

c) Radioactive decontamination

Following the Chernobyl catastrophe, groundwater was contaminated. The CEA (Atomic Energy Commission) put zeolite barriers in place, designed to trap radioactive material.

4 OPTIMISATION OF THE EXPLOITATION OF KARST AQUIFERS

Karst springs often have a high variability, and exhibit an alternance between severe dry periods and high flood discharges. It is therefore tempting to try to manage them so as to sustain dry season discharge by using floodwaters. The first possibility is the creation of dams downstream of karst systems: Sainte Croix (France) dam regulating the karst Verdon waters, Oymapinar (Turkey) dam regulating the Manavgat and Dumanlı spring waters (50 $m^3 \cdot s^{-1}$). But this solution is demanding in terms of space, and, in France, few sites remain available. However, since limestone, thanks to the size of the cavities (0.5 to 10%) that it contains, makes up a reservoir, it is interesting to benefit from these capacitative properties.

4.1 Underground dams

Dams inside karst systems have been known for a long time in China (Luota syncline), for potable water storage or for electricity production.

A Guilin Karst Institute (China) and Western Kentucky University (USA) project is supposedly under way in Hunan (China) to raise level of the karst aquifer by 200 m thanks to an underground dam, in order to supply drinking water to the villages in the spring's watershed.

A prototype built in Coaraze on a small karst spring (Figure 115) led to the observation that the 8 m rise in the water table enabled, on the one hand, the filling of karst drains, and on the other hand, the recharge of the fracture network in the rock mass (Gilli & Mangan, 1994).

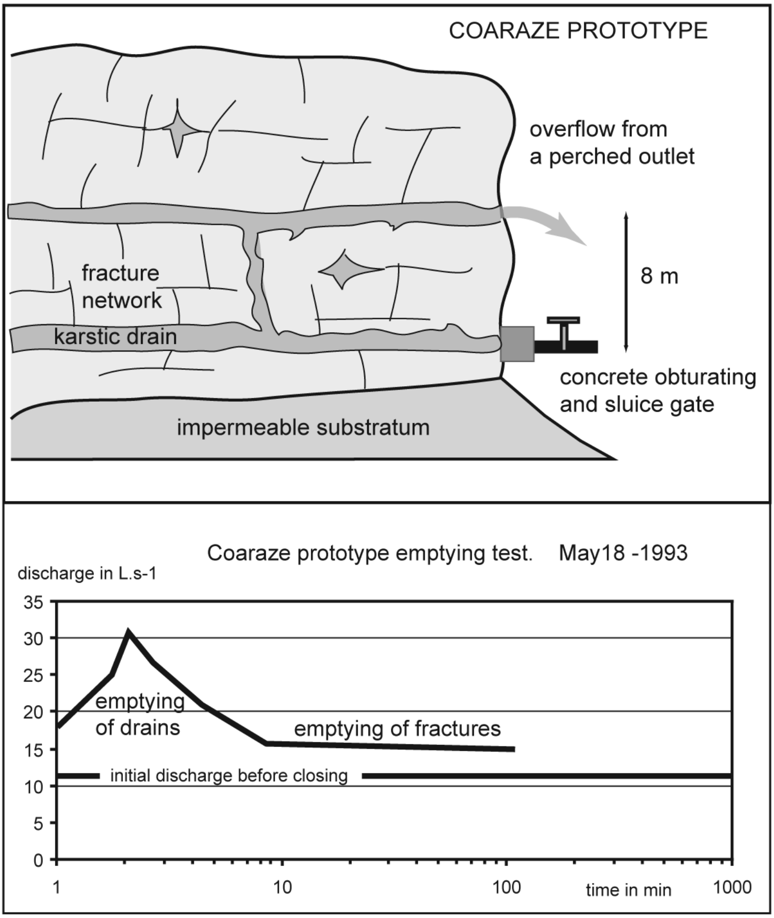

Figure 115 Emptying of the Coaraze (Alpes Maritimes) prototype.

In Croatia, the Ombla project (Figure 116) consisted of damming the karst circulation feeding the Ombla spring and waterproofing the rock with the help of a 100 m grout curtain supported by flyschs, in order to form an underground dam intended to supply water and to feed a 68 MWe electric plant in the Dubrovnik region (Breznik, 1998).

However, underground dams can modify the stability of the limestone units in which they are built, or cause the reopening of unused karst conduits. Following a flood, a collapse occurred over the underground reservoir in Jedres (Herzegovina) (Milanovic, 2001).

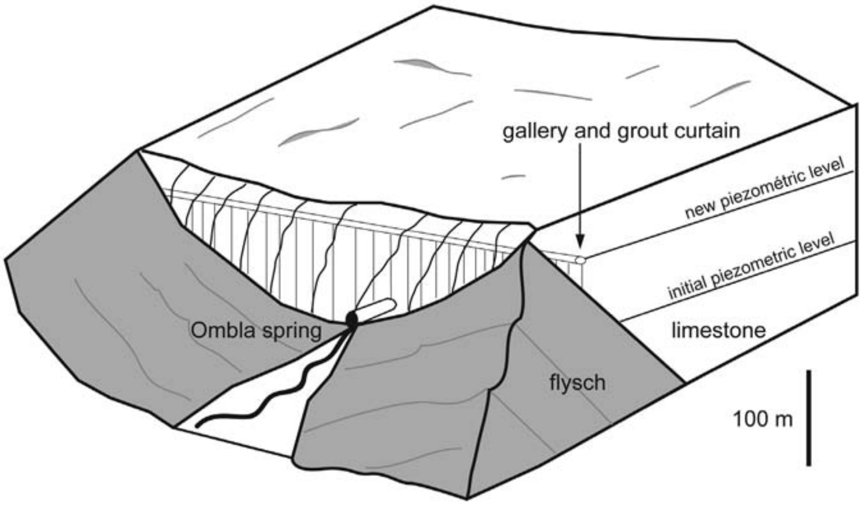

Figure 116 Block diagram of the Ombla project (from Breznik, 1998).

4.2 The case of the Lez spring

The vauclusian emergence feeding the Lez river drains the northern Montpellier limestone plateaus, of which it is the low point. The basin extends over approximately 400 km^2. The natural discharge varies between 300 and 10,000 L·s^{-1}.

The spring has supplied the town of Montpellier since the 19th century. The demand for water increased regularly, and the contributions from the Lez went from 25 L·s^{-1} in 1859 to 400 L·s^{-1} in 1931. Gravity-driven extraction then reached the limit that the spring could provide. In order to increase the available discharge, pumping tests were done in the spring's pool in 1965. They enabled a discharge increase to 1,000 L·s^{-1} with a drawdown of 8 m. At this period, advances in sub-aquatic speleological exploration enabled the exploration of the karst passage upspring of the pool and the observation that this passage continued deep into the heart of the limestone units. In 1979, at the initiative of the Compagnie Générale des Eaux (now VEOLIA) and the City of Montpellier, a team from Hydrokarst, a subsidiary of COMEX, reached a depth of 75 m 536 m from the entrance. A catchment project was then proposed in order to provide an alternative to supplying Montpellier with water from the Rhône river. Following a war of influence opposing the powerful supporters of a surface water adduction and the hydrogeologists, led by the tenacious Professor J. Avia, the subterranean solution was chosen.

The project consisted of reaching the karst passage with boreholes and of placing pumps to create a drawdown of several tens of meters which would theoretically enable the exploitation over several months of a discharge of 1,700 L·s^{-1}.

Construction took place in 1981; an underground station was excavated and four boreholes with a diameter of 1.8 m reached the passage. Three pumps were installed, each enabling a discharge of 1,000 L·s^{-1} (Figure 117).

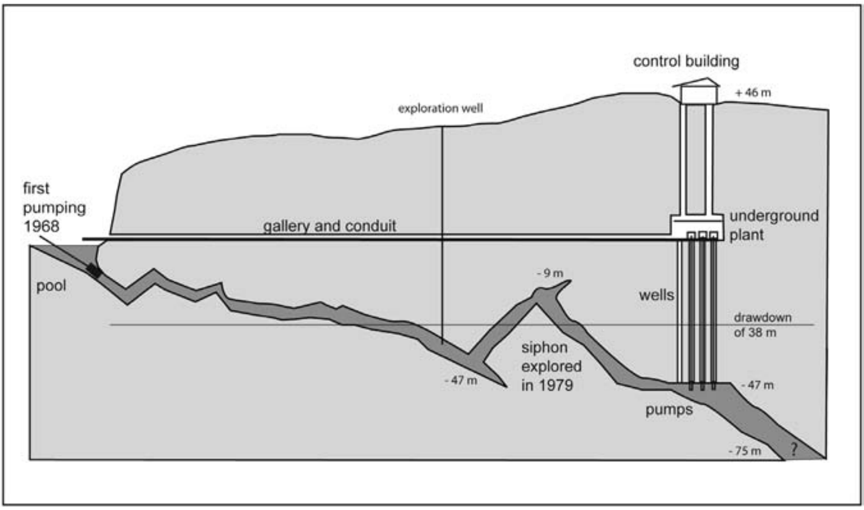

Figure 117 Lez (Montpellier) spring catchment system (from a CGE document).

The resource is managed so as to allow a complete recharge of the aquifer during the autumn rains. Currently, the system is functioning perfectly. The drawdown, limited at 38 m, enables the extraction of 1,700 L·s^{-1}.

Part of the water goes to Montpellier and the other sustains the flow of the Lez, guaranteeing a minimum discharge of 160 L·s^{-1} and conserving a satisfactory surface water quality.

The system could provide greater quantities, but at the risk of drying neighboring springs and causing turbidity problems greater than the capacity of water clarification unit to treat. In order to manage this risk, the spring and a network of 24 piezometers distributed over the entire watershed are regularly monitored (Périssol, 2004). The drainage basin, the limits of which remain poorly defined, is estimated to cover between 170 and 200 km^2.

A similar example exists in Montenegro, in Opacica, near the mouth of the Kotor, where the karst aquifer can be lowered by 20 m below sea level, thanks to a favorable geologic environment protecting it from marine contamination.

Chapter C5

Examples of the Search for Drinking Water

1 EXPLOITATION OF AN UNCONFINED AQUIFER (MOUANS-SARTOUX, ALPES-MARITIMES)

The town of Mouans-Sartoux originally relied on two very unequal resources for its potable water:

- the Foux de Mouans-Sartoux, a karst spring issuing from the Muschelkalk limestone (Middle Triassic), which provides an interesting discharge (250 $L \cdot s^{-1}$ as a yearly average), but the use of which is complicated by several disadvantages: low elevation (69 m a.s.l.), requiring a costly uplift, high sulfate content during dry periods and frequent turbidity peaks during flooding, vulnerability to pollution, requiring a complete treatment process;
- the Saurin spring, outlet for a ledge of Jurassic limestone above the Keuper marl. The physico-chemical characteristics of this spring are better, but its production is smaller (from 100 to 300 $m^3 \cdot day^{-1}$, depending on the season).

The borough undertook a search for another water resource to reinforce and secure its supply, based on a phased study that took place from 1990 to 1995 and resulted in the use of the new Pinchinade catchment field.

Preliminary research found only one site that could be retained, at a town territory scale. This site was the small Jurassic carbonate hump feeding, in particular, the Saurin spring. The outcrop is small, totally bounded by impermeable Upper Triassic formations, but its partial shaping by a NNE-SSW tectonic rift, the Pinchinade graben, creates an interesting local hydraulic trap (Figure 118).

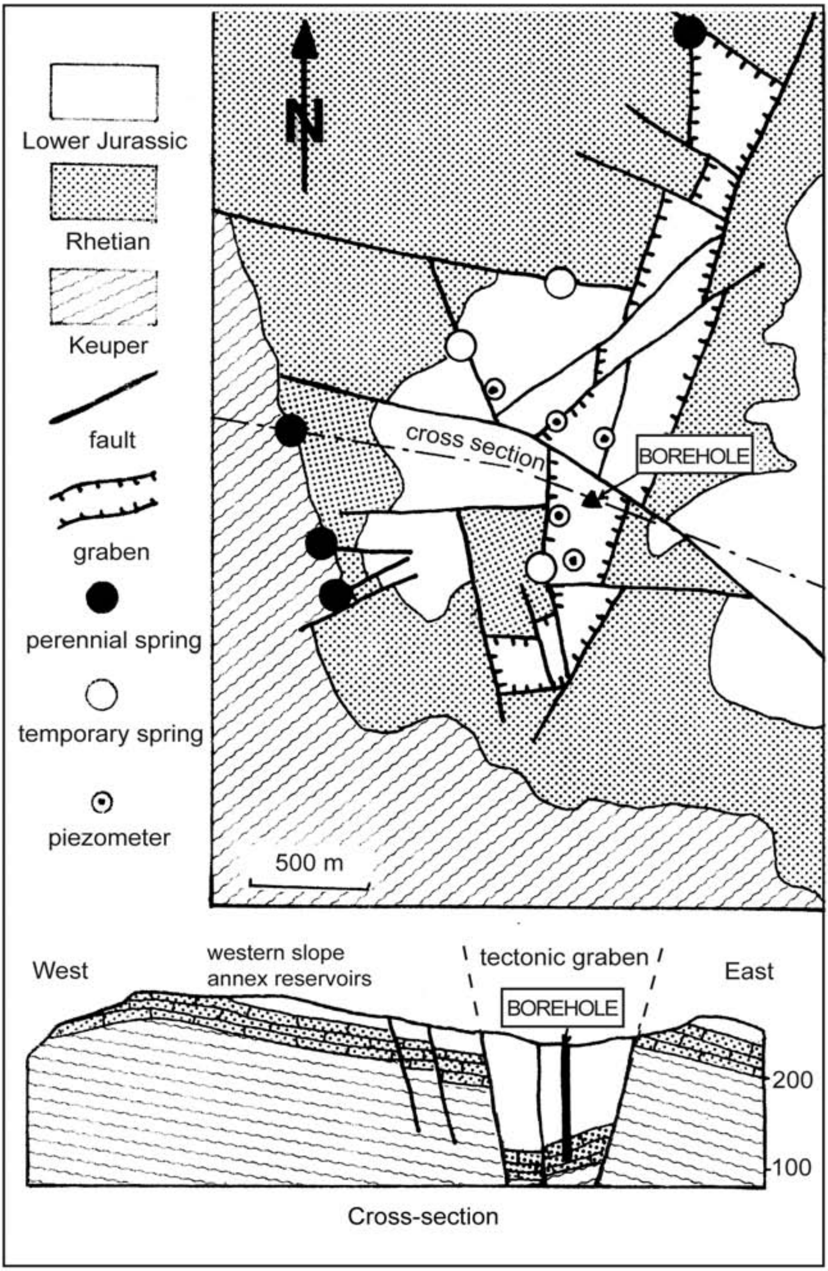

Figure 118 Hydrogeologic context of the Pinchinade catchment field (Mouans-Sartoux, Alpes-Maritimes).

After a detailed analysis of the geometric limits of the aquifer reservoir, exploratory drilling found, at the heart of the graben, 120 m of Lower Jurassic dolomite and limestone above Triassic formations, enclosing a rich aquifer with a static water table at a depth of 25 m.

The exploitation borehole was drilled in 1993 and doubled in 1995, in the graben's axis, at the elevation of 250 m a.s.l. After the creation of a piezometer network along the length of the basin and along its edges, a pumping test revealed a northern impermeable boundary, corresponding to a strike-slip fault, and a clearly ovoid drawdown surface, the long axis of which is aligned with the direction of the graben.

A prolonged emptying test was undertaken, and monitoring continued during the exploitation of the catchments, based on a daily recording of the piezometric level, the extracted volume, and the physico-chemical parameters of the water (conductivity and hardness). Regular sampling provided, in addition, an understanding of the evolution over time of the pumped water (Figure 119).

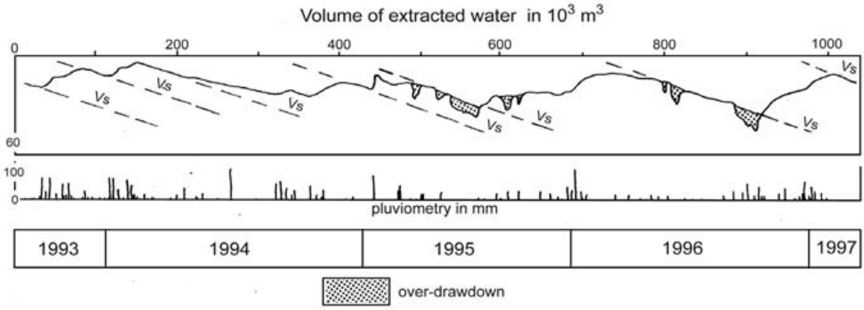

Figure 119 Pinchinade wells (Mouans-Sartoux, Alpes-Maritimes). Prolonged emptying test.

Sampling corresponds to the extraction of 950,000 m^3 in a little over 3 years. Analysis of the graph leads to the conclusion that the part of the aquifer connected to the boreholes has a specific volume Vs of 4,000 $m^3 \cdot m^{-1}$, and that the permanently exploitable resource has an estimated volume of 260,000 m^3 and a yearly renewable reserve of 270,000 m^3.

Management of the resource nevertheless runs into limits, shown by monitoring results, on both qualitative and quantitative levels:

- from a quantitative aspect, it has been observed that when the extracted discharge exceeds 1,000 $m^3.j^{-1}$ (simultaneous pumping in both wells), a sizeable increase in drawdown (on the order of 15 to 20 m) occurs, which stops immediately as soon as the pumping rate decreases;
- from a qualitative aspect, it has been observed that, during such intensive pumping, the water chemistry is significantly altered, demonstrated by a decrease in nitrate concentration (marker for

infiltrated water) and an increase in sulfate concentration (marker for the Triassic formation bordering the graben) (see chap. B3-6.1.4).

These observations nicely illustrate the mechanisms of the reservoir being drawn upon, which is composed of two distinct parts (Figure 118):

- on the one hand, the principal graben reservoir, which is highly transmissive and makes up the drainage axis of the aquifer system;
- on the other hand, the western slope, which, due to its increased extent and its elevated position, makes up an annex reservoir primarily serving as a storage site, but also highly regulating the subterranean inflows to the drainage axis.

The reaction limits of the annex reservoirs are revealed when the graben's karst conduits are emptying the reservoir; which results in a marked increase in drawdown, when the water taken from the graben exceeds the compensating input from the annex reservoirs and from the surrounding Triassic units (which enclose gypsum lenses), with an accompanying increase in sulfate concentrations (Guglielmi *et al.*, 1997; Reynaud *et al.*, 1999).

The characteristics of the site therefore lead to a perfectly understood water resource, the exploitation of which must imperatively be regulated by the quantitative and qualitative limits revealed.

2 EXPLOITATION OF A CONFINED AQUIFER (PAILLON BASIN, ALPES-MARITIMES)

- The SILCEN (Association of municipalities of the counties of Levens, Contes, l'Escarène and Nice) regroups some twenty towns, for which potable water is taken directly from the Vésubie River and directed through a 30 km long tunnel, which then feeds into three secondary channels 25 km long.

  Complementary inputs come from the Var alluvial aquifer, but the Paillon sector, located at the eastern extremity of the service network, needed an additional supply on the order of 100 $L \cdot s^{-1}$.
- The studies done in 1989 led to the search for such a resource in the Jurassic karst aquifer, which offers large infiltration surfaces in the Paillon basin, and for which the budget appeared to have a large deficit.

The Jurassic ranges in the area form an arc in the periphery of the Contes syncline, and are organized in anticlinal folds, tilted over towards the south and thrusting over narrow, pinched Cretaceous synclines until they reach the coast, where they are submerged beneath the sea. In the Paillon valley, these units show a distinct tilt in their axes and plunge deep below their Cretaceous cover (100 m of Cenomanian marls, overlain by a thick series of Turonian marl-limestone) (Figure 120).

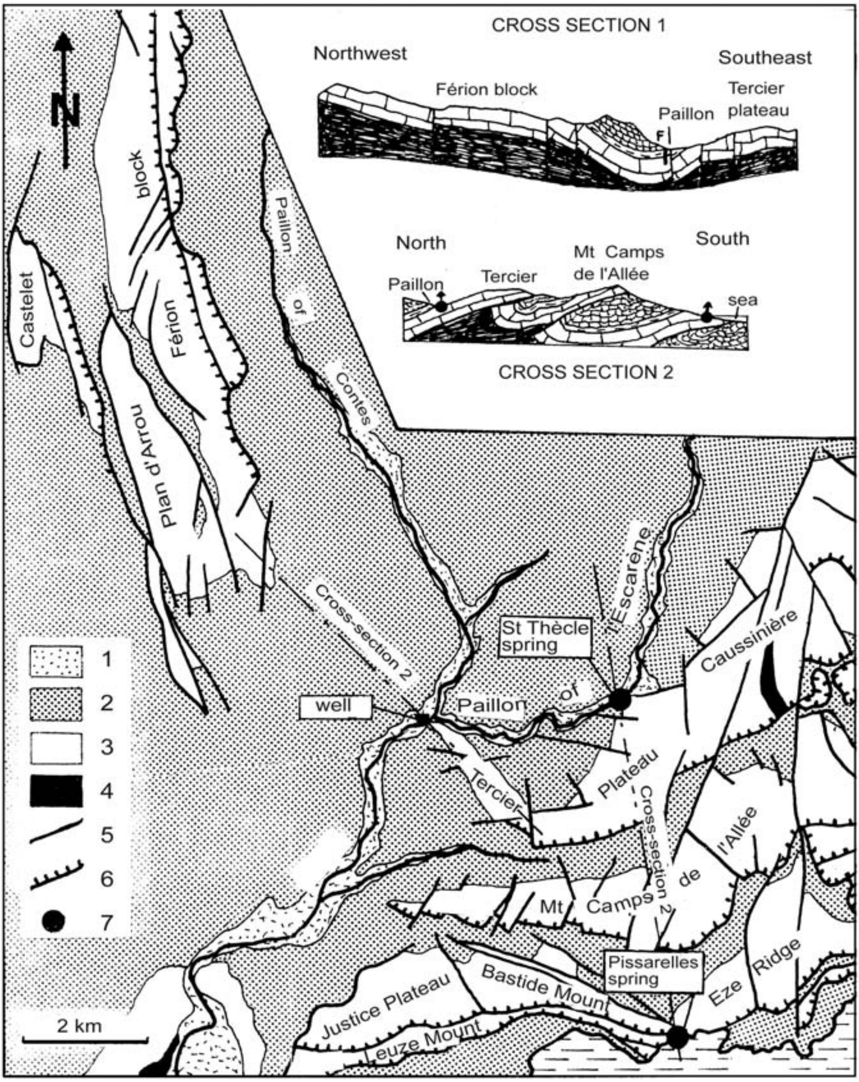

Figure 120 Hydrogeologic map of the Jurassic karst aquifer in the Paillon valley (Alpes-Maritimes).
1-alluvial aquifer, 2-Cretaceous cap, 3-Jurassic karst, 4-Triassic base, 5-major fault, 6-overthrust, 7-karst spring.

From a hydrogeologic point of view, the Jurassic aquifer is limited by continuous impermeable formations: Upper Triassic clays at its base and Cenomanian marls at its roof.

The intensity of the brittle and ductile deformation, however, enables complex geometric relationships (and therefore undeniable exchanges) with the surrounding anticlinal slices, with the alluvial valley fill, and with the Turonian marl-limestone in the overlapping Cretaceous synclines.

The different karst units provide preferential drainages following fold axes, and suffer significant transversal leakage, particularly during high-water periods, thanks to transfers between stair-step slices, from north to south (Emily, 2000). Two outlets drain this aquifer, one, the Ste Thècle spring, along the Paillon, at an elevation of 150 m a.s.l., and the other, the Pissarelles spring, which is partially submerged by the sea, at an elevation of 0 m. With an average annual discharge on the order of 130 $L{\cdot}s^{-1}$, these emergences indicate a distinct restitution deficit, estimated to be around 250 $L{\cdot}s^{-1}$, based on a catchment basin of 42 km^2 and a specific infiltration module of 8 to 10 $L{\cdot}s^{-1}{\cdot}km^{-2}$.

The search focused on the confluence of the two Paillons, on the Sagna site, established at an elevation of 100 m a.s.l., where the karst aquifer becomes confined under its cap of Cenomanian marl, while infiltration occurs laterally, on outcropping areas where the aquifer is unconfined, between the elevations of 300 and 1,000 m. This area corresponds to a magnificent hydraulic trap (cross-section 1 of Figure 120), and the water present was revealed to be highly artesian, with a pressure head varying from 2 to 5 bars depending on the season (aquifer between the elevations of 120 and 140 m a.s.l.).

A prolonged emptying test was undertaken in 1994, using the aquifer's artesian properties, and resulted in the extraction of 900,000 m^3 of water in a little over 5 months (Figure 121).

This test enabled an estimate of the following characteristics for the part of the aquifer hydraulically connected to the well:

- a specific volume Vs of 45,000 $m^3{\cdot}m^{-1}$;
- a permanent reserve of 2.7 million m^3 up until an elevation of 100 m a.s.l. (corresponding t to the ground level on-site) and of 9 million m^3 up until an elevation of 30 m NGF a.s.l.;
- a renewable reserve of 1.6 million m^3.

The results obtained went above the initial goals, and enabled the discovery of a sizeable, well-protected resource.

Another well was drilled later on in the same area, in order to supplement Drap's drinking water supply, and two others are being considered in order to back up the water supply for nearby towns.

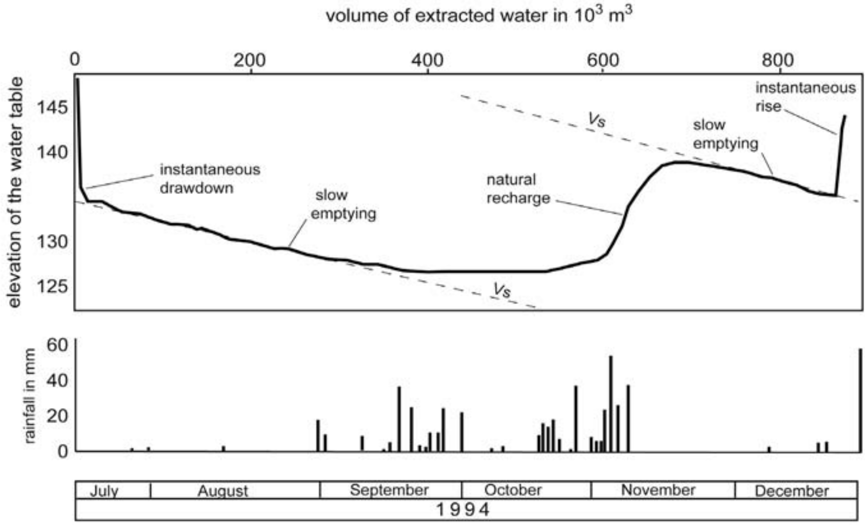

Figure 121 Sagna well (Paillon Basin, Alpes-Maritimes). Piezometric evolution of the aquifer as a function of the pumped volume during the forced emptying.

Additional demands on this resource can be considered as a future possibility, as long as the extracted volume and the piezometric level of the aquifer are carefully monitored, and as long as the inevitable environmental effects of increased exploitation are examined (loss of inflows to the alluvial aquifer, exhaustion of the Ste Thècle spring).

D

HYDROGEOLOGY IN CIVIL ENGINEERING

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Chapter D1

Water and Construction

Groundwater plays an essential role in most projects undertaken by humans, and the hydrogeologist holds a more and more important place within the teams studying and following civil engineering operations. The hydrogeologist must, indeed, specify the influence of the projected construction on the behavior of the aquifer, evaluate environmental effects, and define the eventual modifications or compensatory measures to be adopted.

Difficulties linked to groundwater can concern all types of construction or development, whether during their construction or during their use, and whatever their nature, their size, or their degree of permanence. Problems are resolved by setting up a classic hydrogeologic study, obviously adapting to the natural context and the particularities of the development under consideration. This also requires that historical data and surrounding installations be taken into consideration, enabling a solid understanding of the piezometric fluctuations of the aquifer over time, and the impact of the construction on the natural and human environments of the site.

The reciprocal influences of construction on groundwater and *vice versa* is principally determined by their respective positioning, as well as by groundwater flow conditions and the inter-seasonal and inter-annual variations of the aquifer.

1 NATURAL FLUCTUATIONS IN THE AQUIFER

The piezometric surface of an aquifer is directly influenced by the pluviometric conditions in its environment and shows permanent variations that regulate the state of its inflows and its drainage possibilities.

The amplitude of variations changes significantly, depending on the nature of the aquifer, but also from one point to another within the same aquifer. It can reflect as a significant rise in the water table during periods of excess rainfall, or, inversely, lead to noticeable drops following periods of deficit.

Development projects must imperatively take into account these natural fluctuations, if they do not wish to suffer various problems or damages, ranging from simple flooding due to overflow from the aquifer to structural damage caused by hydraulic pressures or, inversely, by excessive draining and settling of the land.

The basements and foundations of construction projects are frequently flooded when the water table rises. This is, in fact, a very common case in plains, where a river and its accompanying aquifer coexist, and the latter can react very quickly to flooding in the former.

In the old city portion of Nice (Alpes-Maritimes, France), built on the alluvial fill of the Paillon valley, most old buildings have overflow wells in their basements to relieve pressure. These wells, otherwise used to draw water from the aquifer, are built with rims high enough to contain the known high-water level, in order to guarantee the safety and soundness of the buildings.

Today, with the multiplication of basements buried several levels below ground in urban zones, specific protection equipment is deployed, either by waterproofing the entirety of the vulnerable portion of the building with an impermeable casing, or by incorporating collection and evacuation systems for groundwater (draining and collecting foundations equipped with pumps).

Another example, very representative of the effects of a rise in the water table, can be provided by a construction site where a buried pool had just been installed in the pit opened for this purpose. The excavation, very near a river, cut into silty and sandy alluvium containing an accompanying aquifer. During a sudden flood, the pool was lifted up by pressure from below due to the sudden rise in the water table, and was then dislocated when the level dropped again.

In order to resist such piezometric pressures, buried constructions are often weighted at their base, or welded to the bedrock by anchorages.

Such events are usually short-lived, and cause only scattered accidents of limited severity. The disaster caused by the Somme's flooding in the winter of 2001 is, however, of an entirely different scale. This phenomenon was of an unusual intensity, both in its length (7 months) and in the extent of the zones its affected (Somme, Aisne, and Oise departments, in North-western France). The combination of, on the one hand, topography and geology favoring infiltration, and on the other hand, unusual and sustained rainfall, led to the rapid saturation of the superficial silty cover and of its underlying chalky bedrock. In addition to the overflowing stream network, a general rise in all of the aquifers submerged low-lying areas, flooded a number of buildings, and led to the fissuring and collapse of various buildings and construction sites (Caudron, 2002).

The opposite effect, corresponding to abnormal drops in piezometric levels, can also lead to the disorganization of certain buildings, due to modifications in the characteristics of the soil supporting them. This was the case, in particular, in several regions of France during the droughts of 1989 to 1992, where numerous structures, built on clayey terrain, were affected by multiple fissures, due to shrinkage linked to the drying of the underlying soil.

2 INFLUENCE OF CONSTRUCTION IN WATER-BEARING TERRAIN

Infrastructures implanted in aquifer formations perturb, in more or less permanent ways, the state and order of flow in the aquifer, by creating blockages or reducing the cross-sectional area of flow, or, inversely, by accentuating the drainage.

These situations will have repercussions on the work being done, and require detailed studies in order to resolve problems with foundations and stability. They can also have repercussions on the environment in the construction site and require an examination of foreseeable impacts and protection measures to be taken.

2.1 Role of hydraulic barrier

The simplest situation is that of a retaining wall built at the front of a temporarily water-bearing terrain. This is a frequent case on clayey, marly slopes thickened by a weathering mantle or by a scree cover of variable thickness. It is common, especially when construction occurs during the dry season, for the building to be under-dimensioned and often even completely devoid of drainage. The rainy season and the sustained saturation of the soil will often precipitate failure, either as a direct effect of hydraulic pressure, or as an effect of the decrease in the angle of repose and the increased pressure on the construction in the case of consolidated terrain.

The role of the hydraulic barrier is fully exercised when a building is set well into a permanent aquifer over a representative length, which is often the case in urban areas, where the use of the space below ground tends to be intensified in order to create basement levels (underground parking lots) and subterranean passageways (subways). In certain sectors, the concentration of underground construction is such that the aquifer, initially unconfined, can become confined by the built structures.

It is when structures are built transversal to the flow direction in the aquifer that perturbations are the most noticeable. They can result in a piezometric rise upslope and a drop downslope, as well as in a change in the flow direction of the aquifer and an increase in its hydraulic gradient, between structures and at their extremities. The most common consequence for the surrounding buildings is the flooding of basements and of lower levels in the area immediately upslope, due to piezometric rises, as well as localized slumping induced by internal erosion caused by the washing away of fine-grained particles due to the increase in flow velocities in sites with steep hydraulic gradients.

In such a context, construction can proceed only when the site is surrounded by an impermeable belt, which can be created through a number of procedures (grout curtains, diaphragm walls, belt of sheet piling, secant pile wall), and kept dry through pumping in collection wells or in perforated boreholes.

The mechanisms put in place to maintain the flow of the aquifer generally enable the limitation of induced piezometric variations to a few tens of meters or even to a few meters, whether they are permanent or temporary.

In certain cases, drainage of the aquifer is assured by the buried portion of the structure itself, either by open drainage channels in the impermeable barrier, by a draining foundation, or even by a mixed arrangement. The outflow, collected in sumps and moved out by pumps, is then dumped into the storm water runoff network or re-injected into the aquifer downslope, if the surrounding context allows it.

In other cases, as much during construction as afterwards once the impermeability of the structure is total, hydraulic continuity is ensured by systems external to the building, whether these consist of filtering units enveloping the underground structures, or of subhorizontal radial drains created below buildings. Haffen (1977) mentions adaptations of this type for the underground sections of the Munich and Duisburg subways in Germany, and for the Vienna subway in Austria, buried in the sandy-gravelly alluvium of the Isar, the Rhine, and the Danube respectively.

In Nice (Alpes-Maritimes), the underground Cours Saleya parking lot, built in the alluvial aquifer of the Paillon, near the coast, is equipped with an original system of four ducts ferrying the aquifer's water from the upslope side of the lot to its downslope side (Pline, 1991). This setup did not, however, stop the rise in the piezometric level, which was responsible, in particular, for the destabilization of the Miséricorde Chapel, the preservation of which required the recent re-anchoring of the foundations with micro-piles.

2.2 Induced drawdown

Drainage induced for large-scale construction projects can have distinctly more sizeable repercussions on their environment than that of construction sites limited by impermeable barriers and therefore proceeding in a confined environment.

The influence of this drainage can, indeed, result in drawdown of several tens of meters and can be felt in relatively distant locations, with all of the consequences associated with such modifications of the groundwater system:

- drying of springs, lowering of the water level in wells and boreholes, drying of lakes or of hanging valleys, as a direct effect of the excessive drawdown of the aquifer;
- slumping or induced collapses, in relationship with the drying of the ground and with the increase in hydraulic gradient of the aquifer (washing out of fine particles and of unconsolidated fill).

These effects are in large part tied to the long duration of certain construction sites in which induced drawdown is necessary (several months to several years), or to the great spatial extent of the aquifer affected by the construction (a few hundreds or thousands of meters). The damages are, additionally, irreversible when the characteristics of the structure do not allow the reestablishment of initial hydraulic conditions.

The role of tunnels passing through aquifers perfectly illustrates this problem (see chap. D 3-3 to D 3-5).

The origins of the drawdown can also be involuntary and result from poorly-adapted actions or from the beginning of construction without really taking into account the various components of the natural and human environment. The case of the use and development of the lower Var valley in the area around Nice (Alpes-Maritimes) is revealing of this state of being. In its lower part, the Var River flows through a plain ending at the Mediterranean Sea, and the alluvial fill of which contains a large accompanying aquifer, which is intensely exploited for the drinking water supply of coastal urban areas. At the end of its course, the river initially spread out over a wide bed, varying in width from 600 to 1,000 m, that it occupied fully in flood, and within which it meandered during the dry season. The progressive channeling of its course between 1850 and 1970 reduced its width to an average of 250 m, enabling the use of part of the surrounding previously-flooded land for cultivation and various other purposes, but also favoring erosion and the lowering of the channel as its flow velocity increases. In parallel, a large quantity of alluvial material was extracted from deep gravel pits, enabling the mining of a volume of material estimated at 30 million m^3 between 1946 and 1980. The intensive usage of alluvial deposits led to a rapid acceleration of erosion by the river, and consequently, to a significant lowering of the water table in its accompanying aquifer, particularly between 1965 and 1978. Upstream of a catchment field for the city of Nice, where the water table reached the surface in 1965, the level dropped by 8 meters in 1967. This evolution continued, leading to the drying of 370 agricultural wells and seriously endangering the productivity of potable water catchments. Limitations on gravel mining in the active riverbed were very progressive, and conservation measures were put into effect as early as 1971. These consisted of 10 overflow dams with waterfall heights of 4 to 6 meters, built transversally across the river, and intended to stop the aforementioned harmful effects and to reestablish the river's waterline. These mechanisms, although they did, indeed, stabilize the Var's erosion rates and the dropping water table, also modified the solid particle transport conditions of the river, increasing erosion in certain areas due to lack of deposition, and decreasing the inflow to the aquifer from the river in other areas, due to sedimentation and clogging of its bed and its banks (Thévenin, 1983).

Chapter D2

Mass Wasting

1 WATER AND INSTABILITY

Mass wasting is a natural process, which has a great influence, along with erosion, on the shaping and evolution of landscapes. They can generate significant risks for humans and the built environment, which has resulted, over the last few decades, in different prevention studies, first ZERMOS maps (zones exposed to risks linked to movement of the soil and bedrock), then PERs (risk exposure plans), and finally, more recently, PPRs (foreseeable natural risk prevention plans).

There are generally several factors governing these risks, but two of these play a primary role in the mechanisms of destabilization:

- gravity, which leads to mass wasting sometimes being termed gravity-driven movement;
- water, which often acts as a trigger for instability.

Human interventions can also worsen the situation in sensitive areas, or generate truly anthropogenic instabilities due to ill-adapted construction, which most often fails to adequately take into account the various components of the natural environment.

The most common types of mass wasting can be grouped into the following families:

- gullying, which cuts more or less deeply into slopes under the effects of surface runoff;
- rockfalls, which generally affect massive rock units;
- landslides, which shape unconsolidated slopes;
- collapses and subsidence, which are caused by the dissolution of soluble rock or the washing away of fine particles due to groundwater circulations.

Only the last two types will be described in further detail, due to the importance of groundwater's role in their genesis and evolution.

2 LANDSLIDES

2.1 Characteristics and particularities of landslides

These are mass movements mobilizing variable volumes, going from a few m^3 (small-scale slips) to several million m^3 (hillside slides). They generally affect plastic and granular terrain, but large-scale slides can also affect unconsolidated or ground up rocky slopes (example of the Clapière slide, chap. D2-4).

There are two principal types of slides, characterized by the geometry of their rupture surface (or shear surface):

- planar slides, where the rupture occurs through simple translation along a planar surface. This surface generally coincides with a natural discontinuity: stratification joint, tectonic break (diaclase, fault), or tilted contact between two distinct formations (superficial cover over rocky substratum, for example);
- circular slides, which develop due to rotation along a curved surface and can affect relatively deep horizons.

The evolution velocity of these processes is generally fairly slow, from a few millimeters to a few centimeters per day, and rarely exceed a few meters per day, but their progression can occur over long periods of time, marked by alternating periods of relative stability and more or less abrupt remobilization, as well as regressions upslope.

When the liquid phase becomes predominant, some slides can evolve into mudflows, characterized by rapid dynamics and significant propagation. These are highly destructive events, as can be seen from the following two examples, which deeply marked the Alpes-Maritimes (Perriaux, 1927; Menéroud, 1976):

- on November 24th, 1926, the village of Roquebilière, built on the left bank of the Vésubie, was hit in the middle of the night by a flow with a volume estimated at 2 million m^3, after an accumulation of 440 mm of rainfall over the 3 preceding days. The event mobilized morainic clay deposits in large blocks thanks to the emptying of a water pocket in the underlying gypsum, causing 19 deaths and destroying some 20 houses;
- on April 24th, 1952, the town of Menton was hit by several landslides, following an accumulation of 306 mm of rainfall in 3 days. The clayey eluvial cover of the flysch slopes, gorged with water, generated several flows, the propagation of which caused the death of 11 people and the destruction of 17 buildings.

2.2 Causes of landslides

There are multiple factors governing slope stability (geology, topography, climatology, hydrology, the rocks' state of disintegration), and it is often very difficult to specifically identify the causes of a landslide. There is generally a complex combination of a number of factors leading to the rupture, but it is usually set off by changes in the geometry of a talus slope and in the role of water.

The equilibrium of natural slopes varies noticeably as a function of the characteristics of their constituent rock, and can evolve over time due to weathering of this rock and to the influence of external factors. Disequilibrium can be reached at any moment through a decrease in resistant forces, following the elimination of a basal abutment. This is classically the case when a large-scale excavation generates a brutal instability in the overlying talus, but also when natural erosional processes slowly destabilize the foot of a slope (basal undercutting by the sea or by a river, melting of a glacier). The disequilibrium can also be a result of the creation of a point surcharge which increases destabilizing forces (the emplacement of an embankment on a slope, for example).

The role of water is always highly important, even if it is not the only factor, and there exists a strong correlation between the setting off of landslides and the intensity of rainfall. The accumulation of water in a sensitive slope, either by direct or nearby infiltration, or by subterranean influxes of more distant origin, directly influences the characteristics of the component materials, by reducing its resistance to shearing through an increase in interstitial pressure and by reducing its cohesion. These effects can influence the entirety of a sensitive site, and can translate as marked amplitudes in the level of the water table, with periods of instability often in phase with piezometric rises. The effects of the increased presence of water can also concern only certain permeable areas within an impermeable formation, or a deep permeable horizon likely to be filled with water below impermeable formations. Such permanent or episodic upwards pressure facilitates the setting off of landslides.

2.3 Treatment of landslides

Landslides being essentially provoked by gravitational and hydraulic factors, it is normal that stabilization techniques focus preferentially on geometry and mass distribution as well as on drainage.

Changes in geometry and masses tend to restore an equilibrium profile to unstable areas, either through excavation (substitution of high-friction materials for the slipped mass, basal buttress, unloading at the head of the unstable area), or through shoring up of the base with the help of various constructions (gravity walls, anchored supports, soil nailing).

Water plays a primordial role in all types of landslide occurrences, and its elimination must remain a principal goal in order to move towards stabilization. This is why drainage is almost systematically used in curbing landslides, either as the principal method or accompanied by another stabilizing measure. The goal is to reduce the interstitial water pressure in the terrain, in order to increase the resistance to shearing and therefore the security coefficient with respect to potential or declared ruptures. The goal is also to maintain this pressure below a threshold deemed critical in order to guarantee the future security of the site. A very thorough hydrogeologic study is then essential in order to design an appropriate drainage system. The development of the project particularly requires a solid understanding of the nature of the concerned aquifers, of their extent and eventual exchanges, as well as the origins of the water influxes maintaining the system, in order to enable the control of disfavorable hydraulic factors by an adapted drainage type (superficial, upslope, lateral, deep). Design or construction errors can, indeed, lead to the total ineffectiveness of the drainage system, or even to negative effects on the stability of the site, as is also the case when the system is poorly maintained after construction, even if the initial construction was highly effective. Several types of interventions can be considered, as a function of the depth of the rupture, the global geometry of the landslide, the local topography, and the water inflow conditions: surface drainage, drainage ditches, subhorizontal drains, vertical drainage, or drainage galleries. The definitive drainage of a slide or of an unstable slope is generally put in place progressively, in parallel with the creation of a piezometer network which allows the monitoring of the drainage's effectiveness. The system is rarely fixed, and can, over time, require complementary or restoration work, particularly when monitoring reveals ineffectiveness due to lack of maintenance or to the clogging of certain drainage structures.

2.3.1 Superficial drainage

The good management of surface water plays an important role in slope stability, and it is undeniable that the gradual abandonment of ancient drainage and irrigation systems is now leading to the rapid degradation of many slopes, made fragile by the anarchic outflow of previously channeled water.

Immediately after a landslide is set in motion, superficial interventions are always very useful in attempting to curb its progression, and can lead to emergency measures when the protection of the downslope area justifies them and when the surface in question allows them. The goal is then to limit the inflow of water in fractures and slope reversals (plugging of fractures, local impermeabilization with polyane sheets, leveling of the unstructured surface) and to encourage the outflow of water accumulated on-site (opening of springs, creation of drainage ditches).

Superficial drainage can contribute to a return to equilibrium, when runoff or sub-superficial flow originating upslope contributes in large part to the supply of water. This is especially the case when the dominating bedrock allows an important, concentrated runoff towards the sensitive zone, either naturally (large impermeable catchment area), or due to human activity (intensive irrigation, voluntary dumping of storm water runoff, breaks and leakages from irrigation canals and buried pipelines).

The uphill drainage of these influxes and their lateral collection towards stable outlets often allow a distinct amelioration of the situation.

2.3.2 Drainage ditches

This mechanism is often used when the aquifer horizon does not extend below a depth of a few meters. It consists of excavating ditches, then filling them with clean draining material, after having emplaced a perforated pipe in the bottom, and with measures to prevent future clogging (choice of particle size respecting filtration rules, or interposition of an anti-contaminating geotextile). These ditches must have a high longitudinal slope and be connected to a gravitational collection system.

Such projects are sometimes built to follow topographic lines in order to intercept the groundwater flow from further upslope and to collect them laterally, out of the sensitive zone. This geometry must nevertheless not be recommended, due to the real risk of reinjection of the collected discharge into the body of the landslide, through leaks due to local movements or to poor maintenance.

In most cases, drainage ditches are opened along the line of the steepest slope, or structured in oblique herringbone patterns connected to collection ditches following the direction of the slope. Their purpose is to lower the piezometric level by cutting across the maximum number of water-bearing horizons or lenses.

These ditches can have very large dimensions when the stakes justify it and when the depth of the slide allows it. Such is the case for the ditches bulldozed down to the shear surface and filled with draining material. They can reach tens of meters deep, and they are then essentially buttresses encased over the entire height of the slide and adding a sizeable mechanical reinforcement to the effects of the drainage (example of the Ardisson landslide, see chap. D2-5). In a similar line of thought, other mixed structures are sometimes used at the toe of a slide in order to lower the water table and create a favorable mechanical effect: masking earthworks made up of draining material, implanted along topographic lines, or herringbone drains, arranged following the line of greatest slope.

2.3.3 Subhorizontally drilled drains

These are widely used, most often in combination with other supporting methods. They consist of small-diameter perforated tubes (generally made of metal or of PVC), which are installed in boreholes sloping slightly upwards, over lengths reaching or exceeding one hundred meters. Their principal advantages are their fastness of construction, their great flexibility in terms of location and orientation, and the gravitational outflow of the collected discharge. Their durability, however, is unfortunately not guaranteed, they can become less effective over time:

- either as an effect of the reactivation of the landslide, causing the rupture of drainage pipes, especially if they are made of PVC, and therefore the reinjection of water into the moving mass;
- or as an effect of gradual clogging of the drains, particularly when the water has a high mineral content and when it carries fine particles or when the flow is too irregular.

These subhorizontal drains are generally drilled in diverging arrays from a small number of specially equipped work chambers, which allows a sweep of the entire landslide, sometimes relying on a succession of arrays at different elevations.

When the zone to be drained is too deep, or the surface topography is too gentle, the drains can be drilled from a specific work chamber encased in the terrain, accessible via a short passage or a well.

2.3.4 Vertically drilled drains

Their use is less frequent, but they can complement other stabilization mechanisms.

They consist of perforated tubing installed in vertical boreholes and designed to inject water from the superficial aquifer into a deeper reservoir. This operation requires a preliminary understanding of the deeper aquifer's outlets, and verification of its absorption capacity and peak piezometric variations, in order to avoid an effect opposite the one desired due to sizeable increases in hydraulic head during high-water periods.

When injection at depth is not possible, the water collected by the vertical drain can be extracted by pumping, with the inconvenience of requiring permanent maintenance. Pumping is generally done with submerged pumps installed at the bottom of the boreholes. Surface suction pumps (sand point wells) or continuously primed siphons, which guarantee gravitational extraction (siphon-drains), are sometimes used, but these methods are limited to boreholes under 10 meters deep.

2.3.5 Drainage galleries

When the slip surface is very deep or the local topography is not conducive to surface-based drainage operations, these operations can be undertaken with the help of a gallery, the main inconvenience of which is its high cost.

The gallery can enable a significant lowering of the water table saturating or threatening the zone in movement. Its effectiveness can also be increased through the creation of peripheral subhorizontal drains drilled from the gallery (example of the Quiaus landslide, see chap. D2-6).

2.4 Example of the La Clapière landslide (Saint-Etienne-de-Tinée, Alpes-Maritimes)

The La Clapière landslide, one of the largests in Europe, was a result of deep ruptures and set in motion a volume of over 50 million m^3 of material over an area covering around a hundred hectares and over an elevation change of 700 m. It resulted on-site in an upper escarpment 800 m long and 100 m high, in a general stair-step morphology shaped by multiple fractures and numerous slope reversals, and by a clear basal rise at the level of the valley (Follacci, 1987).

This slide is located in the northwestern portion of the Argentera-Mercantour external crystalline mass, immediately downslope of the village of Saint-Etienne-de-Tinée. It affected the slope on the left bank of the Tinée valley until its confluence with the Rabuons valley, and disorders developed between the elevations of 1100 and 1800 meters, while the mass of mountains reaches 3,000 meters (Figure 122).

The slope is made up of Variscan metamorphic material, caught up in Alpine tectonics. It consists of plagioclastic gneiss with two micas, said to be “of Anelle”, within which is interbedded a stratiform metadiorite body, making up the Iglière bar. This last unit, distinctly more massive and compact, is marked by a noticeable projection mid-slope and provides a useful cartographic reference point. The foliation of the rocks, which appears to be very steep over the majority of the area, with dips of 55 to 85° to the northeast, is much less tilted and is sometimes even subhorizontal in the area immediately surrounding the slides. It is, in addition, obliquely cut across by Alpine schistosity. Finally, the rock mass is cut through by a fracture network organized around several principal axes, inscribed within the context of the transverse fault-overthrust system oriented N 120–140, which dictates the course of the Tinée and which locally pinches narrow Triassic basement synclines.

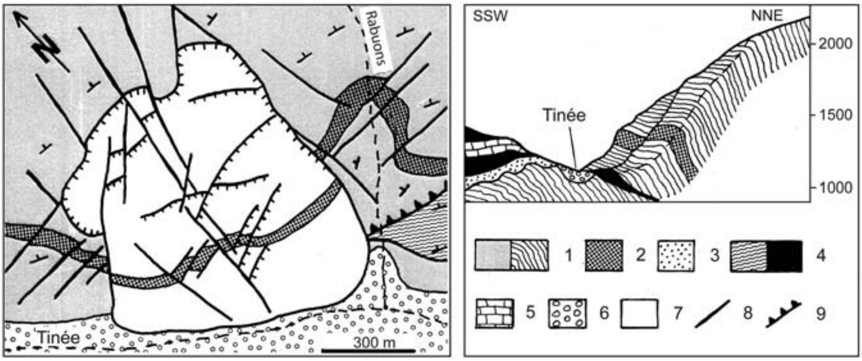


Figure 122 La Clapière landslide (Saint-Etienne-de-Tinée, Alpes Maritimes). Map view and cross-section.
1-Anelle gneiss, 2-Iglière bar, 3-Permo-Werfenian, 4-Triassic cellular dolomite, 5-Triassic limestone, 6-Alluvium, 7-Landslide, 8-Fault, 9-Overthrust.

Activity on the slope probably goes back to the beginning of the 20th century, when it must have been only very gradually visible, but picked up noticeably starting in the 1970s, then again starting in 1983 (with seasonal alternations of acceleration and deceleration). During phases of activity, the amplitude of the movement could reach 3 to 4 meters per year, with values of 8 cm per day during the summer of 1987.

The causes of the landslide appear to be primarily mechanical, then hydraulic (Follacci, 1987; Follacci *et al.*, 1988):

- initially, the melting of the Würmian glaciers occupying the Tinée and Rabuon valleys would have, by eliminating buttressing support, prepared the slope for its future evolution by allowing a large-scale downturning of dip near the slope surface and a gradual destructuration of the rock under the effects of decompression;
- subsequently, water acting in this highly fractured environment would have engendered more or less stacked initial movements, gradually evolving towards a deep rotational landslide.

Water is without a doubt the primary factor in the historical evolution of the landslide, with an annual rainfall of around 1,000 mm in Saint-Etienne-de-Tinée and a slice of water equivalent to 600 to 900 mm induced by the fusion of mountain mass's snow cover. One can, indeed, observe a very clear correlation between phases of acceleration and local precipitation, and especially with snowmelt (Follacci, 1987).

The most recent hydrogeologic research, based on a detailed inventory and quantitative monitoring of the outlets, as well as on isotopic and chemical analyses of the extracted water, detail the role of water in the disequilibrium of the slope (Compagnon *et al.*, 1997; Guglielmi *et al.*, 2000 and 2002):

- infiltration occurs preferentially over a recharge area above the slide, where a perched superficial aquifer is developed over an area of 4 to 5 km^2. There exists a lateral perennial drainage of this spring, but most water is injected through vertical exchange into the moving mass, where it rejoins a deeper aquifer;
- a secondary inflow of water appears to originate from the tectonically deformed Triassic syncline on the southeastern edge of the slide and clearly marks certain deep aquifer outlets with a strong sulfate-magnesium signature, with, in particular, sulfate concentrations reaching 800 $mg \cdot L^{-1}$;
- a rough budget can account for only a small portion of the quantities infiltrated discharged at various outlets (13% in lateral springs and 1% in basal springs), which indicates significant internal circulation and hidden influxes directly connected to the basal alluvial aquifer (86% of infiltration);
- it is essentially during the melting of the snow mantle at higher elevation that the inflow quantities are large enough to result in a significant recharge of the rock's fracture network and to maintain the mechanism under way.

Given the size of the phenomenon, the topography of the area, the apparent depth of the ruptures (100 to 200 meters) and the impossibility of considering an economically feasible reinforcement system, the responsible parties opted for careful and continuous monitoring of the phenomenon and for measures directly oriented towards the protection of people and property:

- topometric monitoring of the slope's surface has been operational since 1982 and enables the following, with a good level of precision and total regularity, the kinetics of the slide;
- an alert and rescue plan was created in order to coordinate the response in the event of a sudden rupture;
- prescriptions were included in the PPR beginning in 1983 in order to define at-risk zones requiring evacuations or construction bans;

- the departmental road 2205, which passes below the foot of the slide and leads to Saint-Etienne-de-Tinée, was rerouted in 1985 to the right bank, in order to follow a less exposed path;
- a diversion gallery for the Tinée was built from 1989 to 1991, in order to alleviate the potential obstruction of the valley if the slide were to brutally set itself back into motion.

2.5 Example of the Ardisson landslide (La Trinité, Alpes-Maritimes)

During the construction work for the Paillon-Turbie section of the A8 highway linking the Nice area to Italy, a sizeable landslide in 1977 affected an embankment at a location called "Ardisson".

The highway passes through the subalpine range of Nice, structured as a series of east-west folds thrusting over each other towards the south. It is locally set into the northern flank of the Mont Camps-de-l'Allée unit, held up by the Jurassic limestone that outcrops widely on the overlooking ridge and that is covered on the slope by Cenomanian marl, then by Turonian marl-limestone. Despite the east-west brittle and ductile deformation affecting the Cretaceous formations, the series is globally monoclinal and is cut across by sizeable north-south transverse faults (Figure 123).

The Ardisson embankment is made up of unsorted limestone and a marly core, over a length of 400 meters and a maximum height going from 10 to 20 meters. It allows the highway to cross a large concave section of the slope, with a transversal slope of 10 to 15°, the Cenomanian marly substratum of which is masked by a more or less developed scree cover.

The landslide occurred following a significant rainy episode, in a rapid evolution, with movements of 1.0 to 1.5 meters per day in certain sections during active periods, and over a large areal extent, since it affected an area of 6 hectares and set into movement a volume of material of over a half a million m^3. It was visible on the ground as a classic slide, characterized by is crowning scarp cutting into the embankment, by lateral shear fractures limiting a stepped body, and by a toe mass locally channeled by a small ravine (Figure 123).

These disorders are in fact located on an ancient landslide, of greater magnitude, which was partially remobilized during the highway construction work. They are worrisome indicators for the future stability of the highway platform and for the immediate security of the residences located downslope.

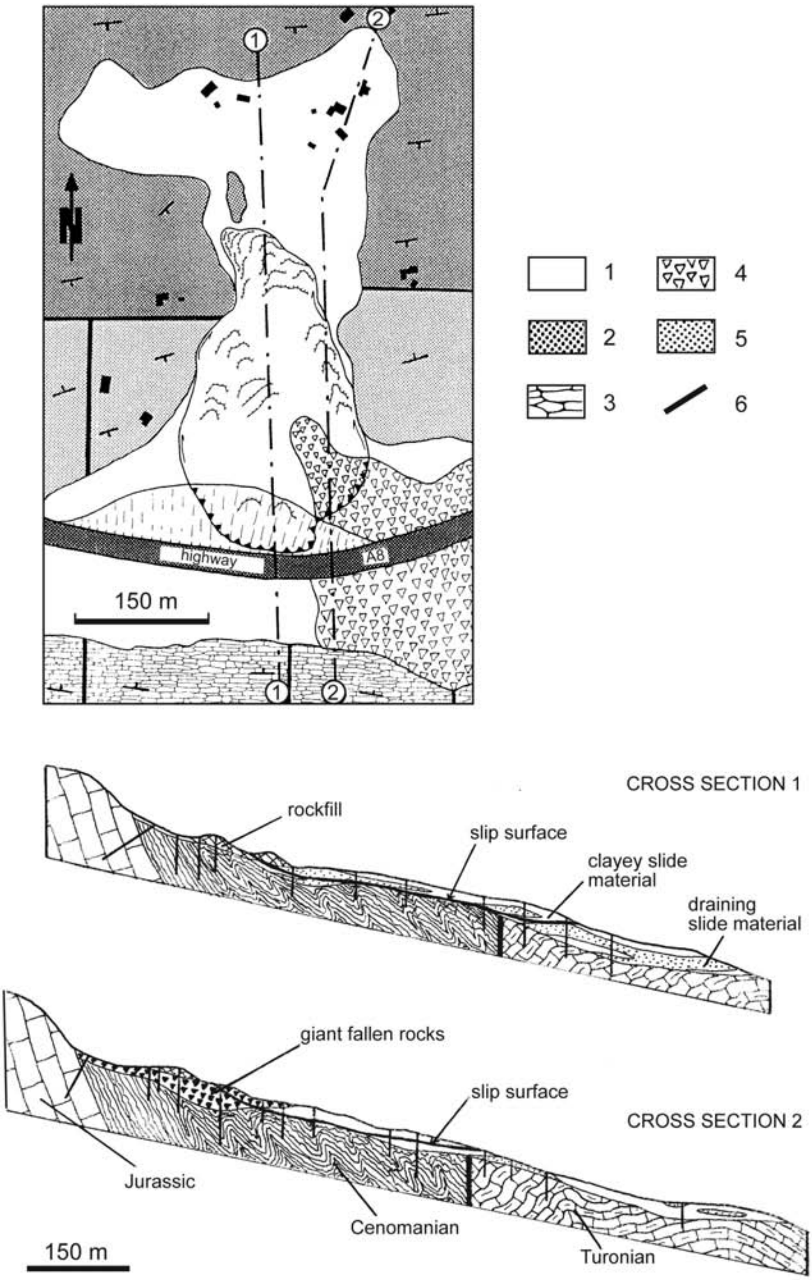


Figure 123 Ardisson landslide (La Trinité , Alpes-Maritimes). Map view and cross-section. 1-scree and ancient slide material, 2-giant fallen rocks, 3-Turonian marl-limestone, 4-Cenomanian marl, 5-Jurassic limestone, 6-fault.

A complete and broadened study was rapidly undertaken (topographic survey, topometric monitoring, field surveys, geophysical prospection, core and destructive drilling, inclinometers, piezometers) and enabled the precise understanding of the roles played by the structure and hydrogeology of the area on the setting off of the landslide.

The ancient landslide's shape fossilized an undercut in the Cretaceous substratum over a thickness of 10 to 15 meters along the axis, reaching up to 25 meters at the level of the basal toe. The material consists of scree mixed with reworked Cenomanian marl and clay, making up a very hydraulically heterogeneous mix of old slide material. The 1977 landslide affected the site over an average thickness of 10 meters, in an area rich in clayey slide material. It was stopped downslope on the draining slide material making up the ancient toe, but its own toe progressed laterally and was blocked in a little valley as a result of local topography.

The supply of water is principally secured by the overlooking Jurassic aquifer unit, which temporarily collects significant quantities of water until it passes into the superficial slope aquifer through transverse thrust faults. Giant rockfall plays an important role in the transfer of these circulations, as they form a continuous hump in the southwestern part of the site. They are made up of large-scale carbonate chunks, the consolidation of which frequently occurs through concretion and the emplacement of which is likely of catastrophic origin (ancient cliff collapses, linked to tectonics and seismicity). Their thickness can reach 40 meters and they are more or less deeply set into the Cenomanian marl, prolonged by diverging branches in the heart of the slide material. Their high permeability enables the hydraulic relaying of the water flowing out of the Jurassic units, then its progression thanks to draining lenses in the slide material, causing sizeable increases in head in culs-de-sac without an outlet.

In addition to the emergency measures put in place immediately after the emergence of the disorders, the shoring up of the slide depends essentially on drainage projects and includes the following mechanisms (Figure 124):

- a deep drainage ditch Y, located in the center of the landslide as a function of the piezometry, so as to cut across the maximum number of lenses and drainage appendages. It has a trapezoidal cross-section of 100 m^2 (base of 5 meters and legs at 45°), a depth of 8 to 10 meters, and a high longitudinal slope. With a total length of 370 meters, it is made up of a common lower trunk and two divergent upper branches, as well as a lateral branch cutting across the end of the giant rockfall. This setup creates a mechanical armature in the heart of the landslide

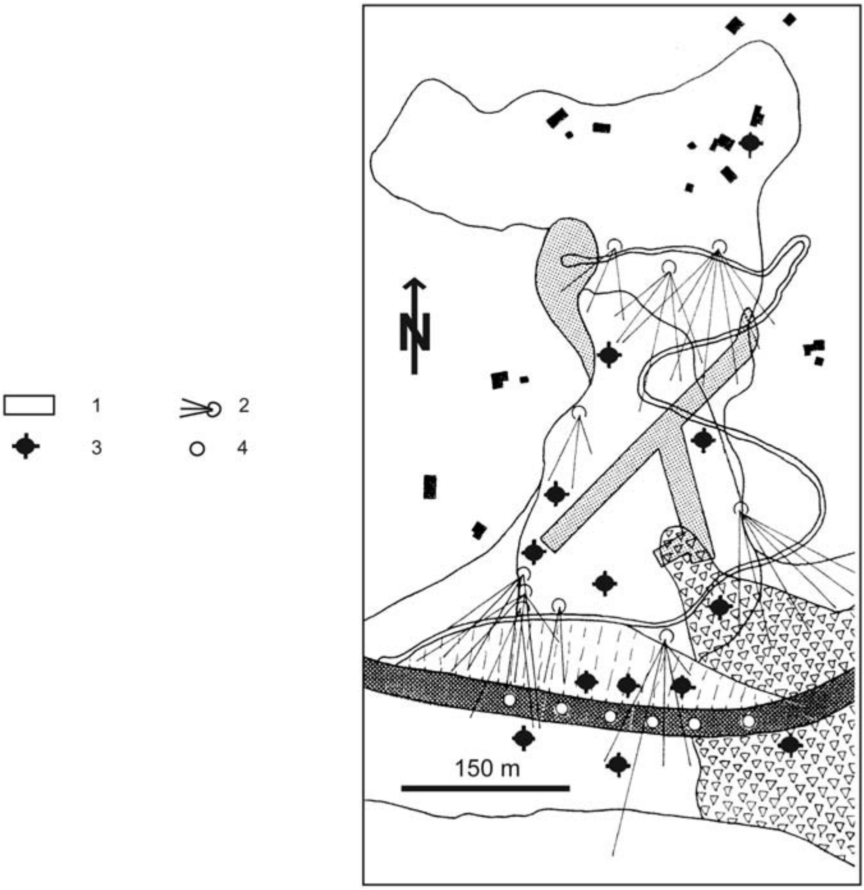


Figure 124 Ardisson landslide (La Trinité, Alpes-Maritimes). Support and surveillance mechanisms.
1-draining substitution, 2-array of subhorizontal drains, 3-monitoring piezometer, 4-pumping well.

and enables a very effective drainage, with the collected discharge varying from 0.1 L·s^{-1} to 30 to 40 L·s^{-1} depending on the season. An embankment of the same type was put in place in the northwestern valley, in order to stop the toe of the slide and to facilitate hydraulic evacuation.

- 10 arrays of subhorizontal drains, drilled in periphery in view to drain the persistent piezometric domes.
- 6 vertical drains equipped with automatic pumps, along the highway to drawdown the aquifer in the rockfill area.

These installations were complemented by an evacuation network or the collected water and by a monitoring system for the extracted discharge and the piezometry. The evolution of the slide was totally stopped, and monitoring confirmed the performance of the setup and the size of the drained discharge.

2.6 Example of the Quiaus landslide (Gorbio, Alpes-Maritimes)

The Quiaus embankment was built in 1967 and 1968 in the context of construction work for the A8 highway linking France and Italy. It enables the highway's passage over the confluence zone of several small valleys making up a left bank tributary of the Gorbio river. With a length of 240 meters and a maximum height of 25 meters, it covers the greater part of the slope, which consists of a nummulitic series with an upslope dip (Figure 125):

- in the lower part of the slope, relatively impermeable gray Priabonian (Upper Eocene) marl;
- in the upper part of the slope, an Oligocene marly-sandy flysch, which acts like a multilayered aquifer with fracture permeability.

In November, 1969, spectacular settling affected the southern pavement of the highway. The problems then evolved slowly until they appeared in August, 1971 as a landslide in the embankment limited by continuous fractures. They finally brutally accelerated in May, 1972, after a very rainy period (Amar *et al.*, 1975).

The studies undertaken led to the conclusion that the movements were a result of significant hydraulic loading, generating abnormal piezometric rises and strong increases in the quantity of water in the embankment. It is most likely the later emplacement of an embankment in a nearby valley that, by obstructing the aquifer's natural outlet, favored critical increases in hydrostatic pressure in the rock mass.

The remediation methods consisted of an emergency rocky buttress at the foot of the slide, preventing a deep slide, followed by further study to find a drainage solution for the flysch, in order to reduce the risk of superficial slides.

The characteristics of the site led to the drainage of the embankment's foundation with the help of a 145 meter long gallery, within which were drilled radiating drains. Subsequently, the setup was complemented by vertically drilled drains equipped with submerged pumps, located along the length of the highway platform.

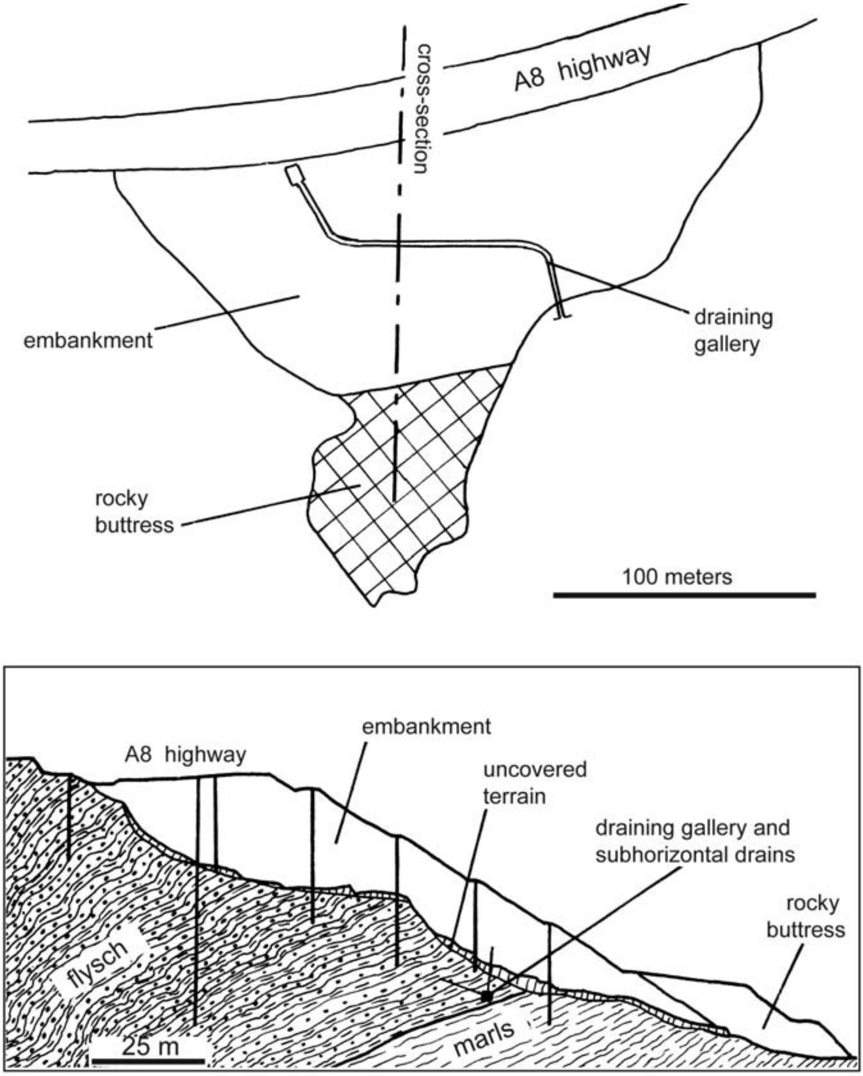


Figure 125 Quiaus landslide (Gorbio, Alpes Maritimes). Map view and cross-section.

3 COLLAPSES AND SUBSIDENCE

3.1 Characteristics and causes

These natural events are vertical movement of the soil, induced by the existence of cavities at depth. They are exclusively a result of groundwater circulation, which hollows out the ground by dissolving soluble rocks or by mechanically or hydraulically carrying out fine particles. The origins and evolution of these processes can, additionally, be directed or aggravated by human actions.

The existence of a cavity at depth causes a redistribution of parameters in its surroundings, and, in particular, creates tension and shear stresses in the overlying terrain (expansion). The increase in vertical constraints and the washing out of crumbled soil maintain this mechanism, which gradually evolves and increases. In certain cases, its progression is stopped by self-filling cavities (expansion of the affected terrain or hydraulic infilling), but it frequently reaches the surface, where it causes collapses or subsidence.

Subsidence is a slow, gradual phenomenon, which manifests itself at the surface as a shallow topographic depression with a wide radius of curvature. It marks the end point of a flexible deformation, due to the continuous rearrangement of the fallen material below ground and the resorption of cavities.

Collapses are the brutal opening of a localized rupture, generally cylindrical, with a variable depth (from a few meters to a few tens of meters). These punctures in the soil are often termed sinkholes, and are a result of the sudden rupture of a rigid horizon which, due to its intrinsic resistance, created a stable roof under which a cavity was able to form and grow.

The surface effects of such phenomena are similar to those occurring above old human constructions below ground (quarries, mines, tunnels). They cause significant stability problems for the built structures within the area they influence, and can lead to serious catastrophes.

3.2 Natural evolution

3.2.1 Dissolution effects

The main soluble rocks subject to such mechanisms present highly variable solubilities, characterized by the following orders of magnitude for pure water at normal temperatures:

- 0,3 $g \cdot L^{-1}$ for calcium carbonate (limestone and dolomite),
- 2 $g \cdot L^{-1}$ for calcium sulfate (gypsum and anhydrite),
- 360 $g \cdot L^{-1}$ for sodium chloride (rock salt or halite).

The phenomena are essentially differentiated by their kinetics of evolution, as the general creation process of underground networks remains the same, with initial dissolution action along the length of fractures allowing the infiltration of water, followed by increased participation by the mechanical action of water as the passageways are progressively enlarged. The gradual organization of groundwater circulation enables the establishment of a karst-type drainage system and its associated train of morphologic indicators: vertical wells, horizontal galleries and chambers in the heart of the aquifer, dry valleys, lapiaz and sinkhole-covered plateaus, sometimes-stepped springs in the sides of valleys.

In carbonate rocks, karst evolution is relatively slow on the human scale and its surface repercussions remain rare in the absence of sizeable aggravations induced by human activity. Surface manifestations, when they occur, generally concern the most active sectors of the aquifer system: appearance of sudden losses in perennial or temporary hanging valleys; localized collapses in the bottom of closed depression, sometimes near existing ponors; opening of sinkholes in dry valleys or closed depressions; temporary modification of emergence conditions at the level of springs.

In the same vein, the Tournaisis collapses in Belgium were a result of natural active dissolution of the Carboniferous limestone below the Escaut plain (Derycke, 1979).

Saline and gypsic rocks, on the other hand, are characterized by a high solubility, which can lead, when they are subject to permanent groundwater circulation, to the export of large volumes of dissolved material.

Nicod (1991) estimates the annual volume of dissolved substances evacuated by the Foux de Draguignan (Var), which emerges from the Triassic units on the left bank of the Nartuby with an average annual discharge of 900 $L{\cdot}s^{-1}$, to be 28.4 million m^3, 85% of which are sulfates and chlorides.

Reynaud (2000) estimates the following annual quantities, from the Folle and Mescla springs (Alpes-Maritimes), which respectively drain a Triassic diapir and a carbonate mass on the right bank of the Var:

- Folle spring (average discharge of 20 $L{\cdot}s^{-1}$): 4 850 m^3 of halite and 1 180 m^3 of gypsum,
- Mescla spring (average discharge of 120 $L{\cdot}s^{-1}$): 5 610 m^3 of halite and 1 885 m^3 of gypsum.

To their high solubility can be added the weak mechanical resistance of these rocks, their alteration in the presence of water frequently generating an easily movable, pulverulent material. Karst evolution is therefore very rapid, generally visible on a human time scale, and can be very dangerous for people and property, particularly in urban and peri-urban areas.

The collapses in the Paris region, a result of the dissolution of Lutetian gypsic masses, are a perfect illustration (Toulemont, 1984 and 1987).

Similar risks are generated by Triassic evaporites in the Var department, particularly in the upper basin of the Foux de Draguignan, which has a sodium chloride and calcium sulfate mineralization on the order of 1.78 $g{\cdot}L^{-1}$ (Nicod, 1990 and 1991). The effects of underground dissolution reach both into the old city of Draguignan and into some its younger neighborhoods (frequent collapses), as well as the banks of the Nartuby, which are regularly punctured by sudden collapses termed “clapes” (1890, 1920, 1978, 1983). More recent events can also be cited, particularly the collapse in Tourettes that, in 1987, destroyed a residence, and the one in Bargemon that opened in 1992 in the middle of a housing development (Nicod, 1993 and 1999).

The prediction of such accidents and the adaptation of construction projects to this type of risk require a solid knowledge of the hydrogeology and the karstification mechanisms of the relevant aquifers. This is rarely the case in practice, where the level of information most often remains fragmentary and where the time limit on interventions is very limiting.

In carbonate formations, problems linked to karstification can often be resolved and treated with a good degree of reliability, given the high mechanical resistance of the unweathered rock, the finite limits of the responsible heterogeneities, and the compatible evolution speed of bedrock conditions with respect to the mechanisms constructed (Mangan, 1985; Amar *et al*., 1988).

The difficulty is much greater in the case of gypsic rock, where the incidence of active karstification constitutes one of the most delicate to resolve problems in soil engineering. In addition to the weak mechanical resistance of the rock and its high solubility, the possibility of rapid evolutions in the subterranean network must be taken into account, as well as, in some cases, horizontal and cross-sectional variations in its later path under the effects of base level variations. A number of hypotheses can frequently be considered which can alter the performance of a treatment solution. The most commonly used methods consist of transferring the load of the building to supports outside of the dangerous zone (piles), filling the threatening cavity, or treating the entire unit through injection. If the underground network is the seat of permanent hydraulic activity, it must also be kept in mind that the process is irreversible and that certain operations (concrete filling, injections) are likely to divert groundwater circulation from its initial path and to move the problem to initially stable peripheral areas.

An innovative and clever treatment enabled the support and protection of the railway viaduct crossing the Suès valley on the Nice-Breil line (Sospel, Alpes-Maritimes). Built in 1913 over Triassic gypsum, this construction originally bridged a permanent valley, which was gradually deepened through headward erosion, abandoning its superficial bed. Studies undertaken by the SNCF in 1963 enabled the surveying, after numerous obstruction removals and widening excavations, an underground river flowing through a 300 meter long gallery, and the observation that in its lower regions, the viaduct’s foundations were partially suspended in mid-air. In addition, this stream received seven small tributaries, also subterranean, and the peak discharge of the network was evaluated to be approximately 3 $m^3 \cdot s^{-1}$. The solution to be implemented had as its goal the avoidance of any further diversion of the subterranean stream and of its tributaries, and their maintenance in their initial path in order to be able to control any possible modification. It consisted of eliminating the narrow sections of the cavity in order to enable an easy visit, of redoing the base of the valley floor and the excavated foundations of the bridge, and of protecting parts of the gallery with masonry and covering the rough gypsum walls with a tarry coating. The construction, which took place in 1964 and 1965, still holds today, but requires regular monitoring visits and appropriate maintenance projects, given the continually active evolution of the underground river (Mangan, 1978; Marchand *et al.*, 1999).

3.2.2 Suffosion effects

Suffosion is a subterranean erosional process enabling the local movement of material, in unconsolidated, insoluble terrain. Water circulations take up the finest particles in a heterogeneous formation and favor flow into channels following preferential axes. This drainage can have repercussions all the way up to the surface and enable the formation of collapses and sinkholes, which line the path of groundwater circulations.

This process generally affects a superficial mantle with an impermeable substratum, with the establishment of a perennial or temporary flow at the contact and outlets located against outcropping substratum. The resulting disorders are termed "ablation funnels" by Barbier, who described them in 1953 in the Vercors (scree slopes over Valanginian marl), then in 1959 in Brazil (quartz sand over granite). An analogous mechanism was studied in Berry by Rat in 1956 (flint clay over Cenomanian marl) and in Brionnais by Letourneur in 1964 (flint clay over Jurassic marl). Such examples are also cited by Weidenbach in Germany, Schomer in Ukraine, and Garald and Parker in the United States.

It is in fact a fairly general mechanism, which most often creates surface depressions of limited areal extent (a few decimeters to a few meters) when natural drainage occurs at a shallow depth. Barbier (1953) nevertheless notes sizeable closed depressions with a diameter of 15 to 20 meters and a depth of several meters in the Vercors, where the scree cover can be tens of meters thick.

Such disorders rarely create high risks due to their small size and their relatively superficial origin. A solid understanding of the local geometry and of the mechanisms at work is nevertheless necessary for an easy resolution of the problems and difficulties they can create for a project set into the ground or for surface installations.

Some forty small collapses were observed in Valberg (Alpes-Maritimes) in 1993, over a site covering 3 hectares intended for the installation of a hillside retaining wall (Gilli & Mangan, unpublished). Over a Liassic limestone substratum, an ancient closed depression revealed a clayey fill of glacial origin with a maximum thickness of 9 meters, the whole being leveled to the average elevation of 1750 m by silty-sandy colluvium with rocky patches, over a thickness ranging from 1 to 3 meters. Studies revealed that the disorders could not be attributed to a deep karst withdrawal, but were instead the result of the high permeability of the surface colluvium and the establishment of temporary water circulations at the roof of the glacial clay. Only the channeling of the outflow along sandier zones and the progressive removal of silt were responsible for the creation of ablation funnels, which, in fact, perfectly followed the identified drainage axes. The erection of the desired construction posed no particular problems, given the size of the excavations in the middle of the rock mass, which largely exceeded the very superficial fringe concerned by the suffosion process.

3.3 Impact of human action

Settling and collapsing can be generated or aggravated by human interventions that are responsible for prompting the dissolution of soluble horizons, the reactivation of ancient karst circulations, or the washing out of unconsolidated fill.

3.3.1 Dissolution

This is a problem essentially affecting deep deposits of highly soluble substances (rock salt or potassium salts) which, after the injection of water into wells, are exploited through pumping in the form of brine, creating sizeable residual cavities.

Letourneur & Michel (1971) cite the formation of a settling depression 30 cm deep and 200 m in diameter in Hutchinson, Kansas (United States), in only 1.5 months, after the extraction of 6,700 m^3 of brine (after Ries and Watson).

The surface consequences can sometimes be much more serious. Such was the case, at the exploitation site of Permian evaporites in Saxony (Germany), where the opening in Viennenburg in May, 1930 of a funnel 60 m in diameter and 40 m deep swallowed a car and caused numerous problems in the surrounding houses (Cramer, 1942 *in* Nicod, 1976). Similarly, the spectacular Haraucourt collapse followed the extraction of Lorraine brine (Nicod, 1993), as did the damage to building in the village of Miery (Jura).

3.3.2 Reactivation of karst circulations

Prolonged pumping in a karst aquifer can significantly perturb its hydraulic regime when it creates a sizeable drawdown. The resulting disequilibrium, partly tied to an increase in circulation velocity in the drainage axes and to an increased renewal of the resources in the aquifer by aggressive water, can be accompanied by the resumption of dissolution, the washing out of fine-grained deposits, and the unblocking of fossilized conduits. These processes can lead to various problems in the periphery of large-scale construction sites where a sizeable drawdown is maintained over a long period of time, or around sites of intensive exploitation of an aquifer.

Prolonged drawdown due to large construction projects can be illustrated by the example of the recent Toulon (Var) highway tunnel, where the difficulties encountered in crossing through karstified formations could surely have been partly attributed to the continuous pumping necessary to keep the construction site above water. The tunnel is, indeed, 20 meters below sea level, and only 750 meters away from the coast. The drawdown of the water table was maintained over several years and significantly altered the flow systems and subterranean drainage circuits of the aquifer, enabling, in particular, the reactivation of certain fossilized ducts and the establishment of new connections with the sea (Mangan & Gilli, unpublished).

The overexploitation of karst aquifers is also accompanied by more and more frequent surface degradation. Such is the case in Tournaisis (Belgium), where numerous collapses dot the banks of the Escaut, as a result of the pumps exploiting the deep Carboniferous limestone aquifer. The onset of the collapses clearly progressed over the course of the last few decades (97 from 1955 to 1984) and their locations are correlated with the zones of large drawdown due to pumping and with zones of recharge from the alluvial aquifer (Kain hole) and from the losses of the Escaut, facilitated by collapses, particularly during the events of January, 1977 and May, 1984 (Delattre N., 1985; Laurent E., 1985).

The same problem occurs in the region around Paris, where karst reactivations affect the Lutetian gypsum under the effect of high volumes being pumped from the underlying aquifer. Surface problems show a marked increase in the last few decades, and can be grouped into clouds geographically concentrated around the main cones of piezometric depression (Toulemont M., 1984 and 1987) (Figure 126).

This type of evolution unfortunately tends to become more and more common in the absence of sufficiently strict regulation and currently affects the most vulnerable aquifers in several regions, adding a resource management problem to a serious safety problem for people and property. In the Triassic formations of the Provence region, the recurrence of collapses

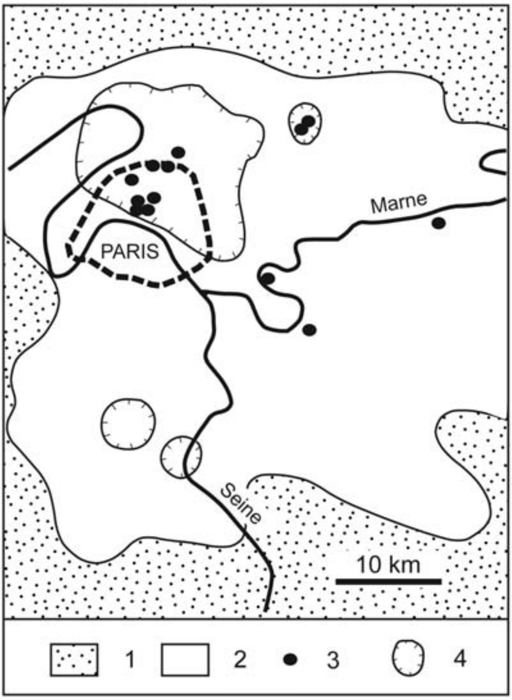


Figure 126 Paris region: extent of the gypsic facies and of the collapse indicators (from Toulemont, 1987).
1-No gypsum, 2-Extent of gypsum, 3-Collapse zones, 4-Cones of depression in the Lutetian aquifer.

due to the karstification of the gypsic masses of the Var department is in part attributed by Nicod to the intensive exploitation of aquifers (1990, 1991, 1993, and 1999). The same observation can be made in the neighboring department of the Alpes-Maritimes (see chap. D2-3.4).

3.3.3 Washing out of unconsolidated fill

In this case, it is the circulation of water in unconsolidated material that can wash out finer-grained particles and locally hollow out the terrain. This phenomenon progresses in the upslope direction and can be concentrated in preferential pathways (internal erosion). It is generally irreversible as long as circulation persists and reveals itself as rising aggravations, likely to have repercussions up to the surface or to affect the base of infrastructures and the foundations of buildings.

This concentrated washing out along flow channels determined by granulometric and cementation contrasts can also affect older, silted up karsts. Its effects can then be more noticeable and more rapid, through the sudden emptying of preexisting fills, through the opening of old passageways and cavities in the heart of the unit, or through the removal of deposits fossilizing the ancient topographic surface (closed depression, lapiaz, dry valleys).

Prolonged drawdown due to extraction pumping in an excavation or in the overexploitation of an aquifer are not the only human actions causing such effects. The appearance of surface damage can also be a result of a large volume of water put into circulation in the upper part of the aquifer (supply) or in the lower part of the aquifer (drainage).

In terms of supply, such evolution is frequently linked to point-source leakage from sewer systems, water pipes, drainage ditches, or irrigation canals. Problems can also be attributed to the dumping of storm water runoff into karst bedrock. This practice, highly commendable in principle as it uses the natural aptitude of the terrain for infiltration, can result in well-adapted and well-integrated setups when it is undertaken parsimoniously. Its application on a large scale, based on the collection of runoff from a large area of impermeable surfaces and on the occasional dumping of large peak discharges into fractures, ponors, or chasms, inevitably causes various problems, either due to the flooding of subterranean passageways (temporary flooding), or following the gradual washing out of the material filling ancient fracture networks (surface settling, problems with equipment).

In terms of drainage, deep excavations and tunnels are the principal causes of sizeable withdrawals and clearings that can be catastrophic (see chap. D2-3).

3.4 Example of collapses in Mougins (Alpes-Maritimes) in 1998

3.4.1 Events observed and actions taken

Towards the end of 1998, two nearby collapses opened suddenly on the northern lane of the R.N. 1085 (a broad speedway, connecting the cities of Cannes and Grasse) and other accidents affected the bordering properties during the same period and into the following year:

- October 24, 1998: opening of two funnels 20 m apart on the speedway and collapse in a private property, 40 m to the north;
- November 30, 1998: creation of a collapse in a garden, 50 m to the northwest;

- December 28, 1998: appearance of a collapse in a housing development, 160 m to the southwest, taking out the service road and fissuring a building;
- October 24, 1999: development of a small collapse and of two nearby depressions in the garden of a property, 210 m to the west-southwest.

This was in fact a cluster of 5 collapses and 3 depressions that occurred over the course of a year in the town of Mougins (Alpes-Maritimes), over an area barely 200 m in diameter.

In-depth investigations on-site were rapidly undertaken by the Nice CETE (Environmental Technical Studies Center) Mediterranean lab, in order to enable treatment of the affected area and reopening of the speedway. The boreholes drilled exposed large, highly karstified gypsic masses under a clayey marl cover around 10 meters thick, and enabled the location of the cavities responsible for the problems, around 20 to 30 m below the surface.

A much larger study was then undertaken, from 2000 to 2002, in order to specifically understand the deep geologic structure along the path of the road, to define and hierarchize the organization and role of groundwater circulation in the development of karst cavities and in the origin of the collapse mechanisms, and finally, in order to research the factors enabling the possibility of predicting such events.

3.4.2 Geologic and hydrogeologic structure

The regional basement is provided by the sedimentary cover of the Tanneron mass gneissic platform, evenly tilted to the northeast. The different horizons of the Triassic series outcrop in successive rings and are capped by a Jurassic age carbonate plateau (Figure 127). The series begins with the siliceous Werfenian sandstone, followed by a hundred or so meters of Muschelkalk limestone sandwiched between two marly dolomitic horizons, and ends with the multi-colored Keuper marl, which encloses scattered dolomite, gypsum, and cellular dolomite lenses, and is capped by thirty or so meters of Rhetian marly limestone.

The overall structure is relatively simple, and can be described as a monocline tilted to the northeast. It is, in fact, complex in the detail due to superimposed tectonic deformations:

- folding with a N 20° to N 45° axis, induced by the Provençal phase;
- subvertical N 0° to N 20° faulting, messily breaking up and offsetting ductile structures, with one set of Oligocene normal faults (first Alpine phase), then another set of thrust faults during the second Alpine phase.

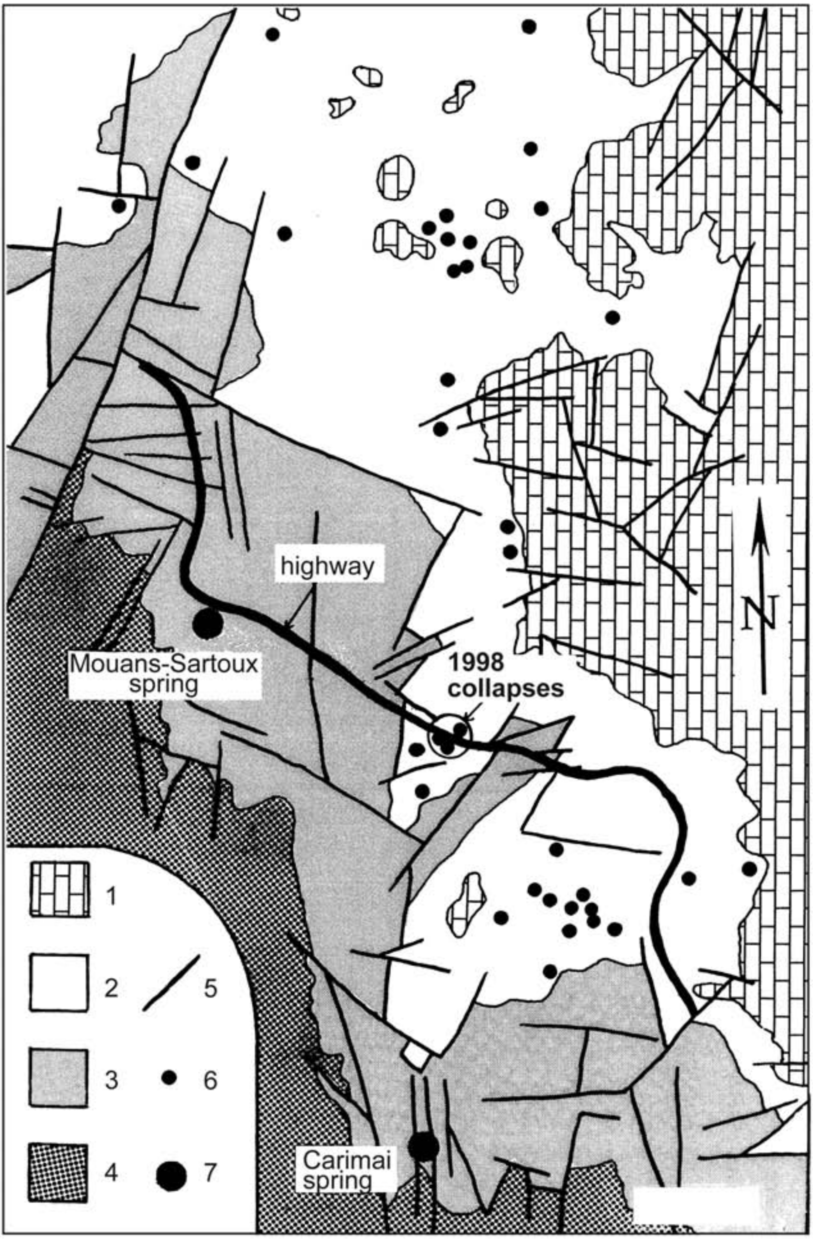


Figure 127 1998 collapses in Mougins (Alpes-Maritimes). Geologic and hydrogeologic context. 1-Rhetian-Jurassic limestone, 2-Keuper marl and gypsum, 3-Muschelkalk carbonate aquifer, 4-impermeable basement, 5-principal collapses, 6-karst spring.

The difficulty of studying the Triassic is locally increased by frequent variations in thickness and facies, by the development of plastic clayey marl horizons implicated in the tectonics, and by the existence, throughout the depression lining the Keuper, of Quaternary colluvial fill (Plans de Grasse and Plans de Saint-Martin). The geometric summary was therefore based on the structural analysis of peripheral regions, on the systematic exploitation of aerial photographs, and on specific surveys undertaken (geophysical surveying by the electric method, core drilling, and destructive drilling).

The rough characteristics of the local structure reveal an intense cutting-up of the rock mass by a tight network of vertical faults, principally aligned N 0 to N 30 and N 90 to N 130, and its dissection into a mosaic of relatively lowered (grabens and synclines) and uplifted (horsts and anticlines) units. The contacts between units are frequently offset in a stair-step fashion or relayed by fault zones, which makes it difficult to differentiate the relative roles played by brittle and ductile deformation (Figure 128). The most notable features are, to the northwest (town of Grasse), the Aspres anticline-horst forming a hump of Muschelkalk carbonate overlooking the Keuper surrounding it, and, in the middle region (town of Mougins), the narrow Touramy anticline-horst (Muschelkalk limestone) separating two Keuper syncline-grabens. It is within one of these lower regions that the collapses occurred.

From a hydrogeologic point of view, the gneissic basement rock and the Werfenian sandstone make up a continuous impermeable base, supporting the region's main aquifer. This karst aquifer is contained within the Muschelkalk carbonate reservoir. It drains to its southwestern edge, through the Foux de Mouans-Sartoux at an elevation of 69 m and the Carimaï spring at an elevation of 32 m (Figure 127).

The overlying Keuper formation also represents an important regional impermeable unit, but contains permeable horizons (dolomite, gypsum, cellular dolomite) containing small reserves of water and feeding scattered springs. The deep drainage for the gypsic and dolomitic lenses is, however, relayed to the underlying Muschelkalk aquifer, along lithologic or tectonic contacts, which explains the calcareous sulfated character of the water at its outlets.

3.4.3 Local characteristics

The 1998 collapses occurred in the Saint-Martin graben, the detailed structure of which is illustrated in Figure 128. Below the superficial colluvium, the Triassic fill consists of multi-colored clayey marl, then of gypsic masses 10 to 30 meters thick resting directly on Muschelkalk carbonate. The hydraulic connection between the two formations was verified thanks to tracer tests,

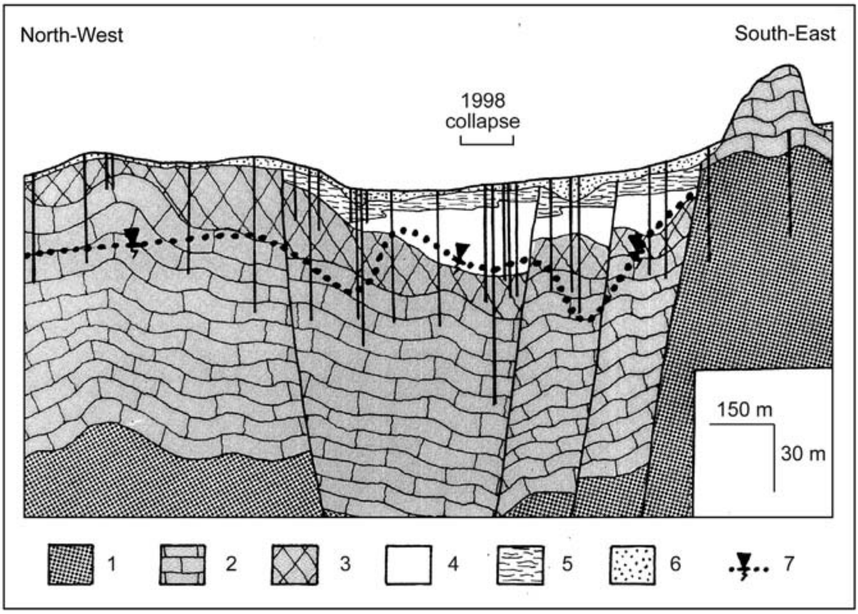


Figure 128 1998 collapses in Mougins (Alpes-Maritimes). Cross-section of the highway in the area around the problems.
1-impermeable basement, 2-karstified Muschelkalk limestone, 3-Muschelkalk marl and dolomite, 4-Keuper gypsic masses, 5- Keuper clayey marl, 6-colluvium and anthropogenic fill, 7-piezometry of the Triassic aquifer.

which also revealed that the gypsum and limestone aquifers drain to the Carimaï spring, 3.7 km away. The existence of these drainage conditions is also supported by piezometric surveys (Figure 129). (Mangan and Gilli, unpublished).

3.4.4 Karstification of the unit and cause of the problems

The in-depth study of the problems, through investigation and historical research, enabled the identification of a great number of indicators of previous surface disorders, widely distributed over the areas of outcropping Keuper (Figure 127).

A detailed examination of the structural conditions revealed that these collapses are essentially concentrated in sectors enclosing large water-bearing gypsiferous lenses, offering similarities in supply and drainage. Their supply is, indeed, ensured by aggressive water from their eastern side with a low mineral content and/or by losses from the stream network, and their drainage occurs towards the deep Muschelkalk aquifer, with which are established direct contacts (sedimentary or tectonic).

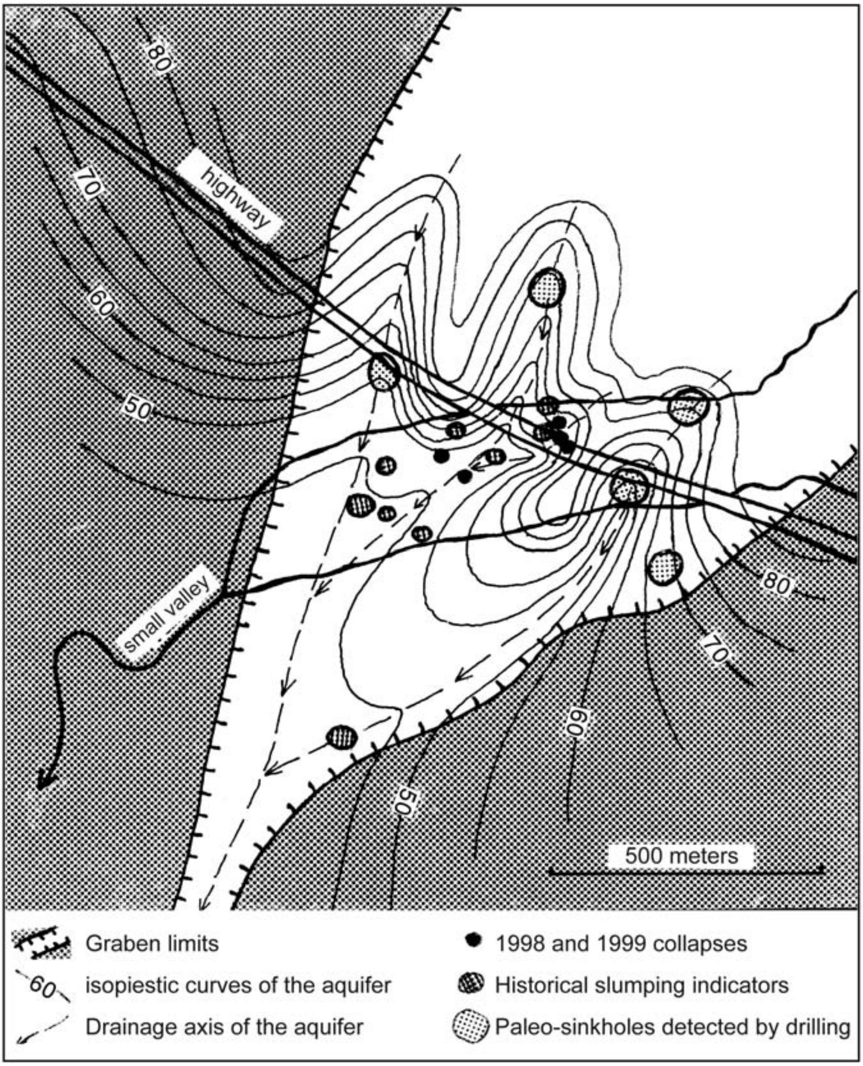


Figure 129 1998 collapses in Mougins (Alpes-Maritimes). Piezometry of the Triassic aquifer and karst indicators in the problematic area.

Some of these collapses are very old, but it appears that 40% of the collapses occurred after 1960 and that a distinct resurgence in their occurrences characterizes recent decades, and particularly, the last ten years (12 significant events from 1992 to 2001).

It must therefore be concluded that this karst mass, which had reached a state of relative equilibrium, is now seeing renewed activity, which can be assigned neither to a change in the natural discharge (elevation of the outlets imposed by the position of the impermeable basement), nor to an increase in infiltration over the upper Keuper outcrops (recharge zone). In fact, the perturbations affect the flow conditions in the aquifer, particularly in its major drainage axes, under the effect of the pumping in wells that greatly increased during the same time period.

The pumped water is not used for the public drinking water supply due to its high mineral content, but private pumps nevertheless are multiplying in the gypsic and dolomitic Keuper lenses, and particularly in the Muschelkalk carbonate reservoir. Its uses are various: watering gardens and filling pools in suburban and spaciously urbanized areas, concentrated agricultural and industrial extraction, and golf course irrigation.

In the graben directly concerned by the 1998 collapses, some water users had observed, over the last ten years, a distinct decrease in the productivity of their equipment, or even, in a few cases, a complete drying up. The deep aquifer circulates in the direction of the southern Carimiaï spring and presents, in the problematic zones, an organized drainage system through several favored axes converging towards a single collecting passage (Figure 129).

The karst problems of all ages are perfectly aligned along the drainage axes revealed by the piezometric map, clearly illustrating an accelerated reactivation of older karst processes under the effects of intense exploitation in the deeper aquifer.

CHAPTER D3

Underground Construction

1 PROBLEMS DUE TO GROUNDWATER

When an underground construction project passes through an aquifer, it acts as a drain and noticeably alters the flow conditions in the aquifer. The probability of encountering inflows of water is high, especially if the project is located under a thick cover of rock.

Two distinct consequences must then be considered:

- on the one hand, the role of groundwater on the construction conditions and the stability of the project;
- on the other hand, the hydrogeologic impact of the project on its natural and human environment.

2 IMPACT OF GROUNDWATER ON CONSTRUCTION METHODS

Encountering groundwater in a tunnel is a frequent cause of more or less serious difficulties, both during the construction phase due to the sudden intrusion of water or the unblocking of unstable terrain, and over the long term under the effects of the hydrostatic pressure maintained around the project, of the washing out of fine particles, or of the gradual alteration of the concerned formations.

The problems encountered are, of course, a function of the nature and characteristics of the rocks being traversed, but also of the magnitude of the discharge collected during excavations. This discharge can vary from a few tens to a few hundreds, or even a few thousands, of $L \cdot s^{-1}$. Duffaut (1981), for example, cites a few very sizeable discharges encountered below ground (Table 22).

Extreme conditions, associated with inadequate preliminary study and poorly adapted construction, can sometimes lead to real disasters:

Table 22 Discharge collected by underground constructions.

Old railway tunnels	Discharge in $m^3 \cdot s^{-1}$
Simplon (Swiss-Italian Alps)	1.2
Col de Tende (French-Italian Alps)	1.1
Mont d'Or (Jura)	3.0 to 10.0
Hydroelectric tunnels (Savoy)	
Ponturin	1.8
Versoyen	6.0
La Coche	2.0
Highway tunnels	
Gran Sasso (Italy)	up to 20.0

- the Lötschberg railway tunnel (Bernese Alps, Switzerland), projected to run 14.6 km, cut across, on July 24th, 1908, an ancient sub-glacial channel filled with highly aquiferous alluvium (Figure 130). This opening provoked the intrusion into the gallery of 80,000 m^3 of material, taking over, in only 15 minutes, 1,800 m of the site and burying 24 workers. The collapse had repercussions all the way to the surface, 180 m above, creating a funnel 80 m across and 5 m deep in the Gasteren plain. The partially completed gallery was abandoned and walled off, and the tunnel was completed on March 31st, 1911, following a different underground path (Gignoux & Barbier, 1955);

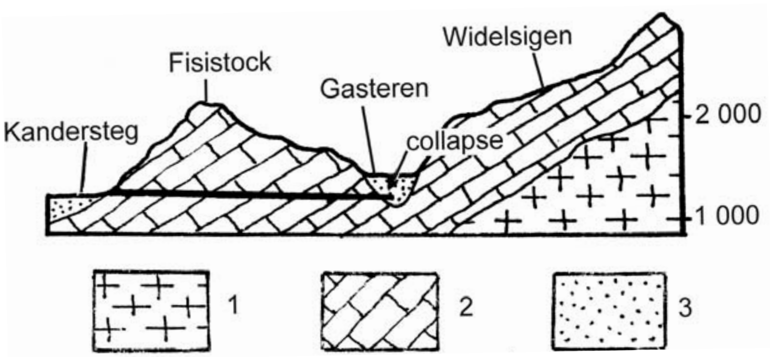


Figure 130 Lötschberg tunnel (Switzerland). Geologic profile of the abandoned path (from Gignoux & Barbier, 1955).
1-Granite. 2-Jurassic limestone. 3-Alluvial fill.

- the Boubard railway tunnel (Vierzon to Saincaize line), 590 m long under a cover no thicker than 26 m, went into service in 1849. The excavation of the tunnel, confronted with sizeable influxes of water through a complex folded structure associating water-bearing limestone and clay with poor mechanical qualities, was marked by multiple material and human accidents. After it was commissioned, increasing degradation and persistent indicators that water pressure was rising behind the roof required multiple phases of strengthening construction, in 1856–57, 1873–74, 1882, and 1945 (re-coating the walls, drainage, injections). On February 13th, 1960, a sudden cave-in obstructed the tunnel over a length of 25 meters, collapsing the roof over a length of 12 meters and a width of 6 meters. A sinkhole also appeared at the surface, 23 meters above the roof of the tunnel, 48 hours after the accident. The disaster was attributed to the gradual formation of a rising bell-shaped cavity above the roof of the tunnel due to the slow washing away of fine clay particles by water circulations. The tunnel was put back into circulation on June 20th, 1960, after the caved-in mass was consolidated through injection and roof and walls were rebuilt (Remondet & Valentin, 1961).

The prediction of water influxes during an underground project is not always easy, and sizeable uncertainties can persist after the completion of preliminary studies. In difficult cases, small-diameter reconnaissance galleries are sometimes excavated in order to verify the nature and geometry of the terrain, as well as the hydraulic characteristics of the rock mass. The piercing of a water-bearing formation can, in addition, pre-empty the aquifer and reduce hydrostatic pressure before the excavation of the large-diameter passage. It is highly recommended, in all cases, but particularly when there is a high probability of encountering water-bearing units, that exploratory boreholes be drilled over a representative distance ahead of the excavations in progress.

The digging of a tunnel in a moderately permeable terrain often allows gradual drawdown of the aquifer in order to gravitationally evacuate the collected outflow, if the tunnel is rising slightly. If the tunnel slopes downwards, appropriate pumping mechanisms must be put in place in order to evacuate the water collected by the excavation and to prevent its immersion.

In highly permeable formations, it may be necessary to induce drawdown in the zone being influenced by the tunnel, with the help of pumping in wells dug from the surface (if the depth of the tunnel allows it) or from drains drilled as the work progresses in front of and around the tunnel.

The catchment and evacuation of water can sometimes prove difficult, particularly during the crossing of perennial or temporary karst passages, as is illustrated by the case of the Pouzergues railway tunnel (Brive to Montauban line), built in 1878 to 1882 over a length of 880 meters at a maximum depth of 40 meters. This tunnel passes through a limestone promontory over a marly basement. During construction, it cut into temporarily active karst, with a peak discharge of 300 $L \cdot s^{-1}$, resulting in the flooding of the site. Only drainage channels were then put in place through the coating on the walls. It was only in 1945, before the electrification work on the line, that the natural cavity that the tunnel cut across was recognized, which enabled the catchment of the accessible water circulations and the waterproofing of the other humid areas in the tunnel roof. The persistence of water inflows and of temporary loading due to hydraulic pressure behind the coating led the SNCF (Railway company) to undertake a new survey of the site from 1957 to 1959, based on intense speleologic exploration, obstruction removal, and detailed topographic surveying. This investigation enabled a solid understanding of the geometry of the karst networks and the aquifer system's behavior. Complex catchment systems, through drainage galleries oriented so as to intercept known outflows, were then created in 1963 and 1964, enabled the effective long-term drainage of the tunnel and the elimination of dangerous loading for the construction (Remondet & Marchand, 1965).

It is sometimes necessary to proceed with injection ahead of the tunnel as it progresses, in terrain that does not hold up well, in order to reconstitute a coherent and waterproof mass enabling the safe excavation of the tunnel. These injections are done through borehole, either in circles around the tunnel, or as a frontal crown (umbrella method). They can equally be put in place preventively with the help of vertical boreholes from the surface (when the depth of the tunnel allows it). This method enabled passage through a very delicate area a hundred or so meters long during the construction of the hydroelectric Pralognan (Savoy) gallery, built in 1943 to 1949 over a total length of 12.9 km. The passage through crushed, water-bearing quartzites occurred with no damage thanks to 1000 metric tons of cement and 100 metric tons of silicate, injected under pressure through 1 900 m of boreholes (Rivière & Roger, 1950; Giron, 1955; Letourneur & Michel, 1971).

Freezing can also be used to cross delicate aquifer zones, when the terrain is difficult to inject, and therefore very poorly permeable, and in urban areas, when the environment is highly sensitive. This procedure consists of turning groundwater to ice in the area affected by the construction and is therefore considered a temporary consolidation method, which nevertheless remains costly and difficult to put in place. This method was used successfully in order to cross a 50 m wide zone of crushed cellular dolomite filled with water, during the digging of a water conveyance gallery for the Hongrin-Leman, in the Swiss Valais (1967–1970), as well as for the construction of a 25 m long sewage collection passage at shallow depth in the Bourget-du-Lac agglomeration in Savoy (1975) (Boutitie & Meyer, 1981).

The complete drainage of groundwater and the creation of waterproof screens may also be necessary in order to guarantee protection from rapidly evolving formations. Such is the case in clayey terrain, susceptible to significant alteration in the presence of water, and particularly, in swelling clays (montmorillonite family), which can degrade tunnel walls due to the pressure they cause when they become hydrated. The same phenomenon can affect certain anhydrites, which, through hydration, turn into gypsum, with a noticeable increase in volume. The 9.2 km long Courbaisse-Massoins (Alpes-Maritimes) hydroelectric gallery, dug in 1947 to 1950, for example, cut across a Triassic anhydrite mass over a distance of 600 meters, at the base of an overthrusting Jurassic limestone unit above Cretaceous marly limestone. This horizon's rapid transformation into gypsum led EDF (National Electricity Company) to locally widen the gallery to a cross-section of 17 m^2, from the planned 10 m^2, to isolate the passage of water into a steel middle duct 3 meters in diameter, and to protect the walls with coaltar distemper and with concrete in the crushed zones. The same problem occurs in the NE end of the Braus railway tunnel, where the later dissolution of gypsum masses has today led to delayed risks of cave-ins under the tunnel floor (see chap. D3-4).

3 HYDROGEOLOGIC IMPACT OF TUNNELS ON THEIR ENVIRONMENT

The crossing of an aquifer by a tunnel intercepts part of the aquifer's water and totally modifies the piezometry and the flow conditions. Such an event can, depending on the real hydrogeologic conditions, cause a decreased discharge in some of the aquifer's natural outlets, or can even dry them completely. It can also stop or decrease the production of water wells and lead to the emptying of lakes or the drying of small valleys at a higher elevation than the construction.

Such a situation can be irreversible (see chap. D3-4) or can require costly and difficult construction in order to restore the norm (see chap. D3-5). The effective waterproofing of the tunnel walls or the creation of injected curtains can, in certain cases, prevent such problems or at least limit them temporally.

Another environmental effect of the drainage provided by tunnels in permeable terrain is the inducement of soil movements capable of having surface repercussions in the entire area of direct influence, whether the movements are more or less pronounced slumps, or full-on cave-ins characterized by the sudden opening of sinkholes. These problems can be generated by the settling of suddenly dry unconsolidated formations, by the collapse of unstable terrain due to the clearing of the gallery, by the washing out of old karst fill, or by the reactivation of induced dissolution of soluble formations (gypsum, rock salt).

Such damage often has a limited scope in totally natural environments with no human development. It can, however, have very serious consequences in urban and peri-urban zones. Taking it into account therefore appears as important as considering difficulties in the construction of the project, during preliminary studies and monitoring of the construction.

The diversion gallery for the Tinée (Alpes-Maritimes), built in 1989 to 1991 near the village of Saint-Etienne-de-Tinée, based on the possibility of the river valley being obstructed if the La Clapière landslide were to suddenly be reactivated, encountered this type of problem (see chap. D2-2.4). The gallery is 2.4 km long and has a cross-sectional area of 10 m^2, and is in the right bank of the river. It follows the gneissic Mercantour basement, principally dug into Permo-Werfenian quartzitic sandstone and Triassic gypsum and cellular dolomite, under a variable cover of clayey, rocky fluvial and fluvio-glacial deposits. During construction, large water influxes (from 100 to 250 $L \cdot s^{-1}$) were drained by the tunnel. They were relayed from the aquifer in the overlooking Muschelkalk carbonate mass, which experienced a drawdown of 40 meters, and led to the drying of the Laus spring, which fed a fish farm and a horticultural establishment. Additionally, these permanent circulations facilitated multiple high-volume evacuations of sand in the passage through quartzitic formations and the racking of fluvio-glacial deposits blocking old karst cavities in the passage through gypsum and cellular dolomite. It is regrettable that there followed the delayed appearance of 3 sinkholes having reached the surface, and the evolution of several zones of active settling.

4 EXAMPLE OF THE BRAUS RAILWAY TUNNEL (ALPES-MARITIMES)

4.1 General characteristics

This underground portion of the Nice-Breil line (Alpes-Maritimes) has a length of 6 kilometers, at a maximum depth of 700 meters. It crosses, at the average elevation of 410 m, a ridgeline with a maximum elevation of 1,330 m separating the Paillon basin to the west from the Roya basin to the east.

It was built by the P.L.M. Railroad Company in 1912 to 1922, with an interruption during WWI. It was excavated simultaneously from each end, as rising galleries which met towards the middle of the tunnel, the highest point of the floor. The rail line, which went into service in 1928, is now used by the SNSEE.

The construction of the tunnel was slowed by significant difficulties, tied to the geologic nature of the terrain being traversed and to abundant influxes of water, which led to long construction delays and multiple adaptations to the construction (reinforcements and drainage).

4.2 Geologic and hydrogeologic conditions

This project is located in the heart of the sub-Alpine ranges of the Arc of Nice, shaped by Alpine tectonics.

The sector under consideration is the Braus syncline, with a NNW-SSE direction, presenting a nice overall symmetry with few tectonic deformations (Figure 131).

Its heart consists of Nummulitic deposits (Priabonian marl over Lutetian limestone) forming the backbone of the relief, and the underlying Cretaceous formations outcrop in the surrounding slopes (Senonian marly limestone over thinly bedded Turonian limestone, then Cenomanian marl).

The Jurassic carbonate basement support is, however, frequently cut up by series of thrust duplexes, resulting in overthrusts spreading concentrically outwards, one part following the principal direction of the compressive constraints on the western border, and the other at the front of the Triassic gypsic clays, which accumulated through diapirism in the Sospel depression, on the eastern border.

The geologic series traversed by the tunnel contains three distinct aquifers separated by impermeable or less permeable layers (Figure 131):

- in the upper part, the fractured to karst Lutetian aquifer, perfectly bounded by the roof of the Senonian marly limestone acting as an impermeable floor. It is drained by two side outlets, the Pissaour spring to the SW at an elevation of 850 m and the Paraïs spring to the NE, which is relayed to a lower elevation by a scree mantle (elevation 820 m). These outlets have an average annual discharge on the order of 10 to 13 $L \cdot s^{-1}$;
- in the middle part, the fractured Turonian aquifer, limited at its base by Cenomanian marl. This reservoir is highly compartmentalized as a function of the distribution of the fracture network and of interbedded marl. Groundwater flow is poorly hierarchized and drainage occurs through multiple scattered outlets with a limited discharge. The known springs are staggered across the space between the elevations of 640 to 800 m in the northern area, and 550 to 680 m in the southern area;
- in the lower part, the karst Jurassic aquifer resting on Triassic gypsic clay (Keuper). The Cime de Pénas is drained at 450 m by the Piaon springs in the gorges of the Bévéra and the Mont Méra is drained by the springs in the Méras valley at 600 m and by the Sambora spring at 520 m. The discharge of the outlets is not well known, but is, for each, greater than 10 to 15 $L \cdot s^{-1}$ as a yearly average.

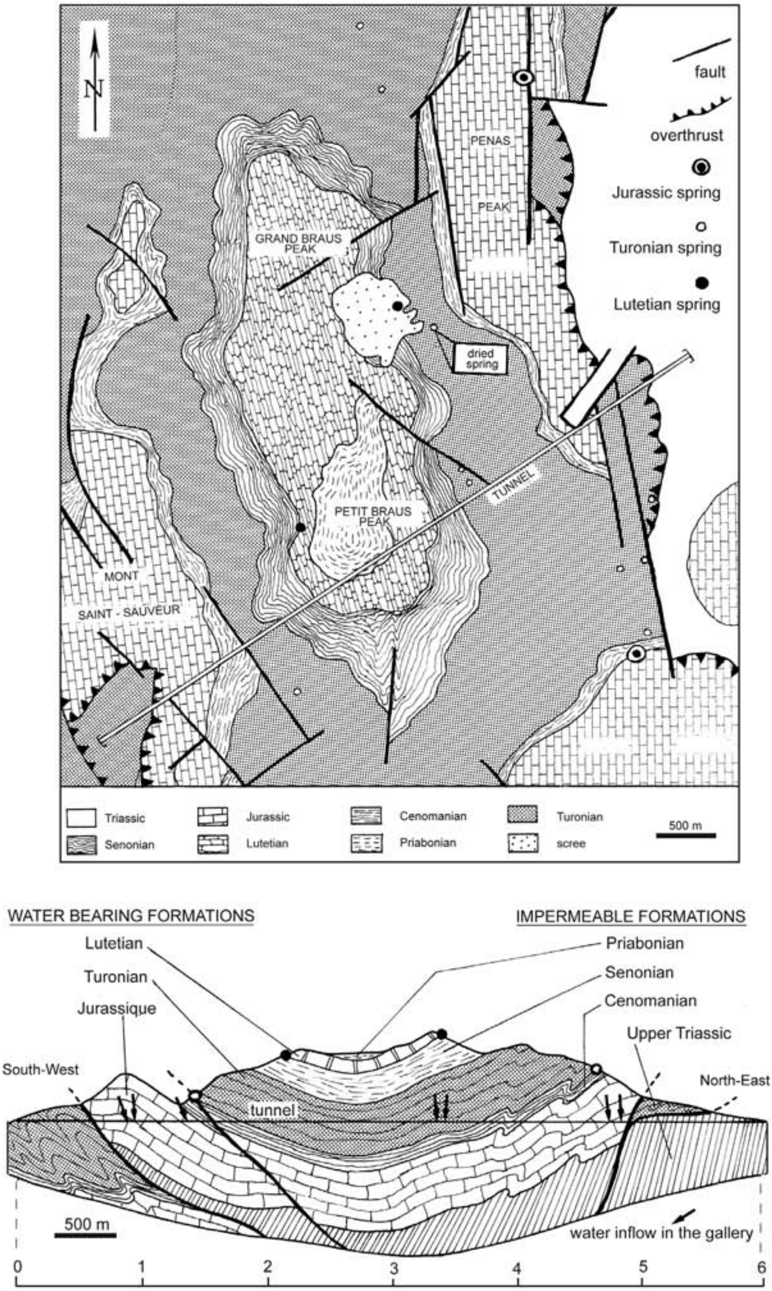


Figure 131 Braus railway tunnel (Alpes-Maritimes). Geologic structure and cross-section along the length of the tunnel.

4.3 Hydrogeologic problems in the excavation of the tunnel

The geologic cross-section along the length of the tunnel shows that the Lutetian aquifer was not affected by the construction, given its perched location. Indeed, the discharge of its outlets remained unchanged.

However, abundant influxes of water marked the progress of the tunnel as it passed through the other aquifers:

- on the one hand in the karstified Jurassic unit, both in the western part, in the southern finger of the Mont Saint-Sauveur, towards km 1.0, and in the eastern part, in the southern extremity of the Cime de Pénas, towards km 4.7;
- on the other hand, in the fractured Turonian unit, mainly towards km 3.3.

The outflow discharge reached 200 $L \cdot s^{-1}$ at its peak, and its residual magnitude varies between 20 and 80 $L \cdot s^{-1}$ depending on the season, since the tunnel was put into use.

The most notable hydrogeologic consequences concern the passage through the Turonian aquifer and the water influxes in the eastern Jurassic next to the Sospel Triassic units.

4.3.1 Passage through the Turonian aquifer

The largest influxes of water were generally located in the most fractured part of the aquifer, between the km 3.32 and 3.34, where the discharge reached 90 $L \cdot s^{-1}$ during excavation. Despite a noticeable decrease in magnitude, these outflows are still today the major source of the water collected by the tunnel.

Their evacuation required the creation of galleries parallel to the tunnel, of periodic catchment systems against the tunnel supports, and of boreholes through the walls in order to limit the pressure against the tunnel. The collected discharge is evacuated towards each entrance by a central gutter and various pipes.

Based on the local geologic structure and the position of the springs fed by the aquifer, the original piezometric height of the water table above the tunnel must have been around 200 to 400 m depending on the area, and the water head is still fairly significant today.

Drainage of the unit by the tunnel is likely to have dried multiple small outlets and decreased the discharge of others, but in particular, it caused the complete and permanent drying, in 1914, of a sizeable emergence located 1 500 m north of the tunnel at an elevation of 800 m, so 390 m above the tunnel (see location on the map in Figure 131). This spring fed irrigation on the Vasta plateau, belonging to the town of Sospel, and its drying was a true tragedy for the fifty or so agricultural operations affected. Numerous litigations followed, and subsequent studies enabled the establishment, as early as 1919, of a causal relation between the two events and of an estimation of the spring's original discharge, which would have varied between 40 and 60 $L \cdot s^{-1}$ depending on the season.

But it must be acknowledged that this catastrophe for some turned out to be a blessing for the surrounding communities, which were able to benefit from the water collected in the tunnel, to provide their drinking water supply. The use of this water was established by agreements between the P.L.M. Railroad Company and the municipalities of Sospel (northeastern entrance to the tunnel) in 1926 and l'Escarène (southwestern entrance to the tunnel) in 1927. Indeed, the railway tunnel, given its passage over a distance of 1 900 meters through an aquifer with high hydrostatic head, is essentially a very productive catchment system, surpassing in production any system that one could hope to create with classic methods in such a compartmentalized aquifer with such a mediocre global permeability.

4.3.2 Passage through the Jurassic aquifer overriding the Triassic

The Triassic formations encountered at the eastern mouth of the tunnel are principally composed of anhydrite, which, once exposed to the water freed during the passage through the overthrust Jurassic unit and flowing along the sloping tunnel floor, gradually turned into gypsum through hydration. This transformation was aggravated by the water coming from the Turonian aquifer and by the interruption of construction during WWI.

The alteration of anhydrite into gypsum, as it is accompanied by an increase in volume and significant swelling of the rock caused serious damage to the stonework in the tunnel. It created the need for the construction of sizeable drainage systems below the tunnel floor, which did not manage to prevent the subsequent dissolution of gypsic masses, which resulted in the creation of localized cavities and cave-ins. This new situation led to the construction of reinforcements, repairs to the tunnel floor and supports, and ongoing surveillance and maintenance.

4.4 Lessons to be drawn from this experience

The geologic structure of the area that the Braus tunnel crosses in particularly simple, and the cross-section along its length differs only slightly from what can be inferred from surface mapping.

It is the perfect illustration of a textbook case, where the geometry of the aquifers can be easily determined based on field observation and where the hydrogeologic constraints can be defined through a rigorous and quantitative inventory of the surrounding outlets.

The water encountered during the excavation of the tunnel through the Turonian formation was, in particular, inevitable, given the trap formed by the synclinal gutter and the hydrostatic head revealed by the position of the outlets.

It is likely that the unknowns at the time of the tunnel's construction were a result of a too-cursory hydrogeologic and geologic approach, which would be totally unacceptable today.

5 EXAMPLE OF THE MONTE-CARLO RAILWAY TUNNEL (PRINCIPALITY OF MONACO)

5.1 General characteristics

The Nice-Vintimille rail line originally passed through the entire length of the Principality of Monaco, following the Mediterranean coastline at the surface. The Principality, wishing to open land in use by the rail line to urban development, concluded an agreement with the French Railways Company (SNCF) in order to study the displacement of the tracks and their relocation underground. Construction took place from 1958 to 1963, and the line went into service in 1964.

The principal project for this relocation was the Monte-Carlo tunnel, excavated over a length of 3056 meters at a maximum depth of 110 meters. Its floor is at the average elevation of 24 m, and in cross-section, it has a semi-circular roof, with a width of 8.60 meters and a height of 6.60 meters. It was excavated simultaneously from both ends, as two rising galleries meeting in the center, from within Monaco territory for the southwestern entrance, and from within French territory for the northeastern opening (city of Roquebrune-Cap-Martin).

The preliminary geologic studies apparently enabled a good understanding of the general construction constraints, but periodic difficulties tied to sudden influxes of water punctuated the progression of the project, causing construction delays and increased costs.

5.2 Geologic and hydrogeologic conditions

- The area through which the Monte-Carlo tunnel passes is located along the southern front of the Arc of Nice subalpine ranges, immediately above the point where they plunge below sea level. Its structure consists of recumbent folds and SW-NE overthrusts (Figure 132).

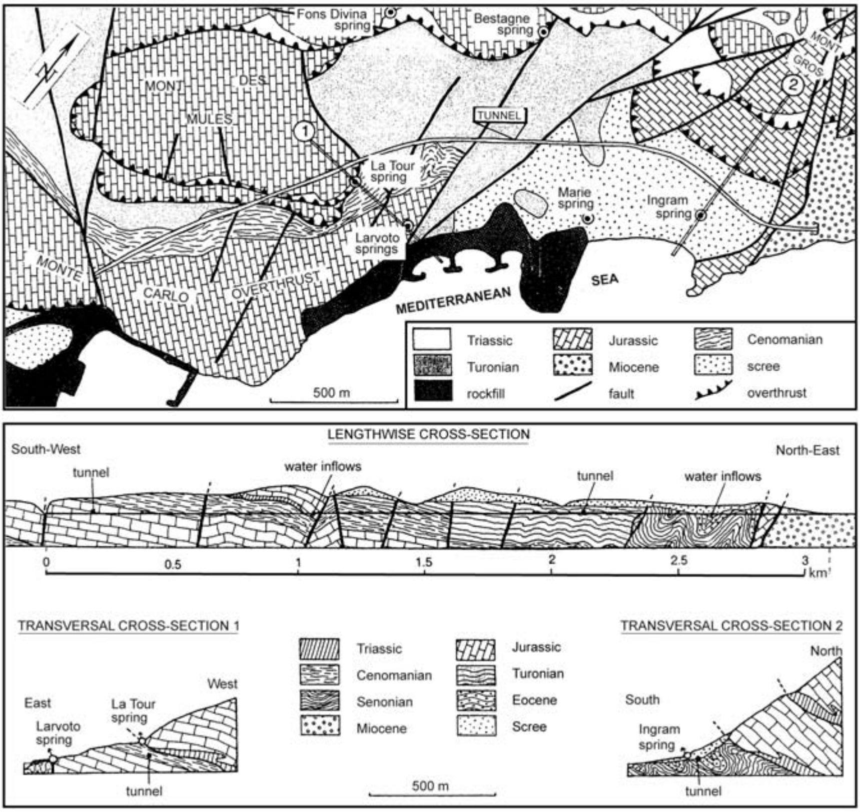


Figure 132 Monte-Carlo railway tunnel (Principality of Monaco). Geologic structure and cross-section along the path of the tunnel.

The landscape is dominated by Jurassic carbonate promontories which, above the plastic Triassic base, form duplex thrust anticlines, in stair-stepped units or overriding scraps of Cretaceous marl and marly limestone. The whole is cut up by subvertical transverse faults and, particularly, the sizeable median Larvoto thrust fault. It should be noted that the overthrusting front is totally obscured by scree slopes extending out to the sea in the northeastern part of the area in question.

The Jurassic units make up the main karst aquifer in the area, with karst circulations blocked at depth by the impermeable screen of the Triassic and frontally barred by Cretaceous formations or tectonic upwellings of Triassic.

The distribution of groundwater flow is perfectly aligned along the extent of the karst units, and is represented by stepped outlets enabling the underground drainage of the surrounding units:

- in the heights, the Justicier and Sainte-Marie plateaus are drained at 200 m and 220 m by the Bestagne and Fons Divina springs, which have a combined average annual discharge of 10 $L \cdot s^{-1}$;
- the Mont des Mules feeds the Tour springs at an elevation of 65 m with an average discharge of approximately 10 $L \cdot s^{-1}$;
- the Monte-Carlo overthrust is drained by the Larvoto springs against the fault of the same name. These emergences are located at less than one meter above sea level and provide an average discharge of 60 $L \cdot s^{-1}$;
- the Mont Gros, due to its intense tectonic partitioning, likely allows for a more diffuse frontal outflow, which is then relayed by scree slopes feeding the Ingram springs at an elevation of 18 m (average discharge of 25 $L \cdot s^{-1}$) and the Marie springs and an elevation of 2 m (average discharge of 10 $L \cdot s^{-1}$).

5.3 Hydrogeologic problems linked with the excavation of the tunnel

The difficulties caused by the hydrogeologic context during the excavation work were a result of very localized complications, of a structural nature, under the Mont des Mules overthrust, and of a paleo-geographic nature immediately uphill of the Ingram spring.

5.3.1 Passage through the Mont des Mules overthrust

The base of the Mont des Mules overthrusting Jurassic limestone on the Cenomanian marl led to water influxes over a distance of 50 m (1.015 km to 1.065 km from the southwestern entrance), with a discharge around 14 $L \cdot s^{-1}$. The affected zone was treated by injection (with the help of 8,000 m of boreholes) and by complete coating of the tunnel walls, waterproofed with extrados (Maury & Carpentier, 1966).

Examination of the map and cross-sections in Figure 132 reveals the difficulty of predicting such a particular structure. It is, indeed, a true basal pivot for the limestone unit, sunk into the underlying marl. This corner geometry materializes the contact between the weakly sloping frontal thrust surface and the lateral subvertical thrust.

This sensitive passage recently showed worrisome new signs of instability, likely tied to water pressure behind the tunnel walls and the ageing of the initial treatment (fracturation of the coating, fallen blocks, deformations of the rails, new influxes of water). The line was shut down for 9 months (June 2003 to March 2004), in order to allow the construction of appropriate reinforcements over the 50 meters concerned. This consolidation consisted of metal arches every meter covered by a concrete shell over the entirety of the section. The setup was completed with a catchment system for the incoming water flow, with evacuation in a central collector (Doublot *et al.*, 2004; Mario, 2004).

5.3.2 Drying up of the Ingram spring

On May 21st, 1962, the progress of the tunnel was halted by a large influx of water which appeared at the top of the arched roof towards 2.6 km from the southwestern entrance. The collected discharge reached 280 $L \cdot s^{-1}$ at the most difficult point, and led to the drying of the Ingram spring, located 150 meters downhill and used for the Principality of Monaco's drinking water supply (Maury & Carpentier, 1966; Varlan, 1981).

The construction had opened a breach in the base of the scree cover, apparently within a paleo-valley filled by slope deposits. This opening diverted the groundwater circulations coming from the Mont Gros mass, initially relayed by the scree cover to the Ingram spring.

The continuation of the project required the emplacement of a catchment system for the incoming water, and reparations for the arch, as well as the conveyance of the collected discharge back into the Monégasque pipe network.

The catchment is set up above the tunnel and includes a drainage network made up of three transversal galleries and one longitudinal gallery. The collected discharge is directed into an evacuation aqueduct leading to a stonework well, and then brought back to the Ingram spring by a 150 m long gallery. The distribution of water was put back into service in September, 1964.

5.4 Lessons to be drawn from this experience

The impact of hydrogeology on the construction conditions for the Monte-Carlo tunnel confirms the difficulty of revealing local heterogeneities, even in the context of a well-done study complemented by heavy mechanical reconnaissance.

This example highlights the importance of exploratory drilling as the tunnel advances, in order to preventively locate contingent water-bearing zones ahead of the tunnel path and to enable a preliminary emptying of the reservoir in order to subsequently continue excavation.

The drying of the Ingram well is a reminder of the absolute necessity of preemptively examining potential effects of the project on the surrounding water catchments. In this case, the geometry of the paleo-valley could have been determined through the creation of an isohypsal map of the roof of the substratum based on an appropriate grid of survey points (geophysics and boreholes).

CHAPTER D4

Dams and Reservoirs

1 GENERAL CHARACTERISTICS

The purpose of these structures is to create surface storage of water (reservoir), by locally obstructing a valley up to an appropriate level (dam). Their goals are varied and can be multiple:

- water storage used for electricity production (hydroelectric dams),
- reserves used for irrigation or drinking water supply,
- smoothing of discharge patterns (flattening of peaks and increased flow during the dry season),
- creation of pleasure lakes.

There are several types of dams:

- gravity dams, in concrete or masonry, support the pressure of the water they hold back along their entire surface;
- arch dams, made of concrete, transfer the load to the banks;
- embankment dams, made of unconsolidated material or of large blocks of rock, sometimes in conjunction.

The dimensions and storage capacity of reservoirs varies greatly. The height of small dams, between a few meters and twenty or so meters, generally enables the storage of several thousand to several tens of thousands m^3. The capacity of the reservoir is, in fact, totally independent of the dam height, and depends mainly on the topography and surface of its watershed.

The creation of a reservoir, by significantly altering the hydrogeologic conditions over the flooded area and its shores, can have noticeable effects on the behavior and the exploitation of infrastructures, as well as on the surrounding and downstream environments. The increased hydrostatic pressure in the area, directly dependent on the height of water in the reservoir, can lead to more or less serious problems:

- appearance of leaks in the reservoir, which can have negative effects on the exploitation of the structure and cause various impacts, on sometimes distant sites;
- creation of water channels under the dam's foundations, directly jeopardizing its stability;
- modifications in the equilibrium conditions on the shores of the reservoir, which can influence the safety of the dam and the downstream population.

The last two cases can lead to real disasters, as shown by the destructive events touching a number of countries:

- in 1802: Puentes (Spain) gravity dam failure: 680 victims;
- in 1889: Johnstown, Pennsylvania (USA) earthen dam failure: 2,200 victims;
- in 1895: Bouzey, Vosges (France) gravity dam failure: 86 victims;
- in 1911: Austin, Pennsylvania (USA) concrete gravity dam failure: over 100 victims;
- in 1923: Gleno (Italy) multiple-arch dam failure: 600 victims;
- in 1928: Saint-Francis, California (USA) masonry gravity dam failure: 450 victims;
- in 1959: Malpasset, Var (France) arch dam failure: 423 victims;
- in 1963: Vajont (Italy), collapse of one bank of the reservoir: 1,700 victims.

The preliminary study and subsequent construction of a dam and its reservoir therefore require a very serious analysis and, particularly, in-depth examination of the geologic structure and of the hydrogeologic behavior of the relevant units.

2 DAM STABILITY

The rise in water level behind a dam increases the static pressure of the aquifer partially or totally saturating the units supporting the project and its banks, increasing, in particular, the hydraulic gradient between upstream and downstream, especially in the case of large dams. This state facilitates the infiltration of water underneath the dam's foundations or around its supports.

Such forced flow can cause the regressive erosion of alterable formations, the washing out of fine-grained particles and the creation of internal erosion, or even the appearance of pressure from below, so many situations that can be very dangerous for the stability of the dam and the likelihood of which depends on the nature of the formations on the site and their spatial arrangement.

It is in the immediate surroundings of the dam that the risk of percolation is highest, since it corresponds to the shortest path, but it can also affect deeper or more distant areas, when the arrangement of natural discontinuities enables it (stratification planes, foliation, diaclases, and faults).

2.1 Headward erosion and internal erosion effects

This is a risk particularly associated with mobile formations, covering the bottom and sides of a valley, and through which water circulation can occur and gradually create favored channels, as well as washing out fine particles (alluvium, colluvium, moraines, scree, bedrock weathering mantle).

It can also affect massive bedrock formations, when they are heterogeneous and susceptible to degradation in the presence of water, and then to allow headward erosion and the removal of material (sandy sandstone, puddingstone, breccia, marly sandstone flysch).

These processes are sometimes accompanied by upward pressure under certain particular conditions (favorable structures and very marked permeability contrasts).

The 15 m high Bouzey gravity dam in the Vosges (France) was built in 1880, spanning 472 m along its crest.

Anchored entirely in Lower Triassic sandstone, its showed partial deformation of its facing as early as 1884, at the same time as the increase in discharge of the springs downstream (from 75 to 232 $L \cdot s^{-1}$).

An anchor block was built in the affected area in 1889, but the dam failed on April 27th, 1895 (Lugeon, 1933; Gignoux & Barbier, 1955; Letourneur & Michel, 1971). Apparently, the disaggregation into sand of poorly consolidated sandstone layers favored the migration of fine-grained particles by internal erosion, and the creation of pressures that the dam could not support.

The Cedar River dam near Seattle (USA) was built on moraine deposits. When the reservoir was filled in 1918, water seeped into gravelly beds, prompting internal erosion. A landslide at the base of the dam then caused its partial failure (Letourneur & Michel, 1971).

The Cheurfas dam near Oran (Algeria) was built in 1880 on the Oued Mebtouh. It rests on highly tilted Tortonian (Miocene) limestone on the left bank, but its right bank consists of ancient alluvium and reworked slope deposits masking the underlying limestone bedrock (Figure 133).

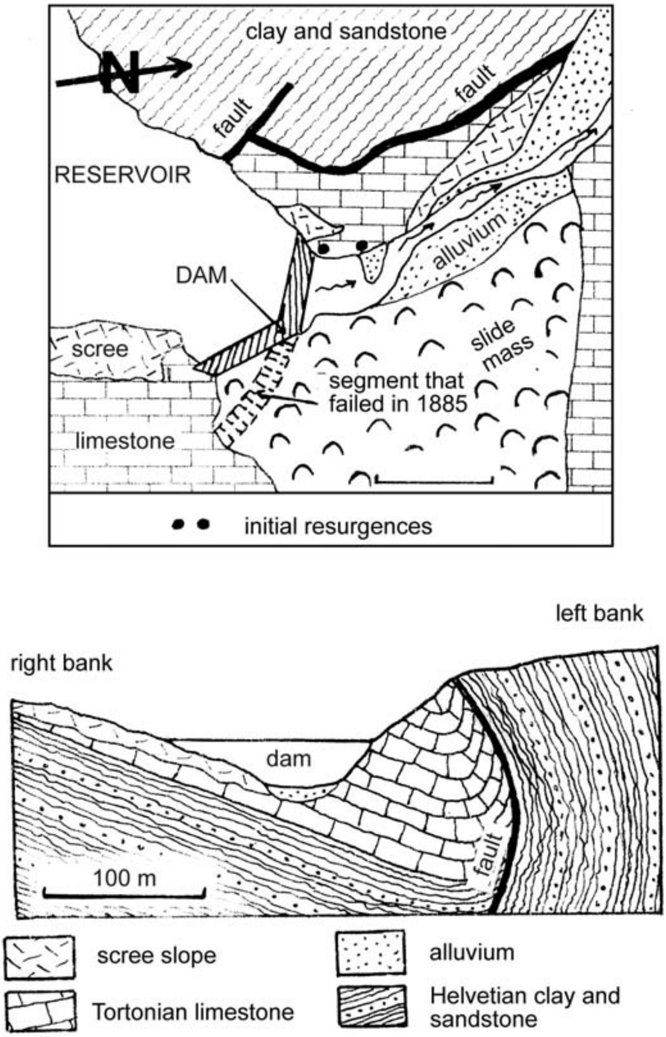


Figure 133 Cheurfas dam (Algeria). Relationship between the dam and the geologic structure (from Gignoux & Barbier, 1955).

On February 8th, 1885, during a high flood, the right bank was deeply scoured by the water and the dam support collapsed. The mantling deposits, initially indurated during construction, had gradually become less and less consolidated due to the effects of infiltration, significantly weakening the ground on which the dam's foundations had been built (Gignoux & Barbier, 1955).

The part of the dam that was destroyed was rebuilt immediately upstream and anchored in Tortonian limestone, which explains the unusual V shape of the new dam (Figure 133).

The Saint-Francis gravity dam in California (USA), 82 m high and set, for the most part, on foliated mica schist, put into contact with volcanic tuff (conglomerate cemented by clay) by a fault on the right bank (Figure 134).

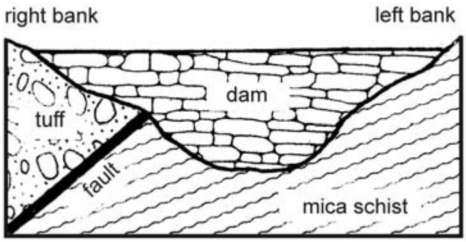


Figure 134 Saint-Francis dam (USA). Relationship between the dam and the geologic structure (from Letourneur & Michel, 1971).

The vulnerability to weathering of the tuff and the permeability contrast between the two formations allowed water to pass through the disaggregated tuff near the fault and is likely to have generated an accumulation of water pressure, leading to the sudden failure of the dam on March 13th, 1928 (Lugeon, 1933; Gignoux & Barbier, 1955; Letourneur & Michel, 1971).

2.2 Effects of water pressure

The most striking example is provided by the Malpasset arch dam in the Var (France), the construction of which finished in 1954, and the left bank support of which failed suddenly on December 2nd, 1959, leading to a catastrophic outpouring from the reservoir.

With a height of 66.5 m over a length, across the top, of 222 m, the dam was founded entirely on the foliated two-mica gneiss of the Tanneron mass, containing pegmatite veins (alternating dark micaceous beds and light-colored quartzo-feldspathic beds). In addition, the site is cut up by a network of faults along two principal directions, N 80 dipping north, and N 150 dipping southwest. This last group can even be confused with the direction and dip of the foliation (Figure 135).

The studies performed after the accident revealed the existence of a N 80 fault, limiting the downstream lip of the left bank failure, and also visible on the right bank. The fault, covered with clayey breccia of variable thickness,

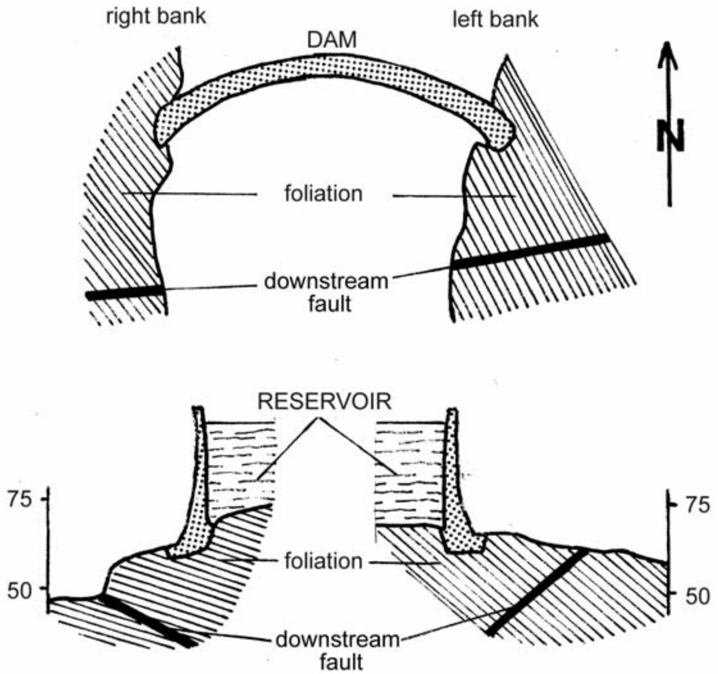


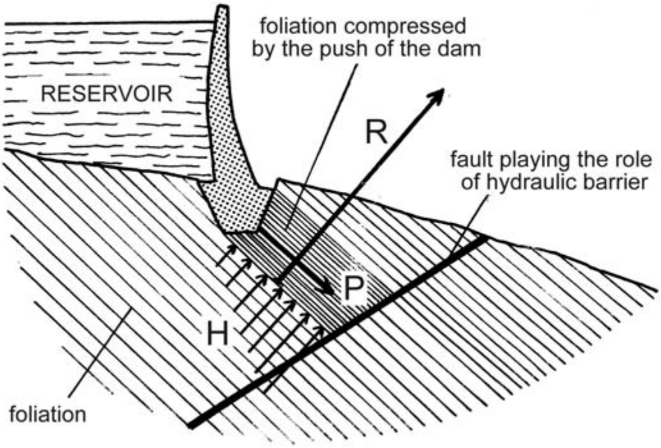
Figure 135 Malpasset dam (Var). Relationship between the dam and the geologic structure in map view and cross-section (from Bellier, 1967).

dips upstream and passed underneath the dam at a depth between 15 and 30 m depending on the location.

In addition, tests on the gneissic rock revealed a spectacular decrease in its permeability under pressure, with an average difference of 100 between the permeabilities measured at pressures of 1 bar and 50 bars (Bellier, 1967).

The results of the studies indicate that the upstream-dipping fault played an important role as a hydraulic barrier, behind which the foliations of the rock, compressed by the pressure P of the dam, closed and created a veritable "impermeable coating" between the base of the support and the fault. The infiltrations possible because of the foliation and induced by the filling of the reservoir enabled the creation, under the double hydraulic barrier, of an intolerable hydrostatic pressure H. The upward pressure R developed in this zone then led to a true cleavage of the supporting rock and freed a dihedral mass of rock limited by the two "impermeable" surfaces (Figure 136).

The structural conditions, however, enabled the dissipation of pressure below the right bank support.



P-push from the dam, H-hydrostatic pressure, R-resultant of the pressure

Figure 136 Malpasset dam (Var). Conditions leading to the failure of the left bank support (from Bellier, 1967).

2.3 Prevention and treatment

In order to avoid the aforementioned problems, the best guarantee is to proceed with a careful and complete study of the structural and hydrogeologic conditions on a dam site beginning with its design, in order to, on the one hand, discard sites that appear too dangerous or too constraining, and on the other hand, to plan for the most appropriate construction designs.

In order to effectively fight infiltration underneath the dam, various arrangements are now used on most construction sites:

- emplacement of an impermeable coating in continuity over the upstream dam facing, along the bottom of the reservoir (small earthen dams and hillside reservoirs);
- consolidation-cementation injections, intended to reestablish the surface continuity of a rock mass shaken by the construction, and to ensure an impermeable connection between the bottom of the dam and its foundation. They are done with the help of short boreholes (a few meters deep);
- creation of a waterproof screen prolonging the upstream facing, either a cutoff consisting of a concrete wall or of sheet piling (unconsolidated terrain), or a grout curtain extending to an impermeable horizon or to a depth allowing an adequate increase in the distance that groundwater circulations would have to cover (rocky terrain).

The creation of a drainage network immediately downstream of the impermeable curtain remains essential in order to account for the real "discontinuity" of the impermeable screen. Its goal is to intercept residual water circulation and to dissipate interstitial pressure below the dam. It is made up of vertical or inclined outflow boreholes, discharging downstream of the dam or collected in a drainage gallery incorporated into the body of the dam.

Similarly, it is desirable to create a representative piezometer network, in order to enable the long-term monitoring of the aquifer's behavior, to be integrated into security checks.

3 IMPERMEABILITY OF RESERVOIRS

When a reservoir is created over permeable terrain, risk of leaks is greater given the greater hydraulic load.

The least favorable conditions are when a reservoir is built on fluvial or glacial fill in valleys slowly migrating laterally (epigenetic phenomenon) and by intensely karstified rock masses, if the geometry of the formations truly allows the bypassing of the dam.

Dam losses can have a significant impact on the use of the water resource and can, in extreme cases, lead to the impossibility of exploiting certain works or to an abandonment of other projects. This is particularly the case when the revealed or estimated leakage discharge is greater than or equal to the natural discharge flowing into the reservoir.

3.1 Epigenetic phenomena

The example of the hydroelectric infrastructure in the Drac valley in Isère (France) is totally representative of this type of difficulty.

Carved out during the Riss-Würm interglacial period, the Drac valley was then filled with rocky alluvium, then by glacial clay containing large blocks, deposited during the Würmian. After the retreat of the glacier, the Drac re-excavated its course following a different path than the initial channel, which it cuts back across in places.

It is within this particular context that the Drac valley storage infrastructure was built, with the establishment of dams in the new sections of the river channel, termed epigenetic, which cut deep gorges into the impermeable Jurassic formations, and the development of reservoirs in the older sections of the river, widened by renewed erosion (Figure 137) (Gignoux & Moret, 1952; Antoine & Barbier, 1973).

The Sautet, St Pierre-Cognet, and Monteynard reservoirs saturate the Würmian fill and are subject to leaks that pass around the dams and, passing through ancient, filled channels, flow out into tributary valleys.

In the case of the Sautet dam, finished in 1935, the bottom of the old lateral valley is located 60 m below the high-water level of the reservoir, causing losses of 2.5 $m^3 \cdot s^{-1}$, which then rejoin the Sézia valley.

The losses are smaller at the downstream reservoirs. They do not exceed 250 $L \cdot s^{-1}$ at the St Pierre-Cognet dam, finished in 1957, where they flow into the Bonne valley, and do not exceed 400 $L \cdot s^{-1}$ at the Monteynard dam, finished in 1957, where they short-cut into the Ars ravine (Letourneur & Michel, 1971).

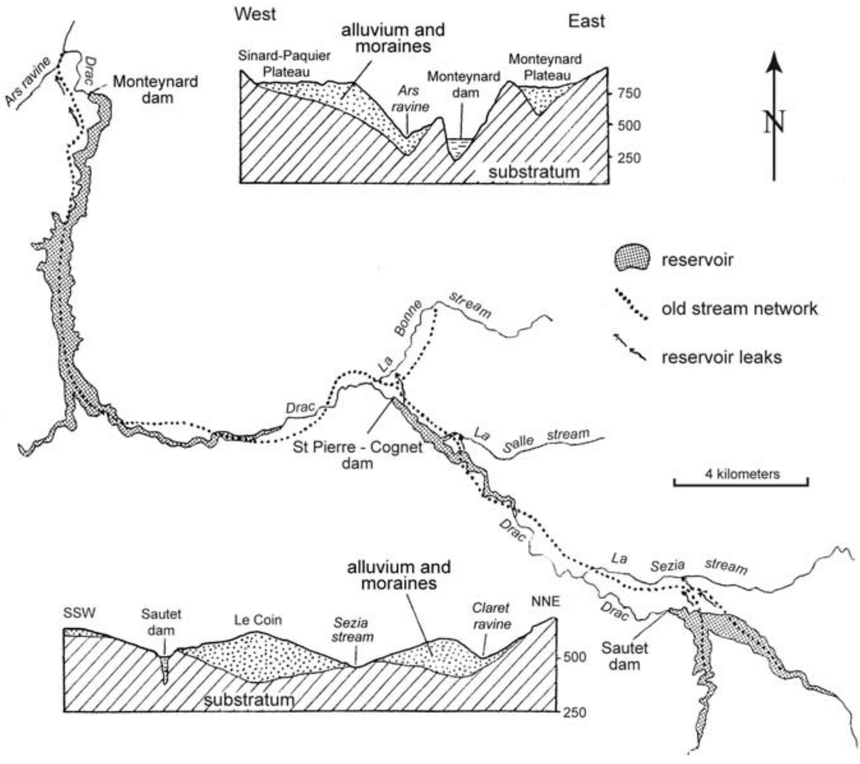


Figure 137 Hydroelectric infrastructure in the Drac valley (Isère) (from Gignoux & Moret, 1952 and Gignoux & Barbier, 1955).

3.2 Karst substratum

In limestone and dolomite formations, the narrowness of the canyons and the good mechanical characteristics of the rock are factors favorable to dam construction. Nevertheless, the presence of more or less evolved karst networks and of natural cavities of various sizes can be a daunting obstacle to the filling of reservoirs.

3.2.1 Extreme risk of empty reservoirs

The most representative example is that of the Montejaque arch dam in Andalucia (Spain), 73.5 m high. It was built on the Rio Gaduares, which flows over a polje before disappearing below ground in the del Gato cave. After a 3.8 km underground course, the water returns to the surface to the south, on the edge of the Rio Guadiaro, 160 m lower in elevation.

The dam, located 500 m upstream of the cave, was to have enabled the creation of a reservoir with a capacity of 5 million m^3 over impermeable flysch. As soon as it was filled, leaks appeared and increased the discharge flowing in the del Gato cave and emerging at the Benaojan springs (Figure 138).

The losses reached 4 $m^3 \cdot s^{-1}$ and tracer tests showed groundwater circulation velocities reaching 160 $m \cdot h^{-1}$. The average discharge into the reservoir being of 0.8 $m^3 \cdot s^{-1}$, these leaks prevented the creation of a reservoir. They proved uncheckable, despite ten years of studies and construction, and led to the abandonment of the project in 1925. The dam today serves only to dampen flood peaks during the winter.

The same fate befell the Maria-Christina dam, near Castillon-de-la-Plana (Spain) and the small Saint-Guilhem-le-Désert dam in the Hérault (France), both built on highly karstified limestone, without a real capacity to store water (Lugeon, 1933).

Such failures, often ancient, are clearly a result of inexistent or very inadequate geologic and hydrogeologic studies.

3.2.2 Effects of waterproofing projects

Relatively limited construction can sometimes solve the problem, when the leaks are very much localized. In this manner, the high losses generated by the activation, in 1925, of the Bouvante dam in the Vercors (France) were reduced in 1937, by covering the absorbent zone at the bottom of the reservoir with a layer of concrete, reinforced with a metal trellis (Gignoux & Barbier, 1955).

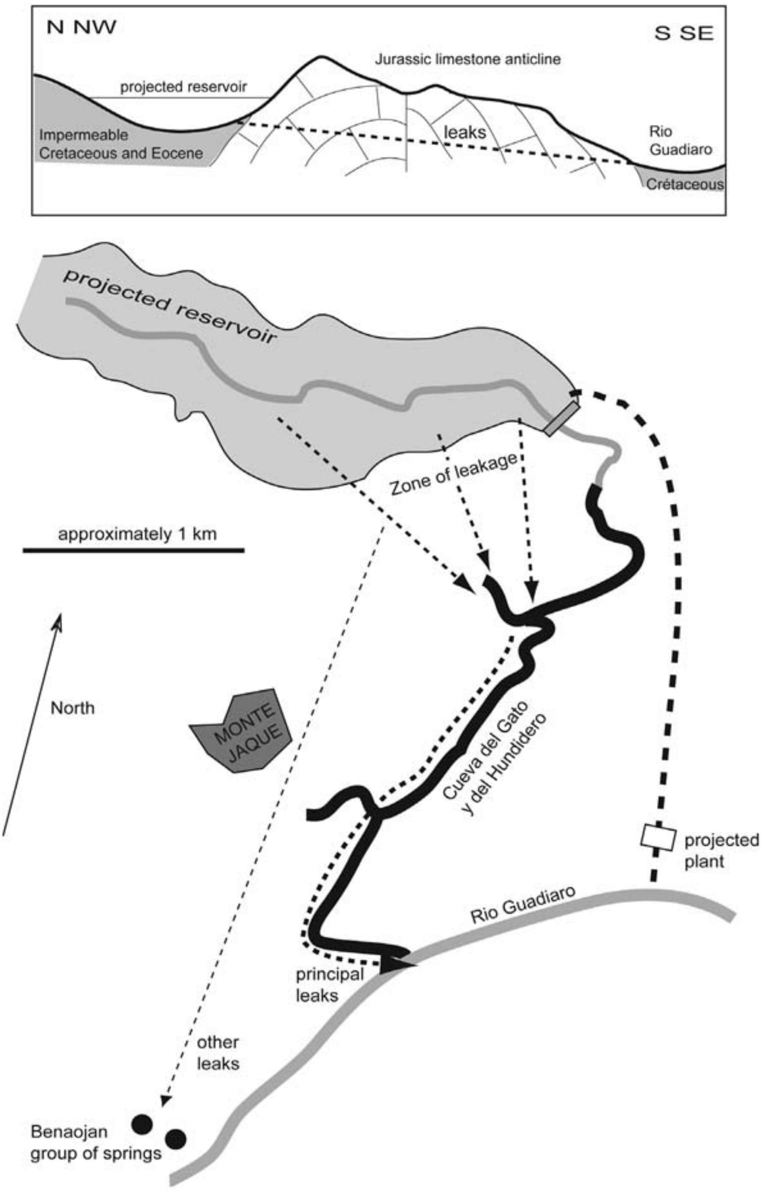


Figure 138 Montejaque dam (Spain). Map and schematic geologic cross-section of the site (from Thérond, 1973).

The installation of waterproofing treatments *a posteriori* is, however, difficult, long, and costly in the majority of cases, and can result in a very limited outcome.

The Hales Bar dam (USA) on the Tennessee River, is likely to set records. Begun in 1905, without a geologic study, it was put into use in 1913, after construction costs four times higher than predicted, due to injection work in cavities encountered during construction. Losses were immediately apparent and did not stop increasing, until they reached 250 $m^3 \cdot s^{-1}$ in 1930, date at which construction halted. When the dam was purchased by another company in 1939, the leaks fed thirteen large resurgences immediately downstream, with a total discharge of 500 $m^3 \cdot s^{-1}$. The almost total suppression of the leaks was nevertheless achieved, through the creation of two impermeable curtains extending to a depth of 30 m below the upstream facing of the dam (Gignoux & Barbier, 1955).

The Caramasa gravity dam in Catalonia (Spain), 92 m high, suffered large losses as soon as it went into use in 1920. Their discharge showed an annual increase of 5% and reached a value of 11 $m^3 \cdot s^{-1}$, flowing over a front of 1.2 km. After detailed studies, spread over several years, the solution consisted of creating a 1 km long grout curtain, constructed using 224 boreholes totaling a length of 132 km, composed of individual lengths between 112 and 394 m. The losses were brought down to a value of 2.5 $m^3 \cdot s^{-1}$, after the use of 1,90,000 metric tons of injected material, including cement, scoria, sand, gravel, sawdust, sisal, and asphalt (Lugeon, 1933).

The Keban gravity dam (Turkey), 185 m high, was built on the Euphrates (average discharge of 655 $m^3 \cdot s^{-1}$), for the purpose of creating a 30 billion m^3 reservoir for irrigation and electricity production. During construction, a karst cavity of 1,00,000 m^3, the Crab cave, was discovered 300 m below the construction site. It was filled with concrete and the waterproofing of the rock below the dam was completed successfully, with the help of a grout curtain. On the left bank, karst indicators were found during geologic studies and during the excavation of a diversion gallery. A grout curtain was put in place to isolate this area to a depth of 250 m, apparently not enough given the depth of the Crab cave. The increase in leakage led, in 1976, to losses of 26 $m^3 \cdot s^{-1}$, when they were initially only of 6 $m^3 \cdot s^{-1}$, and to the partial emptying of the lake, revealing the opening of a large cavity, the Petek cave. It entrance was surrounded by a concrete chimney, in order to reduce its absorption capacity, and it was then filled with the help of a million m^3 of material, and a part of the left bank was waterproofed with a concrete carpeting 50 cm thick. These projects decreased the leakage to 9 $m^3 \cdot s^{-1}$, which represents only a little over 1% of the discharge of the Euphrates and is therefore economically acceptable.

The Cheurfas dam (Algeria), after its reconstruction after its partial destruction in 1885 (see chap. D4-2.1), required significant waterproofing work in order to curb the losses from its reservoir through its Tortonian limestone base. The infiltrated water reemerged immediately downstream, at the level of several springs on the left bank of the Oued Mebtouh (Figure

133). On the right bank, a grout curtain was put in place without difficulty, extending to the underlying Helvetian sandy clay. On the left bank, the particular structure of the site (faulted syncline) imposed the digging of a gallery slightly above the water surface in the reservoir, serving as a work chamber from which the grout curtain could be built. Its construction required 5,824 meters of injected boreholes and 2,631 metric tonnes of injected material. The construction enabled a 90% reduction in leakage discharge.

The leaks affecting a reservoir in a karst site generally feed preexisting springs and use previously empty or filled-in passageways. The clearing out of cavities can be very sudden, and resurgences often appear less than 2 km away from the reservoir. Thérond (1973) showed that the natural catchment basin of the emergences experiencing increased discharge due to leakage collection extends to the reservoir. He estimates that the presence of a karst passage less than 150 m away from a spring constitutes a significant risk. The extent of a spring's drainage basin can be rapidly evaluated, if the specific infiltration modulus of the concerned area is known (a 10 $L \cdot s^{-1}$ spring corresponds to a 1 km^2 basin for a 10 $L \cdot s^{-1} \cdot km^{-2}$ modulus).

In the case of the most recent projects, examples of success are happily more common than failures, due in particular to the undertaking of long hydrogeologic studies, enabling an understanding of the major outlines of karst circulation, and of paleo-geographic studies, evaluating the depth of karstification and therefore the depth to which grout curtains must extend.

In France, the Génissiat dam on the Rhône (104 m), the Vouglans dam on the Ain (130 m), and the Castillon (100 m) and Sainte-Croix (90 m) dams on the Verdon were built on karst sites and were in some cases faced with sizeable underground cavities (Caborne de Ménouille, Fontaine l'Evêque). The undertaking of long studies and the construction of large grout curtains (44,400 m^2 in Castillon, 50,000 m^2 in Sainte-Croix) enabled the success of these projects.

3.2.3 Special case: storage in poljes

The use of poljes to create reservoirs is particularly common in Dinaric karst. These are endorheic basins, drained by absorbent karst cavities called ponors. When the discharge collected by the basin is greater than the infiltration capacity of the ponor, the polje fills with water and a lake forms. Lake formation can also be provoked by upwelling from the karst aquifer, the ponors (in this case termed estavelles) then acting in the reverse direction. Successive inundations shape the relief, creating vast, multikilometric closed depressions, with a flat bottom at an altitude dictated by the location of the ponors.

The sediments accumulated at the bottom of poljes are relatively impermeable, often made up of irregularly alternating clay and gravel. It is therefore tempting to take advantage of this natural coating to store water outside the high-water period, by blocking the ponors. The success of such adventure depends on the nature and thickness of the deposits accumulated in the depression, the possibility of successfully blocking the ponors, and the absence of risk of other areas becoming unblocked. Examples of failed attempts are numerous, as water frequently flows around any construction and opens up old passageways.

The Slivlje ponor, draining the Niksicko polje in Montenegro (former Yugoslavia) was encircled in this manner in the 1950s by a chimney 50 m in diameter and 20 m high, in order to enable the creation of a water reservoir. The construction was based directly on the limestone bedrock, through approximately ten meters of clayey silt. As soon as the basin was filled, new absorption points opened around the edges of the blocked ponor, and old cavities were cleared out, enabling the leakage of sizeable volumes of water.

In Thorenc, a small tourist resort in the Alpes-Maritimes (France), the creation of a pleasure lake was attempted around 1,900, with a similar arrangement. The site was a small polje, at the contact between Cretaceous marl and Jurassic limestone, fed by a permanent stream and drained by two ponors located at the lowest point in the depression. The polje is located at an elevation of 1,165 m and tracer tests revealed a rapid connection between the infiltrated water and the Mouna spring, at an elevation of 1,000 m. The ponors were encircled by chimneys anchored to the bedrock. These were built out of concrete, and equipped with sluice gates in order to regulate the water height in the reservoir and to allow the evacuation of overflow into the natural ponors (Figure 139). The lake filled on the first attempt, but hydraulic short circuits soon appeared in the immediate surrounding of the chimneys, absorbing all of the accumulated water. The project was abandoned and the two chimneys still standing in the middle of a grassy plain now serve as a reminder of this abortive project.

In order to create an adequate degree of impermeability in the floor of poljes, the emplacement of an impermeable membrane is often necessary, but its stability can be compromised by upwelling water in estavelles, when the karst aquifer rises. The Popovo polje reservoir (Bosnia and Herzegovina) was waterproofed in this way by a membrane, and equipped with discharge wells enabling the evacuation of air pushed out by temporary rises in the water table in the passageways under the polje.

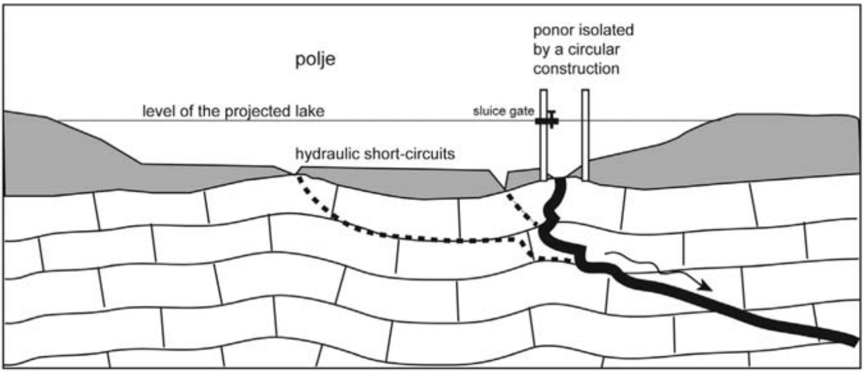


Figure 139 Thorenc polje (Alpes-Maritimes). Conceptual outline of the development project.

4 SHORE INSTABILITY OF RESERVOIRS

4.1 Natural instability

Large-scale landslides (rockfalls or rockslides) can sometimes block a valley and cause the creation of a lake.

This lake is generally quickly resorbed due to the erosive action of water arriving from upstream, which opens a breach in the natural dam that had been created. Such was the case in the Alpes-Maritimes department, where the exceptional rainfall in November, 1926 led to the multiplication of large landslides in the upper Vesubie basin and the complete obstruction of the Madone de Fenestre valley and of the Vesubie's course at the place locally known as "La Muselle" (Perriaux, 1927).

The emptying of these lakes is sometimes artificially prompted by humans, when it is necessary in order to protect nearby infrastructure and development. On January 30th, 1948, a large landslide affected the slope on the right bank of the Var valley, immediately downstream of the village of Puget-Théniers (Alpes-Maritimes). The mobilization of a hundred or so thousand m^3 of gypsic clay, at the place locally known as "Le Breuil," blocked the river across its entire width, creating a reservoir of 440 000 m^3 and cutting off the road and rail line along the left bank. Breaches were then opened with explosives in the displaced mass in order to accelerate the return to the initial hydraulic state.

Finally, permanent lakes resulting from such processes do exist: the Lac de Sillans in the Jura, and the Lac de Parouard, in the Haute-Ubaye (Goguel, 1967).

Ancient landslides can also lead, over time, to a diversion of the river's course (characteristic dogleg turn) or can produce a simple local narrowing of the valley, which creates an ideal dam emplacement. There is therefore significant danger in building such a dam, due to the risk of failure or of very onerous stabilization work. The fate of the Cheurfas dam (Algeria) should be kept in mind, where the right bank support, founded on an old scree slope, was swept away in 1885 (see chap. D4-2.1 and Figure 133). Its reconstruction had to be relocated immediately upstream, out of the reworked zone.

This risk also concerns reservoirs, when they flood the base of old landslides. Remobilization is always a potential danger, even if the reservoir creates a stabilizing counter-pressure. The most delicate phases consist of large variations in the water level (filling and emptying of the reservoir), which modify the pre-existing hydrodynamic conditions and can generate landslides of varying magnitude.

Gignoux & Barbier (1955) cite the abandonment of a dam project on the Romanche, near the village of Villar-d'Arène (Hautes-Alpes), after the preliminary investigations revealed large masses of schisty Lias slide material making up the right bank (Figure 140). Indeed, below these reworked materials, a borehole cut across ancient alluvium from the Romanche, revealing the dam created by the ancient landslide over a height of 40 m and the displacement of the river's course approximately 70 m towards its left bank.

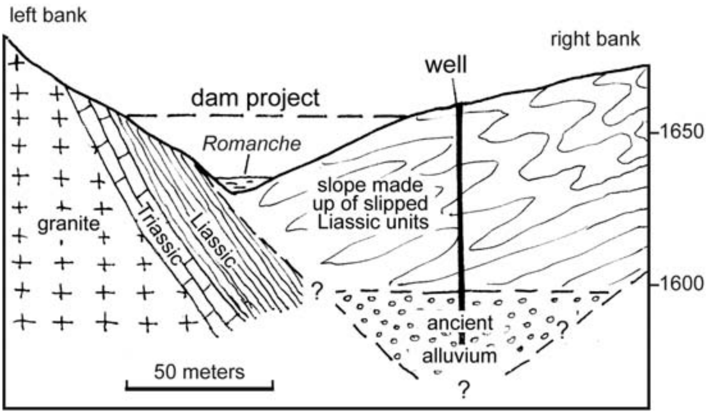


Figure 140 Villar-d'Arène dam project site (Hautes-Alpes) (from Gignoux & Barbier, 1955).

4.2 Role of emptying

When the reservoir level is relatively stable, hillside aquifers are sustained by the water surface, with which a stable hydrostatic level, and therefore a new state of equilibrium, is established.

The variations in water level resulting from the exploitation of the dam (periodic oscillations of hydroelectric reservoirs) or from monitoring or maintenance operations (partial or total emptying), will, however, more or less rapidly disconnect the hillside aquifers from the lake. This situation can generate high hydraulic gradients, especially in poorly permeable terrain, and can lead to movements in the surface cover, or even at depth. In fact, Antoine (1973) warns of the risk run by light constructions, which are more and more being built "feet in the water" at the edge of artificial lakes.

In France, on the shores of the Sainte-Croix reservoir (Alpes de Haute-Provence), a slow slide has been active for decades. It is being carefully monitored, even though the filling of the lake slowed its velocity (Anonymous, 2003).

Behind the Génissiat dam, built on the Rhône, the water level was brought down to an elevation of 330 m instead of 337 (initial project), in order to limit the extent of the waves created by the daily oscillations (which can reach 5 to 6 m). This decision rests on the necessity of protecting the upstream slopes, which have been highly degraded by active slides developing in the morainic cover, both on the French right bank (rail line) and on the Swiss left bank (village of Chancy) (Gignoux & Barbier, 1955).

4.3 Example of the Vajont landslide (Italy)

The Vajont dam was built on a tributary of the Piave, in the Venetian Alps, for the purpose of hydroelectric exploitation. It is a 262 m high arch dam, which allowed, by filling the reservoir to the elevation of 722.5 m, the storage of 17 million m^3 of water.

On October 9th, 1963, an exceptional landslide occurred on the left bank of the reservoir, which it filled partially, and displaced the lake water over the dam, in a wave estimated to be 200 m high, causing 1 700 deaths in Longarone and in the surrounding areas, while the dam itself remained unharmed (Figure 141).

The moving mass detached itself from the Mont Toc, on a 1.9 km wide front and over a thickness of 150 to 330 m, leading to a total volume on the order of 280 million m^3. Its estimated travel velocity would have been between 60 and 90 $km{\cdot}h^{-1}$.

The slide occurred in the Jurassic formations, along a structural surface between the Dogger and the Malm, where the bedding was locally tilted to 40°, while it was subhorizontal at the foot of the slope (cross-section in Figure 141).

It is clear today that ancient landslides had shaped the gentle morphology of this slope (which can be compared to the abrupt right bank). Indicators of movement were, in fact, observed during the first filling of the reservoir, as early as June, 1960, which led to the slope being equipped for topographic and piezometric monitoring, and to a gallery being excavated under the right bank in order to deviate water should the valley be obstructed (Letourneur & Michel, 1971).

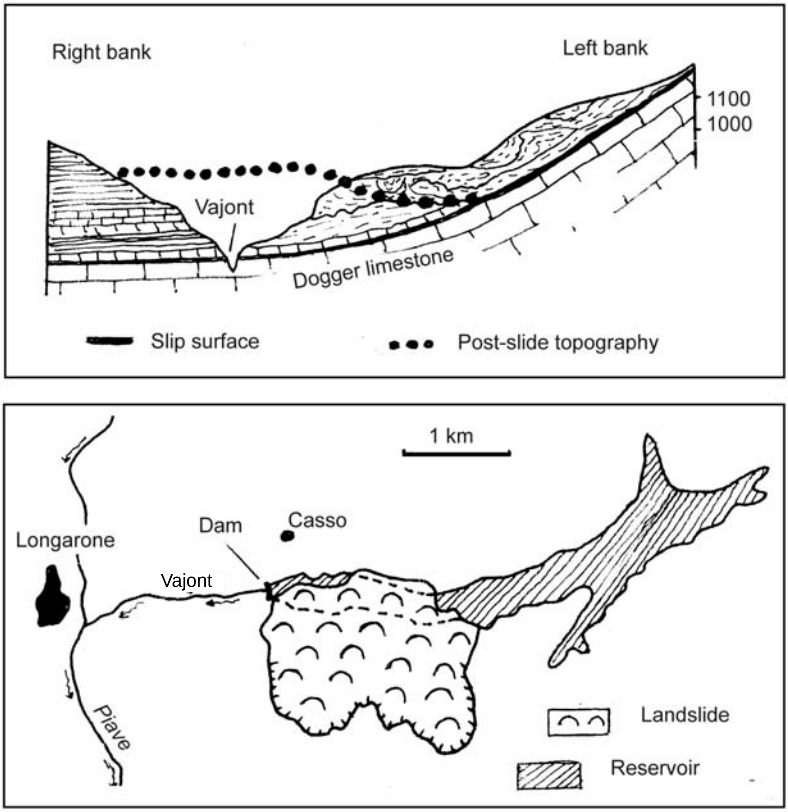


Figure 141 Vajont landslide (Italy). Map and representative cross-section of the site (from Letourneur & Michel, 1971).

During the second filling, in 1962, the slope reactivated when the water level reached an elevation of 700 m, but its stability returned with a lowered level.

During the third filling, in 1963, it was also beginning at an elevation of 700 m that noticeable accelerations in the movement of the slope appeared. It was decided that to keep the water level at an elevation of 700 m in order to minimize the risk, but starting in early October, the slope movement velocity increased, reaching 20 cm·day^{-1} on October 9th (Anonymous, 2003).

The disaster was, on the one hand, a result of a poor choice of location on a site that had previously been shaped by ancient landslides of great magnitude, and on the other hand a result of the successive filling and emptying of the reservoir, and, particularly, of the last rapid emptying to return to the elevation of 700 m, which favored the saturation of already-reworked terrain, then initiated the failure mechanism by suddenly increasing the hydraulic gradient.

CHAPTER D5

Underground Storage

Underground storage is essentially tied to energy problems. It is used for gas storage, to smooth the contrast between the regular restocking by providers and the irregular use by consumers. Aside from daily peaks due to cooking before mealtimes, consumption is, indeed, highly variable: high in the winter due to heating needs and low in the summer. Another need is the handling of nuclear waste. The hydrogeologic problems encountered are different. For gas, the presence of water is absolutely necessary in order to prevent leaks and enable pressurization. For nuclear waste on the other hand, areas with no water circulation are sought out.

1 UNDERGROUND GAS STORAGE

Four types of storage are commonly used:

- gas can be stored in old exhausted gas reserves, and this is the most commonly used method. A project is under way in Trois Fontaines (Marne) where the reconversion of a natural gas deposit will allow a storage of around 3 billion m^3;
- storage in salt cavities, where a cavity is created by injecting water into a salt deposit and extracting the resulting brine. The Manosque deposit (Alpes de Haute Provence), 150 m below ground, has a capacity of one billion m^3. Those in Tersanne (Drôme) and Etrez (Ain) have a capacity of 1.4 billion m^3;
- storage in an aquifer, where gas is injected at a pressure greater than the hydrostatic pressure, in a confined aquifer below an aquiclude, and pushes the water compressing it out laterally. This recreates the equivalent of a natural reserve. The exploitation constraints impose the permanent maintenance of a volume of approximately half of the stored volume (the padding). Part of the gas can then be replaced by nitrogen. In France, the Chémery site (Loir-et-Cher), with a total volume of 6.8 billion m^3, enables the useful storage of 3.5 billion m^3. The boreholes

have a depth of 1,120 m. The sandstone aquifer is confined below a clay later;
- finally, old mining sites can be used.

Demand is constantly increasing, and several projects are under way in France.

2 STORAGE OF NUCLEAR WASTE

The nuclear energy industry and a few other activities produce waste that can be harmful for hundreds of thousands of years, and therefore constitutes a risk for future generations. One of the principal complaints of opponents to nuclear energy, aside from the ethical problems, is that the cost of waste treatment and of dismantling abandoned reactors finally makes this form of energy more costly than other options (dams, gas or coal-powered electric plants). The future of nuclear energy therefore depends on the proof that the management of waste is possible. The problem of storing these products is essentially that of long-term contamination of aquifers. The Chernobyl accident caused a significant contamination, and underground zeolite dams were put in place on-site, by the AEC, in order to stabilize the radioactivity.

2.1 Nature of the waste

Waste from the extraction, purification, and enrichment of uranium contains radon, depleted uranium, and radium. This waste has a long life, but its radioactive activity is low and the danger, outside of treatment sites, is therefore limited. Radium can, nevertheless, be taken up by water and infiltrated below ground. The problems arise mainly from fission products. These long-lived products are major actinides (uranium and plutonium), which, with future technology, may become combustibles or waste; their future is therefore uncertain. Fission also produces minor actinides (neptunium, americium, and curium), with no economic value, and long-lived fission products LLFP, which are definitively waste. The stock of dangerous material is therefore variable, requiring varied solutions. In France, three classes have been defined. Category A waste has low activity and a short life. It is stored at the surface on sites intended to be operational for 50 years and monitored for 300 years. The Aube site, with a capacity of one million m^3, receives 20,000 m^3 per year. Category B waste has a medium level of activity but a long life, and finally, Category C waste has a high activity and radiates heat. At the Hague plant, the minor actinides and

LLFPs making up category C are vitrified and cooled for approximately 50 years while awaiting their final underground storage site, but other waste products are generated by their treatment (cement and concrete), which also await a final storage location. The total volume for 2030 is estimated at 95,000 m^3. In most countries, deep geological repositories are being considered, in deep geologic structures far from tectonically active zones. The two sought-after characteristics are the absence of risk of accidental human intrusion in the future, and the absence of water circulation. This therefore implies a precise understanding of the hydrogeologic mechanisms of potential sites.

The waste is stabilized and placed in a container; the whole makes up a package which must obey very strict standards in order to allow its long-term storage. The goal of burial is to create a subterranean barrier around the containers. At least one of the elements of the packaging-constructed barrier-geologic formation system must remain stable for thousands of years. However, no one today can predict the interaction of groundwater with the containment systems over such a length of time. Geothermal sites and the discovery in Oklo (Gabon) of natural nuclear reactors 2 billion years old fortunately offer natural laboratories under study, which can provide nuclear storage site designers with inspiration (Alexandre, 1997).

2.2 Hydrogeologic context of storage sites

2.2.1 Surface storage

The waste must be deposited on a draining formation, above an aquifer that is blocked at depth by a perfectly impermeable substratum, with no risk of the aquifer reemerging at the surface. The aquifer must have a single, well-understood outlet, in order to enable water quality monitoring.

The Aube site is set up in Soulaynes Dhuys on Albo-Aptian sand, above the impermeable clays of the Upper Aptian.

2.2.2 Burial

On the global scale, no site is yet operational, and laboratories are currently studying the feasibility of storage (Table 23). The sites must follow the following constraints:

- lack of valuable resources below ground,
- absence of any water circulation,

- stable tectonic environment,
- plasticity allowing minor deformation.

Table 23 Deep Nuclear Waste Storage Projects.

Geologic formation	Countries concerned	Advantages	Drawbacks
Salt	United States Germany Russia	Absence of water Plasticity	Natural resource Oil trap
Granite	France Sweden Canada Switzerland Japan	Mechanical strength Low porosity (1%) Absence of mineral ore	Permeable fractures Sensitive to tectonics
Clay	France Belgium	Natural capture of radioactive cations High plasticity	Presence of water (20 to 40%) Fracturable and permeable when compressed
Volcanic tuff	United States	Mechanical strength Absence of mineral ore	High porosity

In France, three sites were studied by the ANDRA (National Agency for Nuclear Wastes): the Gard clays, the Vienne granite, and the Est clays (Haute Marne and Meuse). The Gard site was abandoned.

E

CONCLUSIONS

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Conclusions

1 WATER AS AN ENTITY

Water is an undissociable whole. Necessary to life, its absence is disastrous, but, inversely, floods are the most common natural disaster and have created over 5 million victims since 1850. Surplus *versus* deficit, water must be managed. And yet, integrated in an endless cycle, the water in aquifers cannot be dissociated from the springs and rivers it feeds. In France, the 1992 law on water took into account this oneness of water. But in order to ensure good management, it is necessary to understand this entity to highest possible level, and much remains to be done in order to gain this understanding. In this period of questioning with respect to global warming, we could not insist more on the necessity of a global approach.

2 THE SOCIO-ECONOMIC IMPORTANCE OF WATER

Population growth estimates for the coming century are alarming. According to predictions, the number of inhabitants could reach 9 billion in 2050. And although space is sufficient for agriculture to feed this population, major question arise: how to guarantee drinking water and water for agriculture, when today 1 person in 5 does not have access to drinking water, and every day 10,000 children die of diarrhea caused by unclean water?

In arid regions, the traditional management of water often cemented society. The construction of infrastructures, the distribution of water, and the maintenance chores concerned everyone, and customary rights instilled rigorous management. Deep wells and pumps destabilized these societies. Water, traditionally a common good, has become a product of a central power, or a good reserved to those disposing of the financial means to have access to it. The problem becomes crucial for poor countries. In addition, in 1900, 90% of the population lived in rural areas, near water resources. In 2000, 50% of the population lives in cities, and it is probable that in 2100, 90% of the population will be in cities. And yet, in densely populated zones, where sewer systems do not exist or do not work well, the water is too polluted to be drinkable. The Nile delta is an example:

cities are encroaching on agricultural zones, people live in their own trash, and wash and cook in their sewers. Paradoxically, there is an explosion in bottled water consumption in the poorest countries.

A question is asked: is free water a right? If air remains free (some say, only because no one has invented a way to meter it!) the cost of water increases continually. In most Western countries, water is free, but its treatment and distribution must be paid for. Since public fountains are rare, one must therefore pay in order to have access to water. In France, the water budget for a family today represents approximately one month of a minimum wage salary. What is acceptable, given that the average revenue of French citizens, is not even reachable for the great majority of the planet's inhabitants. And yet, it will inevitably, given demographics and pollution problems, be necessary to launch vast projects to manage and exploit aquifers, to treat sewage, and to carry water, in order to ensure a water supply for poor countries. The use of deep aquifers, which are less sensitive with respect to pollution than surface aquifer, should be developed. But all of this has a cost, and many voices clamor to ask that free access to water be conserved for the poorest people.

3 THE STRATEGIC ROLE OF WATER AND THE RISK OF INTERNATIONAL CONFLICT

Aquifers do not care about borders. Great problems can arise from the unilateral exploitation of an aquifer, which impoverishes other countries dependent on the same aquifer by exhausting their springs and lowering the water table below the depth of wells. Great dams diverting water for irrigation can impoverish the aquifers downstream that relied on the river for their recharge. The conquest of water, or at least the conservation of existing rights to a resource can justify important conflicts. We have lived with the rhythm of wars over black gold for the last few decades; wars for blue gold are on the horizon.

3.1 Water history

3.1.1 Examples in Europe

a) Monaco

The Rock of the Principality of Monaco was, until the 19th century, furnished by rainfall with tanks enabling 6 month autonomy in case of siege, with an allowance of 3 L per person per day, but as the quality of life increased, demand increased considerably and the use of other resources became necessary. Thanks to the invention of steam pumps that could lift water, it became possible, in the 19th century, to provide running water from exploited springs, and then, as urbanization became more and more dense, local resources quickly became insufficient. And yet, despite the small extent of its territory, the Principality of Monaco, located at the convergence of several aquifers, possesses abundant groundwater resources, rendered unusable today by urban development. An adduction from France now satisfies around 3/4 of the demand, and the magnitude of this allochthonous inflow increases regularly, making the Principality dependent on its neighbor. As a result, the siege of Monaco by France in the 1960s, in order to prevent French citizens from owning an anonymous bank account in this tax haven, lasted only a few hours.

b) Malta

Malta's water supply is an interesting subject. La Valette was gravitationally exploiting a perched aquifer in the limestone at the top of the island, then this aquifer, fed by cultivated and inhabited zones with no sewer connections, became too contaminated to be drinkable. The lower aquifer, in the Globigerina-bearing limestone, separated from the upper aquifer by a screen of marl, was heavily drawn upon. But this aquifer is in contact with the sea, and irreversible saline intrusions soon appeared. Catchment systems were built with vertical wells descending to the roof of the aquifer with radial galleries enabling the capture of the upper fringe of the aquifer, in order to avoid the saline intrusions, but this setup is insufficient, and in many cases the intrusions could not be controlled. The emplacement of hillside dams intended to catch runoff and aid infiltration in the limestone allows only an inadequate recharge of the aquifer. Malta, which has one of the highest population densities (1,265 inhabitants per km^2) in the Mediterranean, must now desalinize sea water, but, in order to do so, it is totally dependent on its energy supply. Given the strong sunshine of the island, resorting to solar power is a possibility.

3.1.2 Examples in the Arab world

a) The drying of Iraq by its neighbors

The relationships between Turkey, Syria, and Iraq with respect to the water in the Tigris and the Euphrates are very tense. The Turkish GAP (Great

Anatolian Project) aims to irrigate gigantic surfaces in Anatolia with water from the Euphrates, depriving Syria of part of its water resources. Several pharaonic projects, including the Keban and Ataturk dams, considerably alter the hydrology and hydrogeology of these areas (Figure 142). A convention was signed between the two countries, but the Syrians accuse Turkey of not respecting it. Downstream, the Syrian Tabka dam in turn deprives Iraq of a large inflow. Similarly, Turkish dams on the Tigris are very detrimental to Iraq.

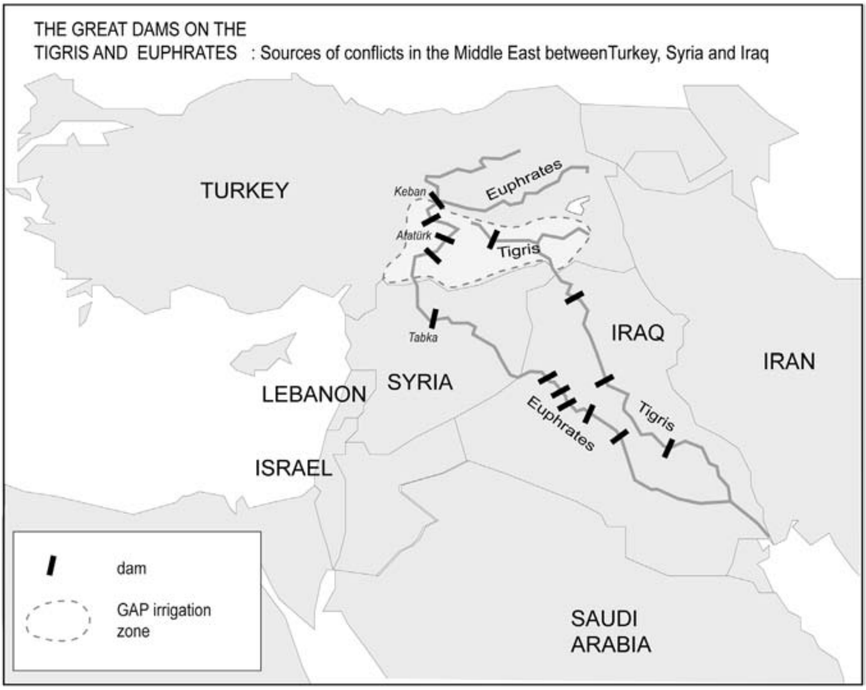

Figure 142 Major dams in the Near East, which are sources of conflict.

b) The Israeli-Palestinian conflict

Tension in the Near East is in large part due to water problems (Figure 143). In Israel, the coastal aquifer is overexploited and the water supply of irrigation systems depends on surface water from the Jordan river and on the West Bank aquifer, where the pumping stations of the Israeli colonies represent 90% of the water extracted from the resource. If a free Palestine were to exploit its aquifers, it would deprive Israel of part of its water resources. The construction of the barrier in the West Bank is probably intended to protect numerous pumping stations. The 1967 conquest of

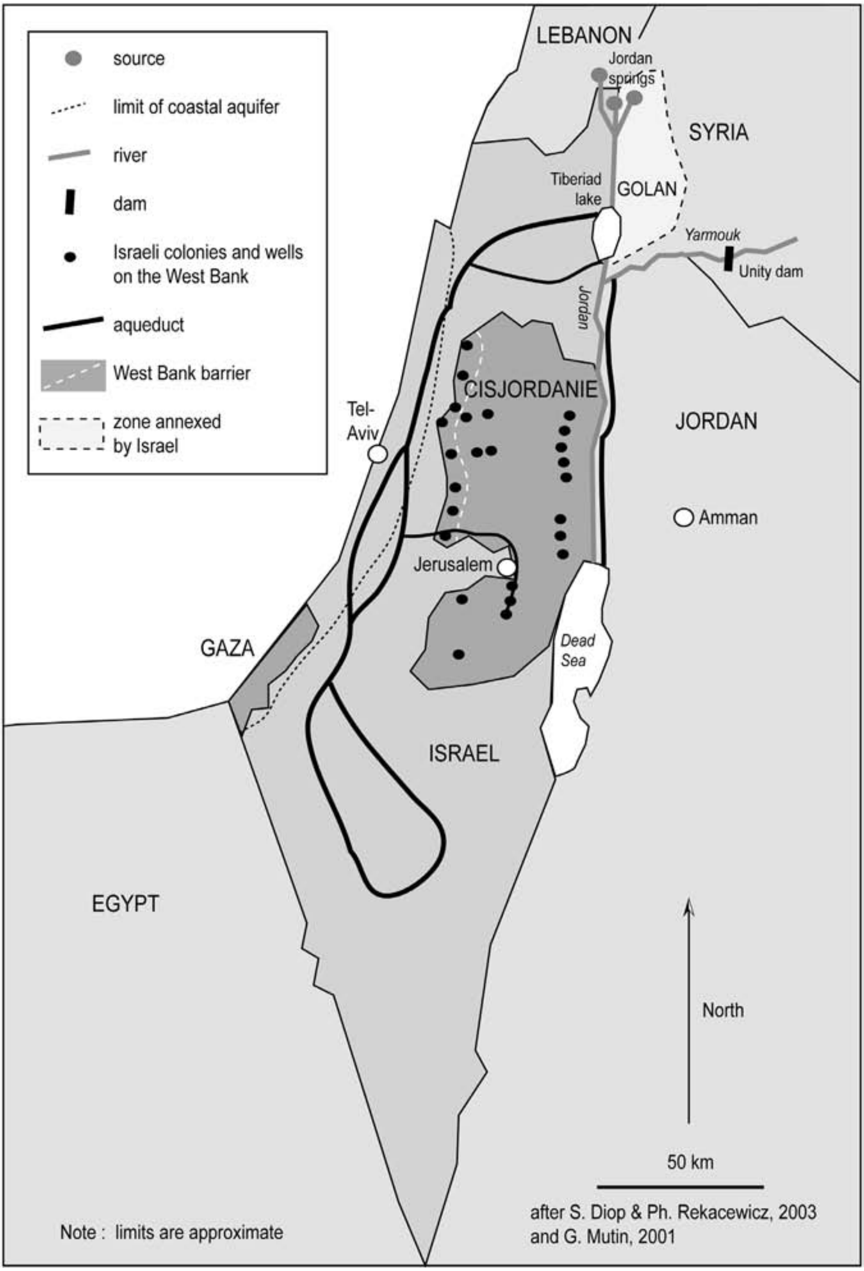

Figure 143 The protection of water resources in Israel.

the Golan plateau, annexed in 1981, allowed Israel to protect the Jordan's springs and to prevent the diversion of its waters into Syria.

c) The Great Man-Made River

Libya now draws on the Saharan fossil aquifer. The GMR project: Great Man-Made River, with a total budget of around 30 billion euros, includes hundreds of boreholes in catchment fields, extracting water from the aquifer in order to direct it, through great subterranean aqueducts, towards Tripoli and the coastal regions (Figure 144). At the end of construction, probably not before 2015 due to the actual problems in Libya, the annual discharge should be of 6.5 billion m^3 per day. The reserves are hoped to last for around 50 years. The impact on the surrounding countries, already handicapped by drought, is unknown. What will the position of the neighboring countries be once the first effects are felt?

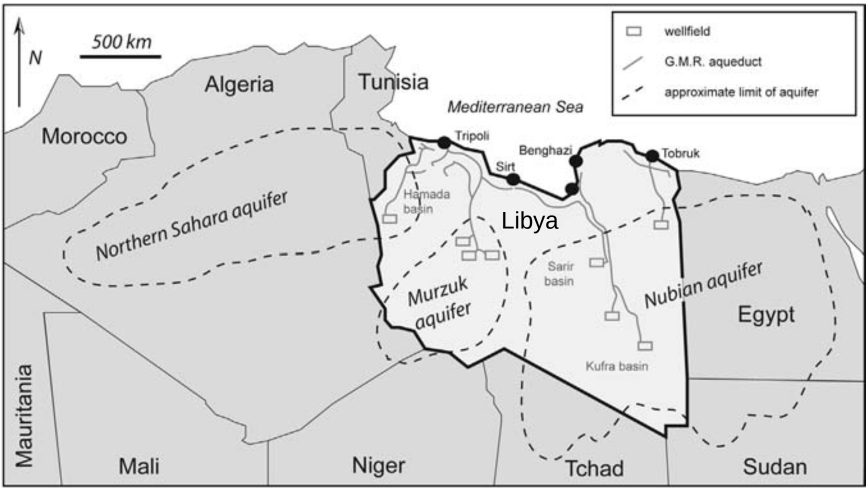

Figure 144 The Great Man-Made River in Libya and its relationship with the neighboring countries.

Three basins are being exploited:

- to the west: The North Sahara Basin is touched upon by Libya, Tunisia, and Algeria. A regional cooperation association was created: The Sahel Observatory, in order to enable exploitation while respecting the interests of the three countries. The annually extracted discharge is estimated to be 600 million m^3 for Tunisia, 400 million m^3 for Libya, and 1.5 billion m^3 for Algeria. The water is drawn from the interbedded Continental aquifer (Albian sandstone);

- in the center: the Murzuk basin (aquifer in the Triassic-Jurassic and Lower Cretaceous continental formations) is essentially contained within Libya;
- to the south and to the east: the Nubian aquifer (Cambrian and Upper Cretaceous sandstone, sand, and conglomerate) is one of the largest artesian aquifers in the world (2 million km^2). It is shared between Egypt, Libya, Sudan, and Chad.

Egypt has clearly expressed its fears, and has threatened Libya with retaliation, if it observes a decrease in its deep resources in the Nubian Sandstone aquifer.

4 WATER AND SUSTAINABLE DEVELOPMENT

It is possible to sustainably impact an aquifer on the qualitative and quantitative levels. The migration of pollutants within the aquifer and the renewal of resources can last for decades. In addition, the overexploitation of an aquifer can have consequences on its natural environment, by drying the soil and destroying the vegetation, or by provoking cave-ins in the terrain (see chap. D2-3.3).

4.1 Quantitative aspect

The problem of drawing upon non-renewable deep resources has been mentioned above. The overexploitation of Saharian aquifers is happening to the detriment of future generations, who will have no other solution than to abandon those areas. In France, M. Detay (1997) cites the example of the overexploitation, since over a hundred years, of the confined Lower Triassic sandstone Lorraine aquifer, which is only weakly recharged, leading to a continuous decrease in the piezometric level affecting the entire Lorraine basin and reaching 72 m in Nancy.

4.2 Qualitative aspect

4.2.1 Saline intrusions

In coastal or island regions, the overexploitation of coastal aquifers can lead to a permanent migration of the salt water intrusion. The case of Malta was described above.

Saline intrusions are difficult to control, and a return to initial condition through the stoppage or reduction of pumping is not always possible.

4.2.2 Nitrates

The water of the Brittany and Normandy aquifers in western France does not currently meet potability standards, due to an elevated nitrate concentration tied to agriculture and particularly to the spreading of liquid hog manure (see chap. C3.5). In the absence of new contamination, it is estimated that it would take 30 years to return to initial conditions. In addition, given the slow kinetics of migration below ground, the nitrate pollution front has not yet reached aquifers everywhere.

4.2.3 Pesticides

The behavior of pesticides below ground remains poorly understood, despite numerous studies, and the long term contamination risks are high. In addition, the problem of identification arises, as new products are regularly offered by manufacturers.

4.2.4 Recent or unknown pollutants

Sanitation studies have revealed the existence of new types of pollutants with the potential for serious consequences in terms of public health: antibiotics and hormones, widely used in human and animal medicine. They are passed into water by urine, they degrade very slowly, and their concentrations are constantly increasing.

Finally, it is important to keep in mind that only what is looked for can be analyzed and measured, and there are therefore very probably substances in the water that have not yet been recognized at noxious, and which are therefore not looked for during analysis.

5 THE HYDROGEOLOGIST OF THE FUTURE: CARETAKER OF GROUNDWATER

The 19th century saw the birth of modern hydrogeology, concerned with the problems encountered in digging wells in porous aquifers. During the 20th century, immense progress was made in the understanding of aquifers and in groundwater study and exploitation methods. At the dawn of the 21st century, the challenge of providing good quality water to an exploding world population is giving rise to new problems, which extend far beyond the physical setting of the aquifer. The concept of management is being imposed on an aquifer, basin, country, or even portion of continent (in the case of the Saharan zone) scale. Humans are moving from water-gathering to water cultivation. The hydrogeologist is transforming from an aquifer specialist into a caretaker of groundwater. Faced with qualitative and quantitative problems, in societies where demand, mindsets, and regulations are constantly evolving, the hydrogeologist must rapidly adapt. In order to do so, he or she can rely on the mathematical, computational, physico-chemical, geological, biological, and technological tools of this era. But each domain is also a specialization, and as in medicine, specialization to an extreme poses the risk of inducing errors in judgement. A global and pluri-disciplinary approach becomes a necessity. The highly capable hydrogeologist in a particular narrow field must nevertheless be able to appreciate and understand, at least in part, the whole problems to which he or she is confronted, including social and political problems that will shape his or her actions. The hydrogeologist can then call on the appropriate experts to refine his or her work.

We have attempted, in this book, to offer a very large vision of hydrogeology, and the reader will understand that each topic addressed is worthy of an entire volume.

Annexure

Annex 1

Directive 2006/118/CE of the European Parliament and of the Council.

Directive 2006/118/CE of the European Parliament and Council has to do with the protection of groundwater against pollution and deterioration.

Groundwater is considered to be a precious natural resource for the production of drinking water (it is the EU's principal water resource) and for the ecosystems it is in relationship with. Due to its sensitivity, it must be protected in order to avoid its deterioration in quality and thereby reduce the degree of treatment necessary in order to make it potable. This protection applies to its current and future uses.

One of the goals of the 6th community action program for the Environment is to cause neither impacts nor significant risks for human and environmental health.

In order to accomplish this goal, the concentration of harmful pollutants (concept of dangerous substances) in groundwater must be avoided, prevented, or limited, by establishing evaluation criteria for the chemical state of water (norms and threshold values), the evaluation of increasing trends, and the determination of the starting points of trend reversals. These trends will be determined by statistical procedures standardized at the international level, in order to enable comparisons between results.

Quality standards are important in order to evaluate the state of groundwater masses, particularly in terms of nitrates, pesticides, and biocides.

Adherence to standards requires reliable and comparable (standardized) analysis and monitoring methods.

In the Common Agricultural Policy, financial measures are provided for adherence to standards.

The measures do not concern high concentrations of naturally present substances, or temporary changes (brief and limited) in the flux of water.

An analysis of the environmental and socio-economic impact of the threshold values is desirable. Research (and distribution of the resulting information) on the definition of criteria to guarantee quality will be encouraged and financed.

A water body is considered to be in a good chemical state when:

- the directive conditions are met;
- the directive conditions are not met, but;
  - the concentrations are not considered to present a risk, due for example to the size of the reservoir;
  - the capacity of the water body to satisfy human use has not been compromised.

Control sites must provide a global and coherent image of quality, as well as representative data, which the member states will publish a summary of.

Trends

The identification of significant long-term trends that are increasing will prompt actions to reduce pollution. The starting point of an increasing trend must be specified.

Complementary evaluations will verify that the plume originating from a contaminated site is not spreading, is not degrading the chemical quality of the water, and will verify that the resource does not constitute an environmental and health risk. The results of these evaluations will be summarized in management plans.

Dangers

In order to reach the goal of preventing and limiting the introduction of pollutants, member states will be required to specify in which cases substances are dangerous or not, and to take into account diffuse pollution. Introduction of pollution by direct discharge or authorized recharge, concentrations with no present or future risk, and the consequences of accidents or natural disasters can be excluded from these programs.

Future

From 2009 to 2013, any new authorization procedure must take the directive into account. The list of substances may be amended by the addition of new pollutants.

Annex I: Quality standards

The limit for nitrates is 50 $mg \cdot L^{-1}$. For pesticides, it is 0.1 $\mu g \cdot L^{-1}$ for each molecule or metabolite, the sum not exceeding 0.5 $\mu g \cdot L^{-1}$.

If the environmental goals cannot be reached, or if significant damages can appear in the ecosystems in relationship with the contaminated groundwater reservoir, stricter threshold values may be used.

Annex II: Threshold values

The thresholds are fixed so as to take into account the contiguous ecosystem—groundwater interaction, the impediments to (even future) use of the reservoir, the reference concentrations (natural background noise), and the hydrologic budget. In addition, the origin of pollutants, their toxicology, their dispersion profile, their persistence, and their bioaccumulation potential will be used.

The fixing of thresholds should be based on controls of the collected data, based on the quality of the data, the analytic capabilities, and the level of background noise.

A minimal initial list of substances needing a defined threshold value includes: arsenic, cadmium, lead, mercury, ammonium, chlorides, sulfates, trichloroethylene and tetrachlorethylene. Conductivity indicates salt water intrusions.

Member states must communicate the number of at-risk groundwater reservoirs, as well as the pollutants and pollution indicators contributing to this classification, with their concentrations, the size of the reservoirs, their relationship with surface water, as well as the geochemical background noise, and the threshold values. The relationship between the threshold values and the background noise, the environmental quality goals and other protection standards, toxicologic and ecotoxicologic information, data on persistence, the potential for bioaccumulation, and the dispersion profiles of the pollutants must also be detailed.

Annex III: Evaluation of the chemical state of groundwater

For any at-risk reservoir and for each identified pollutant, member states will use the collected information, comparing the annual arithmetic mean of the concentration with the threshold value. An estimation of the extent of the zone above the threshold value or the standard is then desired.

Annex IV: Identification of trend reversals with significant long-term increases

It is based on the adequate frequency and number of points being monitored in order to:

- differentiate these trends from natural variations;

- provide enough time to put in place prevention or attenuation measures. An initial identification exercise will be undertaken in 2009, and renewed at most every 6 years;
- take into account the temporal characteristics of the aquifer (flow, infiltration).

The data, conforming to international monitoring principles, must be of scientific quality and of equivalent comparability. Regression type statistical methods will be used for specific monitoring points. The identification of trends will also rely on archive data, predating the monitoring system.

The beginning of a trend reversal will be considered to be the point at which the concentration is greater than 75% of the standard value, except in the case where an earlier or later starting point is necessary in order to limit the economic cost of the degradation. A starting point for a trend reversal will be valid for the entire subsequent 6-year period.

PROBLEMS

Problem #1—Recharge elevation for water circulating in a landslide

The La Clapière landslide, in the Mercantour range, has springs at its base. The main problem concerning the hillside aquifer feeding these springs is the determination of its recharge area. With this goal in mind, two water sampling efforts enabled the sampling of springs with an easily identifiable catchment area (Table 1 and Figure 1), in order to draw an oxygen-18/altitude nomogram, and then determine the average recharge elevation of the springs at the base of the landslide, for which the catchment area is unknown.

Table 1 delta ^{18}0 for different springs.

Reference Point	Recharge elevation (m)	$\delta^{18}O$	
		1st sampling	2nd sampling
1	2,718	–12.16	–
2	2,371	–11.80	–
3	2,024	–11.83	–11.73
5	1,735	–11.53	–11.59
6	1,707	–11.55	–11.40
17°	1,089	–9.82	–
18°	1,355	–	–10.92
19°	1,307	–	–10.76
°off the map			
Point	**Elevation of the point (m)**	**$\delta^{18}O$**	
		1st sampling	**2nd sampling**
11	1,212	–11.02	–11.35
12	1,249	–11.37	–
14	1,105	–10.98	–10.86
15	1,110	–10.75	–10.84
16	1,128	–	–10.75

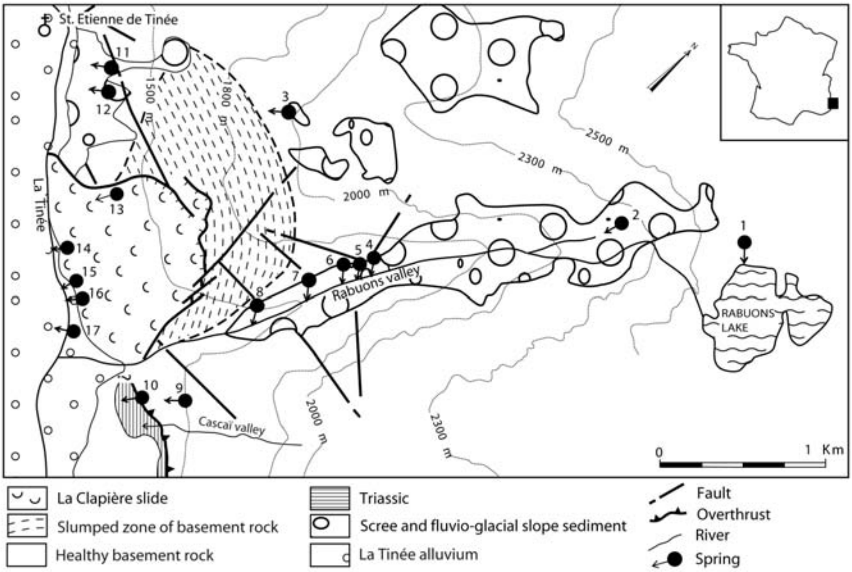

Figure 1 simplified context map of the La Clapière slide.

Question 1: Draw the nomogram of the oxygen-18 gradient as a function of elevation.

Question 2: Determine the average recharge elevation of springs 12 and 14.

Question 3: What can you conclude from this result?

Answer 1:

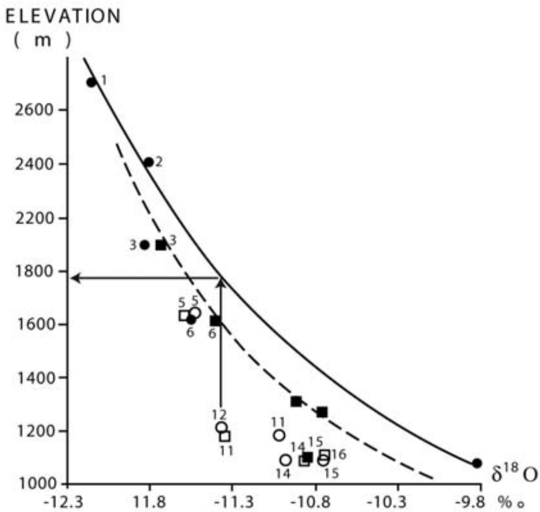

Figure 2 Nomogram of the oxygen-18 gradient as a function of elevation.

Answer 2: The average recharge elevation of spring #12 is on the order of 1,800 m, that of spring #14 around 1,400 m.

Answer 3: Conclusion: the entire slope feeds the aquifer; the gradual infiltration as snow melts creates an entry signal that varies in space: it rises from the landslide area to the Mercantour peaks as a function of time. In a hydrodynamic model of the hillside aquifer, this signal would have to be located as a function of time.

Problem #2—Hydrologic budget

In a hydrosystem fed only by precipitation, the conservative ion concentration can quantify their reconcentration through evaporation. This global input-output approach presents the advantage of requiring no hypotheses with respect to soil moisture, or the field capacity. However, the ion selected must be conservative, and must originate solely from precipitation (not from the geologic context or from anthropogenic inputs). This method uses the flux conservation equation:

$C_p \cdot P = C_s \cdot ER$

C_p & C_s: concentration in the rain and at the exit (the spring),

P & ER: precipitation and effective rainfall.

This flux conservation equation enables the calculation of:

- the recharge coefficient $R_c = ER/P = C_p/C_s$
- the effective rainfall $ER = P \cdot C_p/C_s$
- actual evapotranspiration $AET = P\,(1 - C_p/C_s)$

Question: Apply this method to the calculation of the budget for flow from a stalactite in the Nerja cave (Andalusia, Spain, after Liñán *et al.*, 1999), by completing the table below (Table 2), the average annual rainfall being 490 mm.

Answer:

Table 2 budget for flow from a stalactite in the Nerja cave (to be completed).

	Average concentration (raw data) (mg L^{-1})	**height of rainfall/ stalactite discharge (mm/cm^3 j^{-1})**	**Average weighted concentration (mg L^{-1})**
C_p: Cl^- rain	8.20	764.3	
C_s: Cl^- stalactite	30.18	5256.8	

	(raw data)	(weighted by precipitation/discharge)	
$R_c = C_p/C_s$			
$ER = P \cdot R_c$	_mm	_mm	
$AET = P \cdot (1 - R_c)$	_mm	_mm	

Table 3 budget for flow from a stalactite in the Nerja cave.

	Average weighted concentration (mg·L^{-1})	
C_p: Cl^- rain	7.85	
C_s: Cl^- stalactite	21.05	

	(raw data)	**(weighted by precipitation/discharge)**
$R_c = C_p/C_s$	0.35	0.37
$ER = P \cdot R_c$	171 mm	183 mm
$AET = P \cdot (1 - R_c)$	318 mm	307 mm

Problem #3—Exchanges between components of flow

The Fourbanne karst system (Charmoille, 2005) includes the Verne and Luxiol swallow holes, diffuse infiltration, and the passageways of the Fontenotte cave, which plunge into the saturated zone and lead to the Fourbanne karst spring (Figure 3). The water's path was traced using fluorescein at the Verne loss, and then sampled in Verne, Fontenotte, and Fourbanne. The magnesium and nitrate concentrations of the traced mass appear on Figure 3.

Question: How can you interpret the differences between these three monitoring points?

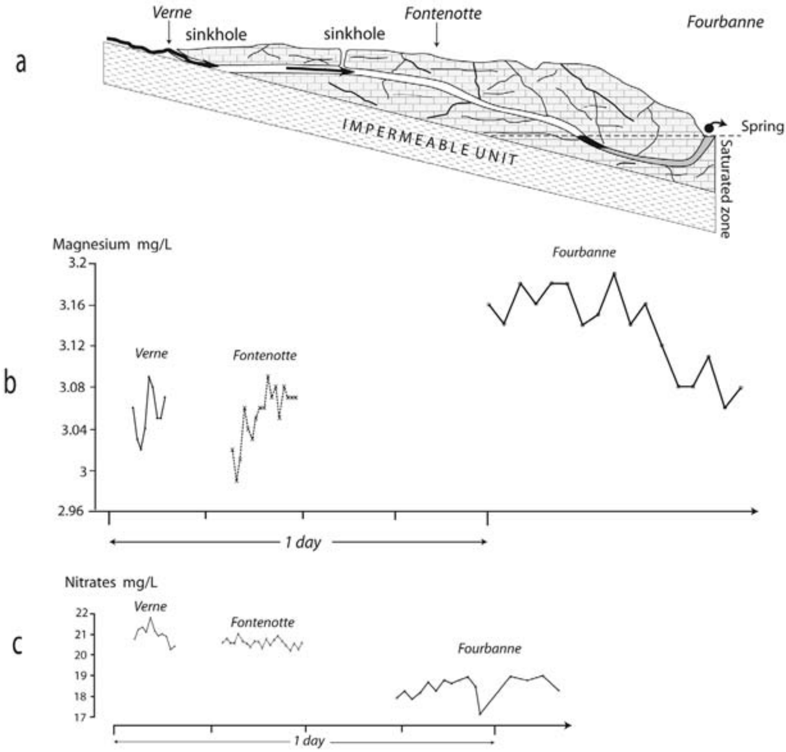

Figure 3 a) Cross-section of the Fourbanne system. b) Magnesium concentrations. c) Nitrate concentrations.

Answer: Verne and Fontenotte show the same concentrations for both ions, showing the absence of mixing of other water with the water from the swallow holes (pinpoint infiltration), between the swallow holes and the underground river. At the Fourbanne spring, on the other hand, this localized infiltrated water is mixed with water of different composition (diffuse infiltration and/or saturated zone), with a higher magnesium concentration (longer residence time in the same limestone) (Figure 3b) and a lower nitrate concentration (less influenced by leaching from agricultural land) (Figure 3c).

Problem #4—Piezometry of an aquifer

The Pontarlier alluvial plain aquifer sits in the superficial portion of a heterogeneous fluvio-glacial evacuation cone (Gaubi, 1993).

Several boreholes and piezometers (Figure 4) enable the measurement of the water table head. During a low water survey, the measured elevations a.s.l. are those of Table 4:

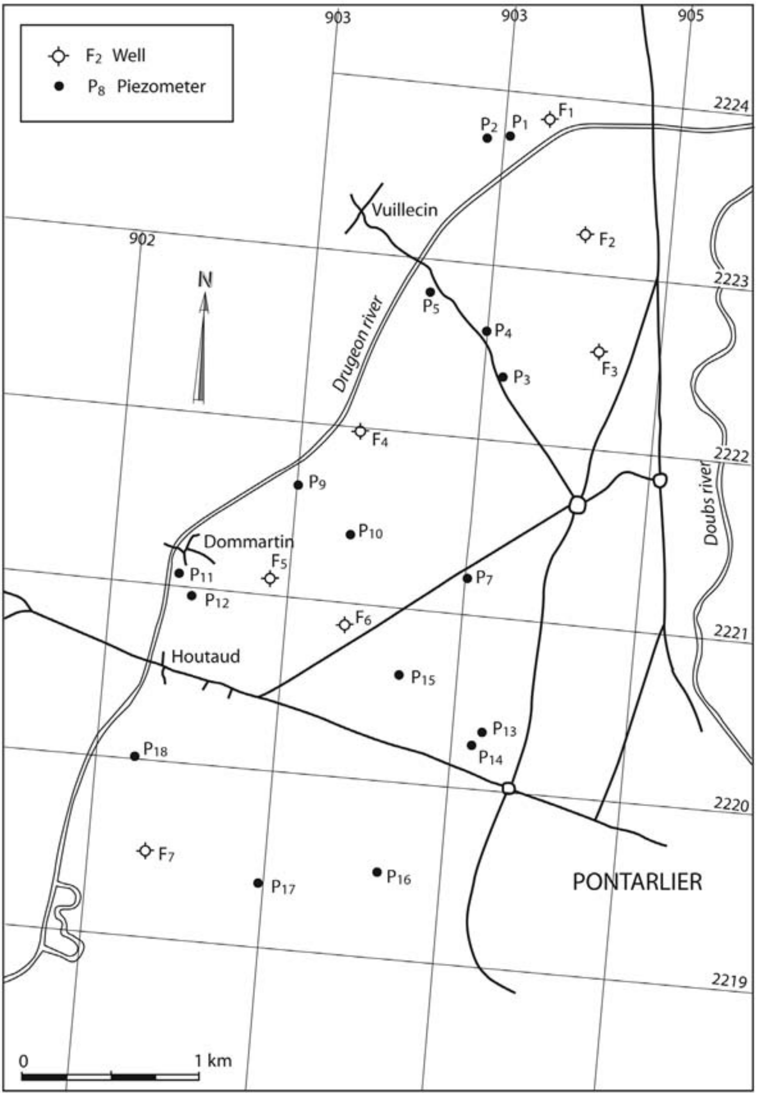

Figure 4 Map of borehole and piezometer locations in the Pontarlier plain.

Table 4 Piezometric data (elevation a. s. l.).

F1	802.87	F2	802.80	F3	804.43	F4	804.74	F5	806.35	F6	807.12
F7	808.26	P1	802.94	P2	803.01	P3	804.08	P4	804.05	P5	803.87
P7	805.74	P9	804.97	P10	805.53	P11	805.60	P12	805.77	P13	806.70
P14	806.70	P15	807.53	P16	809.40	P17	808.83	P18	807.57		

Question 1: Draw the corresponding piezometric map.
Question 2: What principal characteristics are revealed?
Question 3: Give a few values for the hydraulic gradient.

Answer 1:

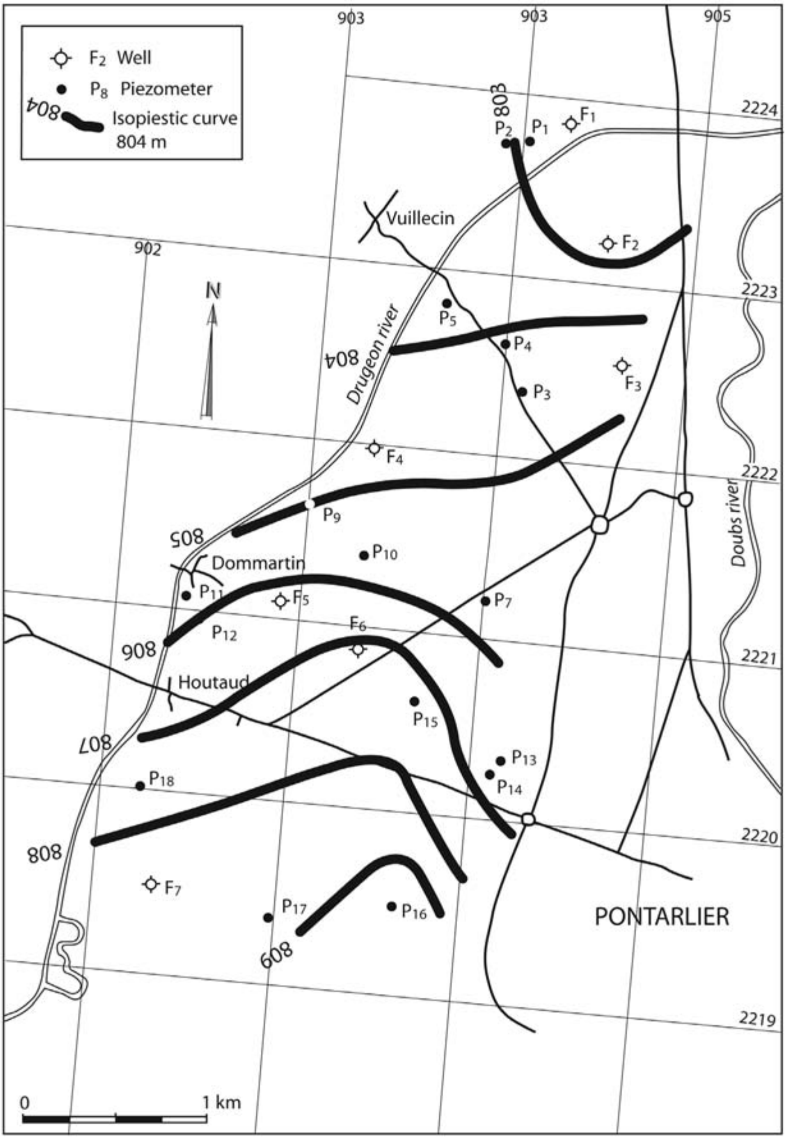

Figure 5 Piezometric map of the Pontarlier alluvial plain aquifer.

Answer 2: Between Pontarlier and Houtaud, the aquifer diverges; it is supplied from the south. Between Houtaud and Vuillecin, the Drugeon drains the aquifer. The Pont Rouge gravel quarry drains the downstream portion of the aquifer.

Answer 3:

- headward (south of Houtaud), the gradient is: 2/1250 = 0.0016, or 1.6 $m \cdot km^{-1}$ or 1.6‰;
- in the center (south of Dammartin): 2/750 = 0.0027 or 2.7 $m \cdot km^{-1}$ or 2.7‰;
- to the north (east of Vuillecin): 2/1350 = 0.0015 or 1.5 $m \cdot km^{-1}$ or 1.5‰.

Problem #5—Mixing in an alluvial aquifer (Durance, from Lacroix, 1991)

As in any alluvial aquifer, the shallow Lower Durance aquifer is fed both by the river and by the hillside aquifers. From an isotopic point of view, the river is characterized by its low oxygen-18 concentrations, tied to the middle alpine zone elevation of the drainage basin. This negatively marked water arrives in the aquifer, either at the level of the Durance minor bed, or below plots irrigated with river water. The local rainfall (on the plain and the neighboring hills) is more enriched in oxygen-18 (Mediterranean climate and low elevation).

Various sampling locations provided the following oxygen-18 values over the course of a summertime survey (Table 5):

Table 5 Oxygen-18 tracing in surface water and groundwater.

Location	Type	delta	Location	Type	delta
Sénas	Durance	–10.90	Pey FOR	aquifer	–10.25
Orgon	Durance	–10.80	Puyv P 12	aquifer	–9.35
Jou P 111	hillside	–8.00	Mal F 14	aquifer	–8.20
Mey P 101	hillside	–6.95	Sen P 20	aquifer	–10.00
Repa SE 4	hillside	–7.50	Sen F 14	aquifer	–8.40
Mal FE	hillside	–7.15	Mer P 2	aquifer	–8.75
Mer F0	hillside	–6.95	Nov	aquifer	–10.40
Che ROQ	hillside	–6.35	Gre STP	aquifer	–8.75
Pla JF	hillside	–7.00	Cav TAP	aquifer	–8.90

Question 1: How can the proportions of water originating from the Durance and from irrigation be determined?

Question 2: What are the results of the above calculation?

Question 3: What phenomena can be sources of error in this calculation?

Answer 1:

Considering an average signal from the Durance (average of the measurements) D = –10.85‰ and from local recharge L = –7.13‰, we can then consider that the water in the aquifer is a perfect mixture of only these two poles.

The percentage X of water from the Durance is then given by a flux conservation equation (N: concentration in the aquifer; D: concentration in the Durance; L: concentration in local aquifers)

$N \cdot 100 = [D \cdot x] + [L \cdot (100 - X)]$, or

$X = [N - L]/[D - L]$

Answer 2:

Table 6 proportions of water originating from the Durance and from irrigation.

Location	Type	X Durance	100-X Local
Pey FOR	aquifer	84%	16%
Puyv P 12	aquifer	60%	40%
Mal F 14	aquifer	29%	71%
Sen P 20	aquifer	77%	23%
Sen F 14	aquifer	34%	66%
Mer P 2	aquifer	44%	56%
Nov	aquifer	88%	12%
Gre STP	aquifer	45%	55%
Cav TAP	aquifer	48%	52%

Answer 3:

Irrigation leads to evaporation conditions that can enrich infiltrated water, and therefore causes an underestimation of the inflow from the Durance.

The simultaneous extraction of well water and surface water is legal only in the case of highly transmissive aquifers, in which the water in the aquifer is from the same season as that in the river.

This evaluation is possible only if there are no other components in the hydrosystem (discharge from deep aquifers).

The calculation is valid only if the aquifer is well-homogenized. In the case of a poor mix (channeling of flow), the calculation will be off.

Problem #6—Aquifer discharge

Figure 6 (after Lacroix, 1991) shows the piezometry of the Lower Durance aquifer. This representation reveals limits to the incoming flux.

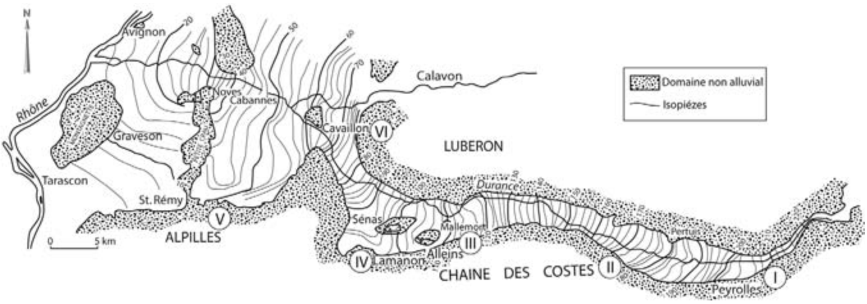

Figure 6 Piezometry of the Lower Durance aquifer.

Question: What is the discharge through the cross-sections I to VI?

Table 7 Hydrodynamic and geometric data for the Lower Durance aquifer (to be completed).

Location	Permeability	width of section	saturated thickness	saturated cross-section	hydraulic gradient	discharge
	$m \cdot s^{-1}$	m	m	m^2	$m \cdot m^{-1}$	$m^3 \cdot s^{-1}$
I Jouques	$1 \cdot 10^{-2}$	500	4		1/120	
II St Estève-Janson	$2 \cdot 10^{-2}$	600	1		1/200	
III Mallemort	$5 \cdot 10^{-3}$	1,500	2		1/600	
IV Sud Sénas	$4 \cdot 10^{-3}$	3,500	2		1/500	
V Nord Alpilles	$3 \cdot 10^{-3}$	19,000	1		1/100	
VI Ouest Lubéron	$1 \cdot 10^{-2}$	10,000	7		1/1500	

Answer:

Based on the piezometric map, the hydrodynamic data (permeability), and a few geometric parameters, one can estimate the discharge of aquifers by applying Darcy's Law: $Q = K \cdot S \cdot i$

Where: Q is discharge in $m^3 \cdot s^{-1}$; K is permeability in $m^3 \cdot s^{-1}$; S is the saturated cross-section in m^2; i is the hydraulic gradient in $m \cdot m^{-1}$.

Table 8 Hydrodynamic and geometric data for the Lower Durance aquifer.

Location	Permeability	width of section	saturated thickness	saturated cross-section	hydraulic gradient	discharge
	$m \cdot s^{-1}$	m	m	m^2	$m \cdot m^{-1}$	$m^3 \cdot s^{-1}$
Jouques	$1 \cdot 10^{-2}$	500	4	4,000	1/120	0.067
St Estève-Janson	$2 \cdot 10^{-2}$	600	1	600	1/200	0.060
Mallemort	$5 \cdot 10^{-3}$	1,500	2	3,000	1/600	0.025
Sud Sénas	$4 \cdot 10^{-3}$	3,500	2	7,000	1/500	0.056
Nord Alpilles	$3 \cdot 10^{-3}$	19,000	1	19,000	1/100	0.570
Ouest Lubéron	$1 \cdot 10^{-2}$	10,000	7	70,000	1/1500	0.467

Problem #7—Irrigation, piezometry, and water quality (after Blavoux & Lacroix, 1991)

Figure 7 shows the seasonal piezometric variation of two boreholes in the Lower Durance aquifer (Plan d'Orgon and Eyragues).

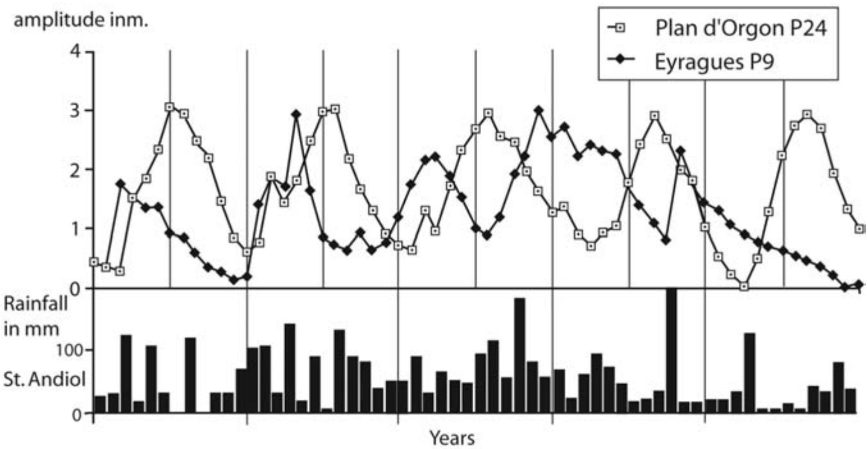

Figure 7 Hydrologic cycles and piezometry in boreholes in the Durance aquifer.

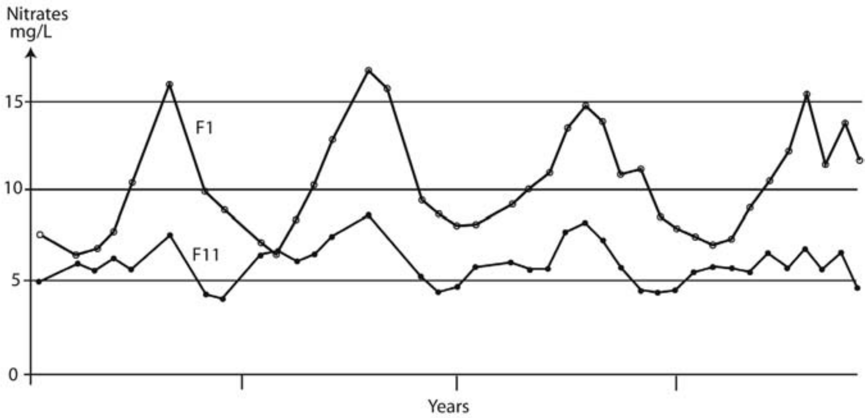

Figure 8 Hydrologic cycles and nitrate concentrations in boreholes in the Durance aquifer (Mudry, 1988).

Figure 8 (after Mudry, 1988) shows the nitrate concentrations of 2 boreholes in the Saignonne catchment field in Avignon, in the Lower Durance aquifer (F1 located 800 m from the Durance and F11 located 560 m from the river).

Question 1: How does the piezometry react to the aquifer being under irrigation?

Question 2: What mechanisms reveal the monitoring of the nitrate concentrations?

Answer 1:

The Eyragues piezometer, which experiences only local recharge (natural regime), shows piezometric maxima centered on periods of rainfall. The piezometry at Plan d'Orgon is more regular and is high from May to September, due to the recharge of the aquifer by part of the water used for irrigation.

Answer 2:

The F11 borehole, closer to the Durance, shows a seasonal sinusoidal signal with a principal peak in the summer (8 $mg \cdot L^{-1}$), and a secondary peak in the winter (6 $mg \cdot L^{-1}$). The minimum, of 4 $mg \cdot L^{-1}$ is observed in the fall. The F1 borehole, further from the river, shows a seasonal sinusoidal signal with a more marked principal peak in the summer (16 $mg \cdot L^{-1}$), but no secondary peak. The minimum of $mg \cdot L^{-1}$ is observed in the fall.

The small peak in the F11 borehole corresponds to the leaching of nitrates in the soil by natural precipitation; the large F11 peak and the single F1 peak to leaching by irrigation water returning to the aquifer. The natural peak is invisible on the F1, which has a higher level of background noise than the peak.

The concentration gradient observed on the catchment field can be explained by the dilution of the water circulating below irrigated plots by less charged water from the river.

Problem #8—Tracer tests

In the Chalk of the Pays de Caux (Lacroix *et al.*, 2000), a tracer test was done in the Bébec swallow hole. The Norville spring, located 4 km away as the crow flies, enabled the monitoring of the restitution of the upper curve in Figure 8: peak at 130 $\mu g \cdot L^{-1}$, 2 days after injection. A nearby well, drilled into 18 m of Seine alluvium resting on 15 m of chalk, gave the lower restitution curve, with a peak of 10 $\mu g \cdot L^{-1}$, 2 and a half days after injection.

Question 1: What conclusions can you draw from these results on the functioning of the environment?

Question 2: What conclusions can you draw on the vulnerability of the two catchment points?

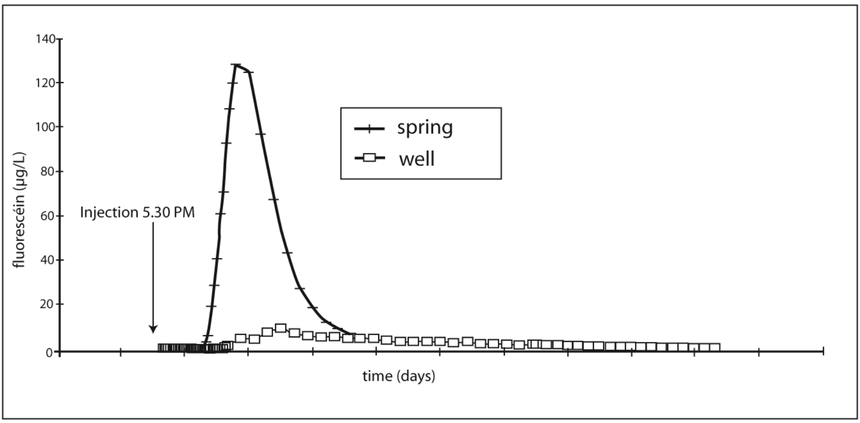

Figure 9 Restitution curves for the tracer test from the Bébec swallow hole to the resurgence point and to the Norville well (from Lacroix *et al*., 2000).

Answer 1: In a karst environment, a spring is the final converge point for subterranean drainages. The spring enables the rapid and concentrated transfer of the water disappearing into the losses. The well, however, which was not drilled into a drain emerging at the spring, receives only a limited inflow from the Bébec swallow hole. Water from the Seine aquifer dilutes these influxes from the fissured chalk.

Answer 2: The velocity of circulation in the karst leading to the spring and to the Norville well (80 and 70 m·h^{-1}, respectively) are of the same order of magnitude, but the factor of 13 observed between the concentrations can be explained by dilution by water from the Seine alluvial aquifer. The spring is therefore very vulnerable at the concentrated Bébec swallow hole, while the well, presenting a lesser vulnerability to these karst waters, is nevertheless very vulnerable to the influx from the alluvial aquifer.

Problem #9—Inquiry into the origin of fractures affecting an individual residence

Residence A has been affected for the past two years by the appearance of fissures on its southern face (Figure 10). It is suspected that the construction of residence B, a few years before, may be the cause of these problems.

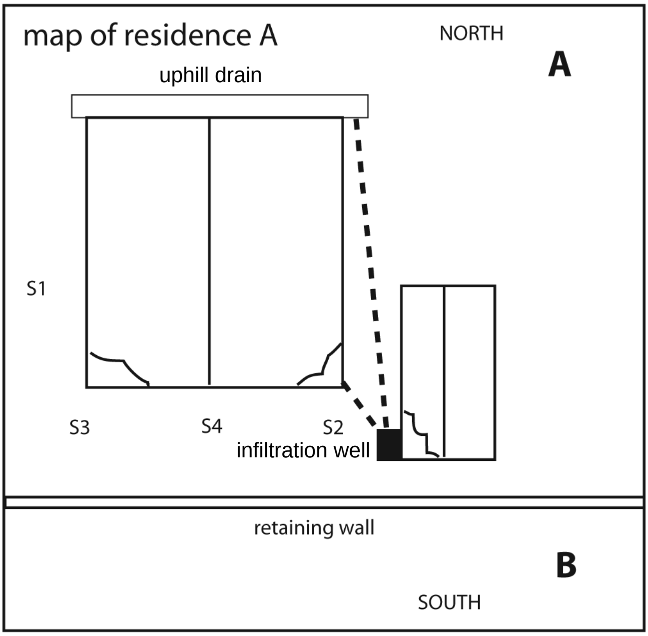

Figure 10 Map of residence A with the location of the fissures and of the boreholes.

A survey was undertaken of the area around residence A, with the help of a penetrometer (soil engineering apparatus measuring the resistance of the soil: a weight strikes a vertical rod equipped with a calibrated point, and the number of strikes needed per unit of length to sink the rod is counted). This investigation gave the following results (see table):

Table 9 Results of the penetrometer survey.

Depth in cm	0–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180
S1	1	1	9	45	60 no passage				
S2	1	1	2	10	24	20	42	72	120 no passage
S3	1	1	2	19	70	89	92		
S4	2	3	1	3	24	36	98		

The geologist then studied the area and made the following observations (Figure 11).

The two residences are built on andesite. Residence A is old, with superficial foundations. It rests on an andesite weathering mantle. Uphill, the residence is protected by a drain, directing groundwater towards an old infiltration well. This well also collects part of the water drained from the rooftops.

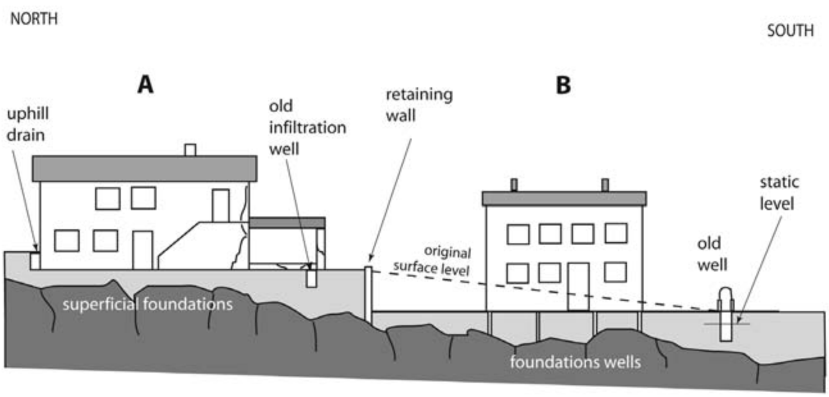

Figure 11 Schematic cross-section of the two residences.

Residence B is founded on piles driven into the andesitic bedrock. Downhill, an old well contains water. The construction required the creation of a 2 m talus along the property line. This talus was reinforced with a concrete wall described in Figure 12.

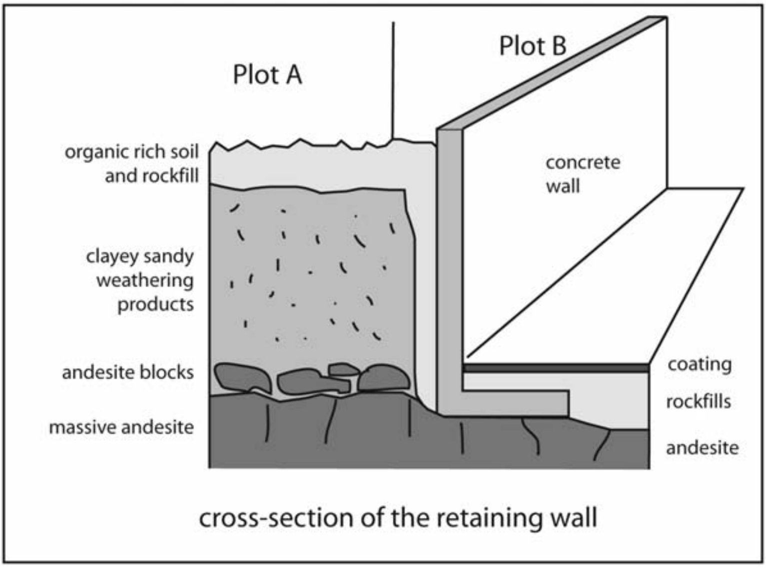

Figure 12 Detailed diagram of the separating wall between the two residences.

Question 1: Based on this data, what can be deduced on the origin of the disorders?

Question 2: What can be proposed to remedy the situation?

Answer 1: The penetrometer results show that the soil is disorganized in S3, S4, and particularly S2, below the superficial foundations of residence A. There is no doubt as to the role of the well, and yet the problems appeared only recently. The existence of an old well downhill indicates the presence of a superficial aquifer. The surface weathering products of the andesite, when the clayey matrix is minimal, are highly permeable and can, indeed, become saturated with water.

The examination of the retaining wall cross-section shows that this wall has neither drainage channels, nor uphill drainages. It therefore plays the role of a hydraulic barrier. The water infiltrated on plot A can no longer flow down to feed the aquifer under plot B. They therefore accumulate behind the retaining wall. Their oscillations, by causing, over several years, the hydrolysis of the material and a redistribution of fine particles, disorganized the soil below the foundations of residence A.

The observed problems therefore have a hydrogeologic origin.

Answer 2: It will be necessary to revisit the water collection system on plot A, and to equip the retaining wall with drainage channels and a collection drain. It will also be necessary to redo residence A's foundations with underpinning.

This example, drawn from a real case, is very frequently encountered.

Problem #10—Location of an individual wastewater system

A residence is under construction. It is surrounded by other buildings and is located in an area with no sewer connection. An individual wastewater system must be included, consisting of a septic tank for all water and of dispersion channels for the effluent. Pumping into existing sewers at a higher elevation is not allowed, and the following distances must be observed: 5 m from the residence and from the property limits, and 10 m downhill.

The hydrogeologist had the following information available:

- Description of the residence: 150 m^2 villa with two floors: entrance hallway, living room, sitting room, office, 3 bedrooms, 2 bathrooms, 1 kitchen;
- Floor plan (Figure 13).

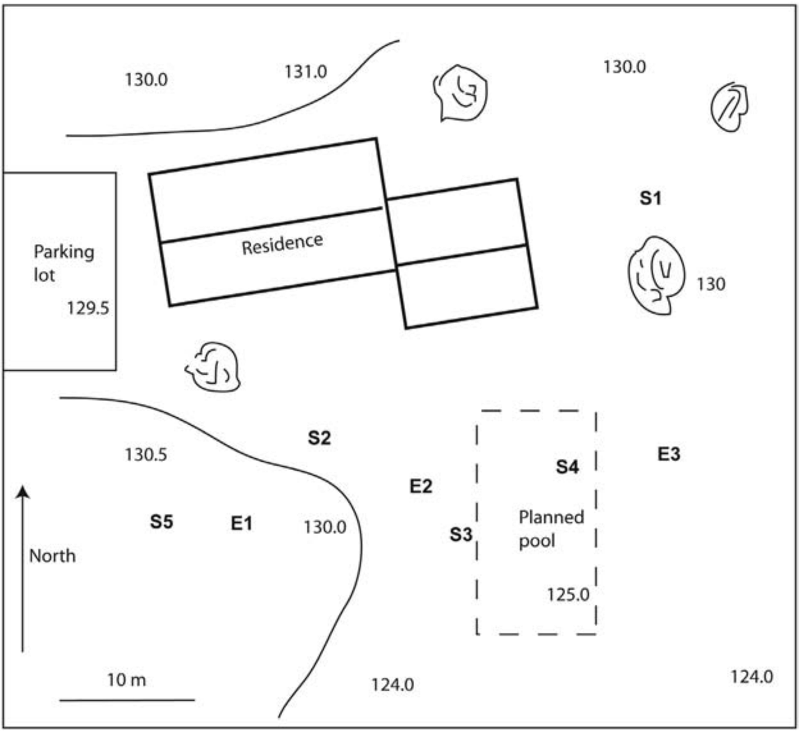

Figure 13 Floor plan and position of boreholes and permeability tests.

The hydrogeologist undertook a soil study, from which follow a few excerpts:

"...The residence is located on a massive Eocene sandstone plateau. This highly fractured formation weathers into decimeter to meter-scale spheres and gives, at the surface, sandy clayey weathering material with a permeability varying with the quantity of clay...

... downhill, at a distance of a hundred or so meters, the sandstone unit is lined with a series of springs at an average elevation of 80.00 m, supported by the Upper Cretaceous marl..."

The following work was undertaken:

- Auger reconnaissance:

Table 10 Result of the auger reconnaissance excavations (see location of points on Figure 13).

S1: 00–30 cm: organic-rich soil 30–50 cm: sand 50 cm: no passage into sandstone	S2: 00–20 cm: organic-rich soil 20–100 cm: clayey sand 100 cm: no passage into sandstone	S3: 00–30 cm: organic-rich soil 30–50 cm: sand 50–150 cm: clayey sand and sandstone 150 cm: limit of the tool
S4: 00–30 cm: organic-rich soil 30–50 cm: clayey sand 150 cm: limit of the tool	S5: 00–20 cm: organic-rich soil 20–150 cm: clayey sand 150 cm: limit of the tool	

- Constant level infiltration tests (see location of points on the floor plan):

Table 11 Results of permeability tests (see location of points on Figure 13).

E1: $K = 5\ mm \cdot h^{-1}$	E2: $K = 40\ mm \cdot h^{-1}$	E3: $K = 50\ mm \cdot h^{-1}$

Question: Based on these observations, what advice can the hydrogeologist give for this construction project?

Answer:

The fractured sandstone is permeable and the line of springs reveals the presence of an aquifer located 40 or 50 m below the surface. The thickness of the weathering mantle appears great enough at several locations to allow the emplacement of the individual wastewater system, as long as the clay content is not too high. Various areas of the plot can thus be eliminated:

- the zones outside the regulatory distances;
- the northern half, which is above the residence and included in the previous zone;

- the area around S1 where the soil cover is thin;
- the area around S5 and E1, where the clayey soil is not permeable enough.

There remains a surface of around 250 m², with an average permeability of 45 mm·h⁻¹, which should be adequate in order to accept the leaching field.

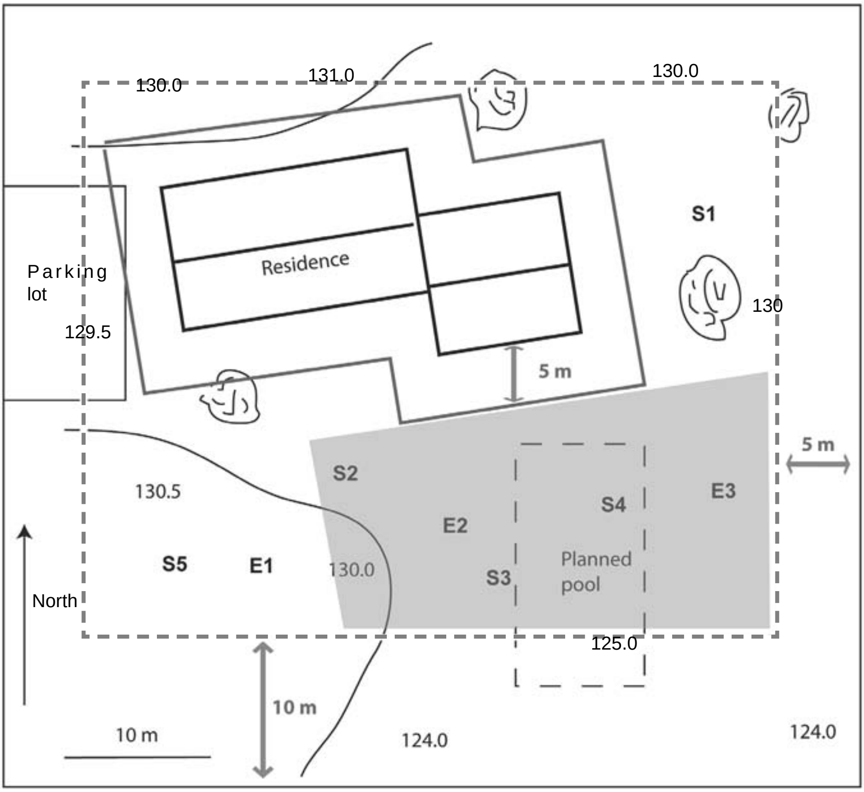

Figure 14 Usable area for the leaching field.

The residence is intended for 6 people (5 rooms), which represents a wastewater production of around 1500 L per day. This requires a leaching field of around 45 m², and a total channel length of 90 m (with a width of 50 cm). The channels must be spaced 1.5 m apart. One could, for example, build 3 channels of 30 m each, for a total leaching field surface of 30 x (0.5 + 1.5 + 0.5 + 1.5 + 0.5) = 135 m².

The plot can therefore accept an individual wastewater treatment system. The future pool, however, which is included on the floor plan, cannot be built in its currently planned location. It could eventually be displaced to the west, but problems of rainwater collection and emptying of the pool would have to be studied.

Problem #11—Study of the emergence conditions and vulnerability of a catchment system

Located in the southeast part of France, at an elevation of 1,500 m, the X karst spring has an average annual discharge of around 100 $L \cdot s^{-1}$ and is used for the drinking water supply. In this area, the specific infiltration modulus was estimated by previous studies to be 15 $L^{-1} \cdot km^{-2}$. The gravity-driven catchment system is equipped with a siphon, which enables the periodic increase of the discharge by lowering the level of the karst aquifer. In order to study the spring's vulnerability, a study including geologic analysis, an inventory of human activity, the monitoring of the physical parameters of the spring, and a multi-tracer test were undertaken. For the tracer test, the following substances were injected on January 6th:

- Naphtionate: 10 kg in the sheep barn B;
- Eosin: 5 kg in the effluent from the wastewater treatment plant S, 1 km north of the spring;
- Fluorescein: 5 km away in the ponor E, into which flows the water from a small stream which receives the effluent of another wastewater treatment plant.

The following documents were created (Figures 15 to 17):

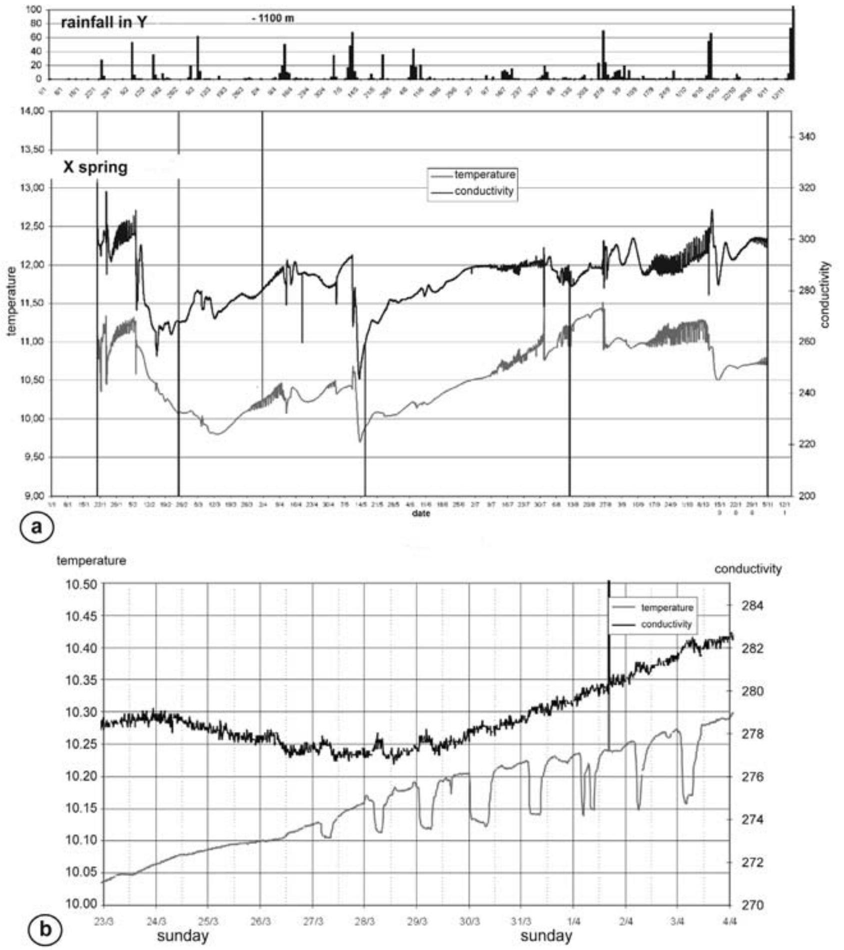

Figure 15 a) Pluviometry over the catchment basin and variations in the physical parameters of the X spring; b) March-April detail.

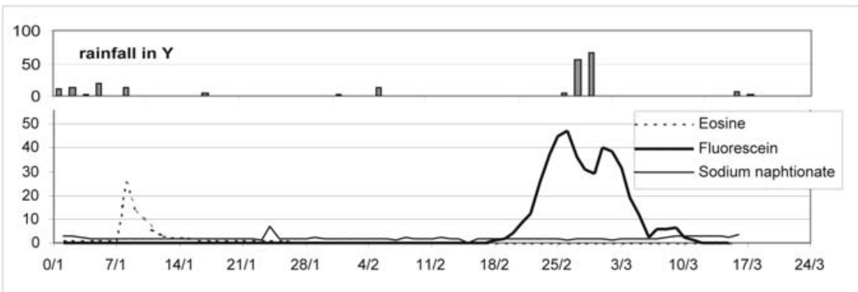

Figure 16 Breakthrough curves of tracers.

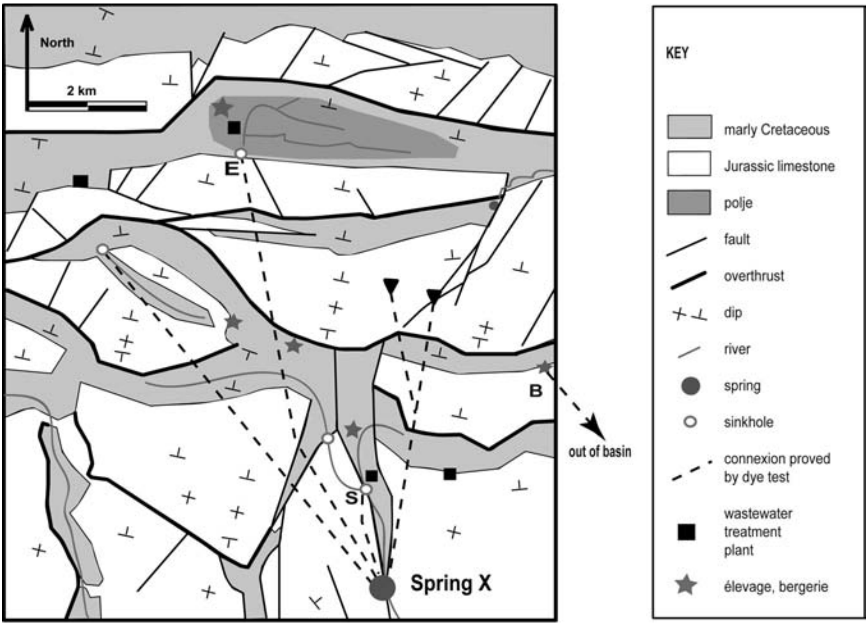

Figure 17 Schematic geologic map of the limestone belts feeding the emergence.

Question 1: What can you conclude about the catchment basin of the spring and its vulnerability?

Question 2: What advice can you give to increase the quality of the water being taken?

Answer 1: The basin can be roughly estimated, using the modulus, at around 10 km^2, in the limestone units uphill from the spring. The geologic map shows that the spring is located in a graben cutting across a collection of limestone belts, the structure of which, in overthrusting depressions, would seem to predict east-west drainage.

This basin filled with impermeable Cretaceous marl therefore plays a primary role in the surface and subterranean drainage. The basin is more clearly defined by the results of the tracer tests.

The examination of the temperature and conductivity curves shows that the spring is subject to important variations and reacts quickly to precipitation. The temperature and mineralization increase regularly as the dry season progresses, but drop immediately after rainfall. The circulation is therefore rapid and the reserves small, which does not favor the dissolution of an eventual contamination.

The analysis of the curves in February, period during which surface water is colder than karst water, shows that significant drops in temperature occur each day during the daytime. A more careful examination shows different variations on Sundays and holidays. Anthropogenic origins are therefore indubitable. These variations, visible only during dry periods, are therefore tied to the overexploitation system, which, by lowering the karst aquifer, provokes an intrusion of surface water in the catchment system.

The results of the tracer test show that the eosin, injected into the effluent of a defective water treatment plant located on the marl of the graben upstream of the spring, is restored only a few hours after injection. The water loaded with effluent is therefore lost into the Jurassic limestone and contaminates the spring.

The same remark can be made for the restitution of fluorescein, which proves a rapid connection between the ponor E and the spring. The curve shows two peaks, the second of which is due to the rainfall episode at the end of February that prompted a flushing of the coloring agent.

The absence of naphthionate restitution enables the exclusion of the eastern belts from the drainage basin.

This spring therefore presents a high vulnerability tied, on the one hand, to overexploitation, and on the other hand to the developments on its recharge basin.

Answer 2: It will be necessary to limit the lowering of the water table during dry periods, or to guarantee an irreproachable surface water quality. The collective sanitation system (water treatment plant) will then have to be improved, for example by including oxidation lagoons.

Problem #12—Search for the origin of a saline contamination (after Blavoux *et al.*, 2004)

The submarine Cassis springs (Bouches-du- Rhône) could supplement the water resources of the region east of Marseille, but the water is brackish (see chap. 9).

The origin of the salinity of the brackish Port Miou river has given rise to two hypotheses:

- the leaching of continental evaporites, whose presence has been observed in certain geologic formations in the drainage basin (Oligocene or Muschelkalk);
- a contamination of marine origin.

Contamination by evaporites, acquired at the level of the recharge area and therefore affecting the entire aquifer, as the concerned geologic series are widely distributed, would rule out exploitation of the water. Marine contamination tied to the presence of the sea would, however, allow the study of a potential catchment far from the coastal zones.

In order to answer this question, water samples were taken at various locations:

- at sea,
- in a neighboring karst aquifer,
- at different heights in the karst conduit through which flows the underground river.

Major elements and Br were measured for these samples. The Br/Cl ratio (in milliequivalents/1,000) was taken.

Question 1: Graphically analyze this data by creating different ratios between the major conservative elements (Cl, Na, SO_4, Mg, K).

Question 2: What do you observe?

Question 3: What conclusions can you draw on the origin of the salinity in the Port Miou waters?

Table 12 Chemical analyses of sea water, a well in karst, and of Port Miou at different depths.

	conductivity	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	Mg^{2+}	Ca^{2+}	K^+	Br^-/Cl^-
LOCATION-depth	$\mu S.cm^{-1}$	$mg{\cdot}L^{-1}$	$mg{\cdot}L^{-1}$	$mg{\cdot}L^{-1}$	$mg{\cdot}L^{-1}$	$mg{\cdot}L^{-1}$	$mg{\cdot}L^{-1}$	$mg{\cdot}L^{-1}$	10^{-3} [mequiv]$\cdot L^{-1}$
sea	55,700	23,137	2,764	154	11,480	1,328	444	565	1.58
karst well	540	14	43	281	6.7	22.3	70.6	0.8	1.36
Port-Miou 0 m	8,580	3,077	352	375	1,688	194	191	70	1.57
Port-Miou –2 m	10,650	3,754	470	324	1 671	203	173	85	1.42
Port-Miou –3 m	21,300	7,806	975	254	3,722	411	233	186	1.44
Port-Miou –4 m	21,300	7,688	1,039	255	3,785	412	232	185	1.44
Port-Miou –6 m	21,200	7,725	937	257	4,073	416	267	157	1,63
Port-Miou –8 m	21,300	7,667	948	254	4,121	445	236	186	1,72
Port-Miou –10 m	21,300	7,508	922	257	3,748	430	239	184	1,61
Port-Miou –12 m	21,400	7,544	803	255	3,688	431	253	183	1,83

Answer 1:

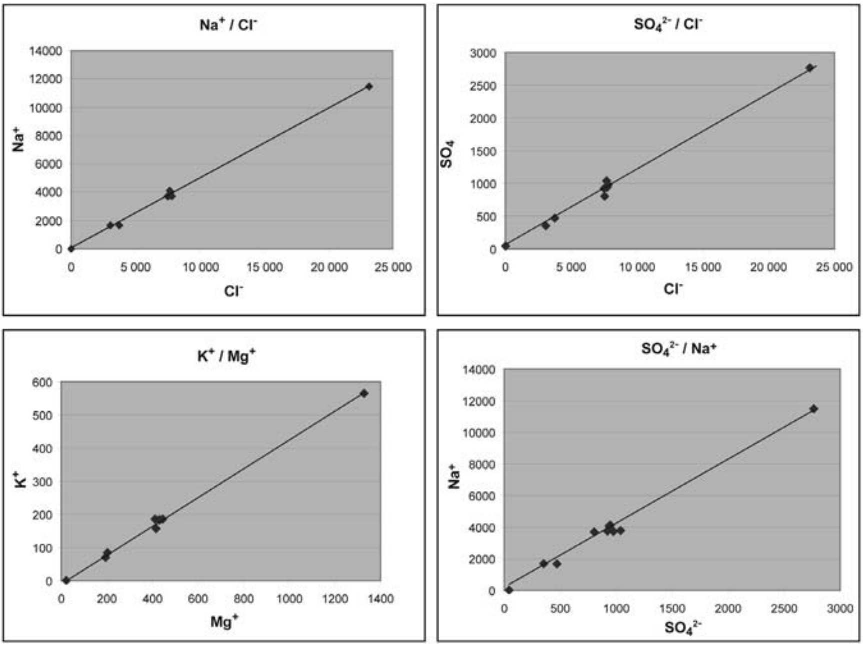

Figure 18 Na/Cl, SO_4/Cl, K/Mg and Na/SO_4 ratios.

Answer 2: By creating different ratios (Na/Cl, SO_4/Cl, ...) one can observe that all of the points measured in brackish water are aligned along a mixing line between pure seawater (upper right) and karst water (bottom left). In addition, the Br/Cl ratio in 10^{-3} milliequivalents/L is close to 1.51, which is characteristic of sea salt. A ratio between 0.7 and 1.2 would have meant the presence of evaporites.

Answer 3: All of this data proves that the salinity of the brackish water is a result of marine contamination, and that exploitation of the aquifer is therefore a possibility far from the coast.

Problem #13—Emptying test on a well in a karst aquifer

In the area around Nice (Alpes-Maritimes), a drinking water supply well draws on the karst Jurassic reservoir after having passed through its cover of Cenomanian marl, beneath which the aquifer is confined.

In order to estimate the productivity of the well and the recharge conditions of the aquifer, an emptying test by pumping was undertaken over a period of 5 months, spanning the summer dry period and the autumnal rains.

During this test, the volume of extracted water and the level of the aquifer calibrated to elevations a. s. l. were the subject of daily monitoring (Table 13).

Question 1: Establish the graphical relationship at the well location between the piezometric evolution of the aquifer and the volume of water extracted during the emptying test; complete the curve with characteristic values (instantaneous drawdown, slow emptying, natural recharge, instantaneous rise), and explain its evolution.

Question 2: Calculate the following characteristics of the pumping well:

- the values of the initial instantaneous drawdown of the aquifer and that of its final instantaneous rise;
- the value of the specific volume V of the aquifer;
- the value of the natural recharge observed during the test, knowing that rainfall remained minimal during the first two months (10 mm in July and 20 mm in August) but were abundant afterwards (261 mm in September, 128 mm in October, 194 mm in November), and dropped off in the last month (13 mm in December).

Table 13 Piezometric variations and extracted volumes.

TABLE OF MEASUREMENTS

time: month	time: day	total extracted water (in m^3)	elevation of the aquifer level (m)
JULY	19	0	139.60
	20	6 831	135.50
	21	13 941	135.00
	22	21 015	134.60
	23	28 292	134.60
	24	35 379	134.55
	25	42 568	134.50
	26	49 833	134.10
	27	57 038	133.90
	28	64 119	133.70
	29	71 202	133.60
	30	78 272	133.40
	31	85 308	133.20
AUGUST	01	92 282	133.00
	02	99 005	132.90
	03	105 652	132.70
	04	112 265	132.65
	05	118 874	132.45
	06	125 430	132.20
	07	131 956	132.15
	08	138 484	131.95
	09	144 989	131.85
	10	151 471	131.65
	11	157 897	131.55
	12	164 334	131.45
	13	170 692	131.20
	14	177 059	131.15
	15	183 413	130.95
	16	189 738	130.85
	17	196 058	130.75
	18	202 349	130.70
	19	208 635	130.45
	20	214 882	130.25
	21		130.20
	22		130.05
	23		129.95
	24		129.75
	25		129.70
	26		129.45
	27		129.45
	28		129.25
	29		129.25
	30		129.05
	31		128.95
SEPTEMBER	01		128.95
	02		128.95
	03	297 736	128.95
	04	303 714	128.75
	05	309 681	128.50
	06	315 635	128.45
	07	321 590	128.35
	08	327 519	128.25
	09	333 420	128.35
	10	339 318	128.25
	11	345 202	128.00
	12	353 910	128.00
	13	359 750	127.95
	14	364 964	127.75
	15	369 727	127.70
	16	374 496	127.60
	17		127.55
	18		127.50
	19	389 015	127.30
	20	393 872	127.30
	21	398 702	127.30
	22	403 543	127.20
	23	408 369	127.10
	24	413 210	127.15
	25	418 044	127.20
	26	422 882	127.20
	27	427 905	127.20
	28	432 757	127.20
	29	437 606	127.30
	30	442 442	127.30
OCTOBER	01	447 302	127.40
	02	452 164	127.40
	03	457 048	127.45
	04	461 927	127.40
	05	466 796	127.45
	06	471 652	127.45
	07	476 521	127.45
	08	481 401	127.45
	09	486 152	127.45
	10	491 515	127.50
	11	495 646	127.50
	12	500 399	127.60
	13	505 131	127.55
	14	509 864	127.55
	15	514 597	127.60
	16	519 324	127.50
	17	524 060	127.50
	18	528 797	127.50
	19	533 511	127.50
	20	538 207	127.50
	21	542 901	127.45
	22	547 604	127.45
	23	552 300	127.50
	24	557 025	127.70
	25	561 769	127.70
	26	566 534	127.90
	27	571 300	128.00
	28	576 070	128.20
	29	580 854	128.40
	30	585 867	128.50
	31	590 494	128.60
NOVEMBER	01	595 329	128.70
	02	600 189	128.90
	03	605 072	129.10
	04	609 952	129.15
	05	614 898	129.80
	06	620 007	131.30
	07	625 191	132.40
	08	630 429	133.40
	09	635 745	134.40
	10	641 172	135.80
	11	646 681	137.45
	12	652 258	137.75
	13	657 873	138.50
	14	663 521	139.05
	15	669 168	139.20
	16	674 835	139.50
	17	680 512	139.60
	18	686 192	139.70
	19	691 878	139.70
	20	697 569	139.70
	21	703 262	139.70
	22	708 940	139.70
	23	714 625	139.70
	24	720 299	139.60
	25	725 993	139.50
	26	731 674	139.50
	27	737 323	139.50
	28	742 965	139.20
	29	748 600	139.10
	30	754 231	139.00
DECEMBER	01	759 860	138.95
	02	765 472	138.70
	03	771 078	138.50
	04	776 674	138.50
	05	782 258	138.30
	06	787 830	138.20
	07	793 398	138.00
	08	798 950	137.90
	09	804 493	137.70
	10	810 023	137.70
	11	815 541	137.50
	12	821 058	137.30
	13	826 559	137.25
	14	832 051	137.25
	15	837 543	137.05
	16	843 001	136.80
	17	848 470	136.75
	18	853 905	136.50
	19	859 342	136.50
	20	864 782	136.30
	21	870 199	136.30
	22	872 108	136.30
	23	872 108	144.60
	24	872 108	144.60
	25	872 108	144.80
	26	872 108	144.84
	27	872 108	144.84
	28	872 108	144.84

Answer 1 (Figure 19)

After the initial instantaneous drawdown, the slow decrease in the piezometric head (12 cm per day) reveals the emptying of the reservoir in an uninfluenced period.

The autumn rains lead to a progressive recharge of the aquifer, marked as early as the September rains by stabilization in the height of the water table, followed by a slight rise that is accentuated during the October and especially the November rains.

Starting November 21st, the absence of rain again results in a lowering of the piezometric head, and therefore an emptying of the aquifer, until the instantaneous rise when pumping is stopped.

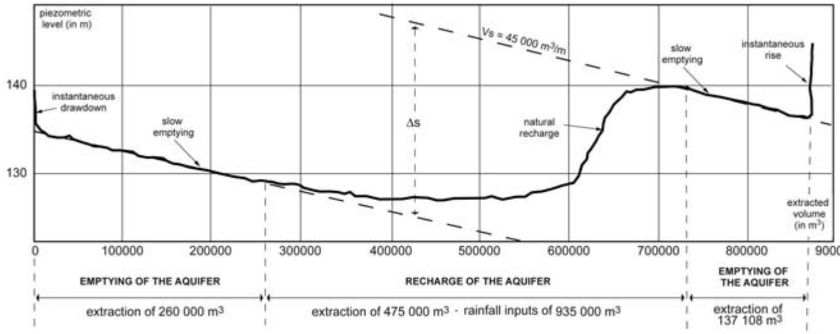

Figure 19 Relationship between the piezometry of the aquifer and the extracted volume of water during the test.

Answer 2:

Value of the instantaneous drawdown = 5 m.

Value of the instantaneous rise = 8.5 m (greater, due to the significant recharge of the aquifer by rainfall).

Value of the specific volume = 45,000 $m^3 \cdot m^{-1}$.

Value of the natural recharge induced by the rainfall inputs = 935,000 m^3 (calculated by taking the product of Vs and Ds, or by directly reading off the graph).

Problem #14—Piezometry of two superimposed aquifers

In a plain in the Grasse region (Alpes-Maritimes) at an a.s.l. elevation of around 100 to 110 m, superficial colluvium covers a Triassic substratum with the following succession:

- at the top, multicolored clayey marl capping Keuper gypsum;
- at the base, limestone and dolomite (Muschelkalk).

Clayey marl separates two distinct aquifers:

- a shallow aquifer, located in the colluvial cover;
- a deep aquifer, established in the gypsic and carbonated horizons, and the drainage of which occurs towards a karst spring 4 km to the south at an elevation of 32 m.

In the context of a general study, a piezometric survey in February 2002 gave the following measurements (location map and data table).

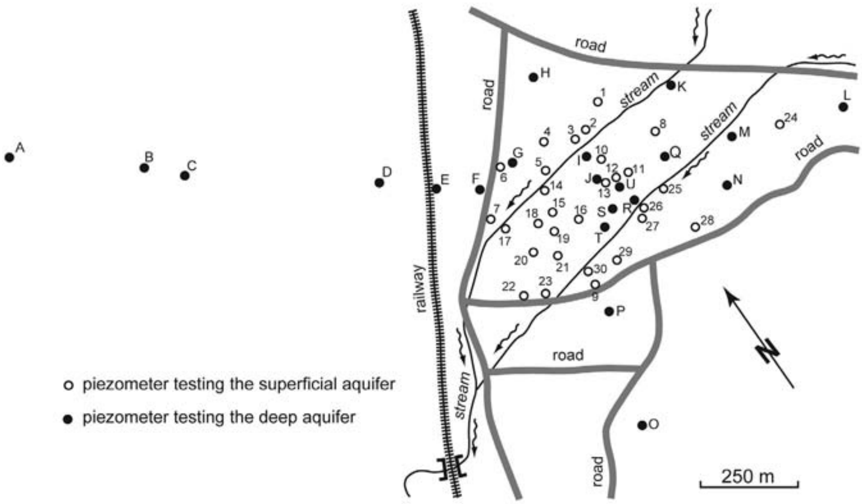

Figure 20 Location map.

Table 14 Measurements.

DATA TABLE				A 72.89
B 65.93	C 71.98	D 80.96	E 67.69	F 51.10
G 86.65	H 67.24	I 64,72	J 48.64	K 79.50
L 83.01	M 84.80	N 69.65	0 45.30	P < 50.50
Q < 51.60	R 77.85	S 68.50	T 55.40	U 84.40
1 105.21	2 103.10	3 103.12	4 101.89	5 96.60
6 98.10	7 < 95.36	8 105.24	9 101.86	10 104.02
11 103.33	12 97.49	13 102.34	14 98.00	15 99.97
16 100.79	17 98.72	18 97.80	19 98.91	20 98.20
21 98.25	22 96.18	23 96.35	24 121.53	25 104.85
26 101.73	27 101.84	28 114.11	29 102.41	30 100.40

Question 1: Draw a piezometric map for the superficial and deep aquifers. Specify the drainage conditions of each aquifer.

Question 2: Does the piezometric data enable the identification of exchanges between the two aquifers? If yes, to what could such exchanges be attributed?

Answer 1 (Figure 21)

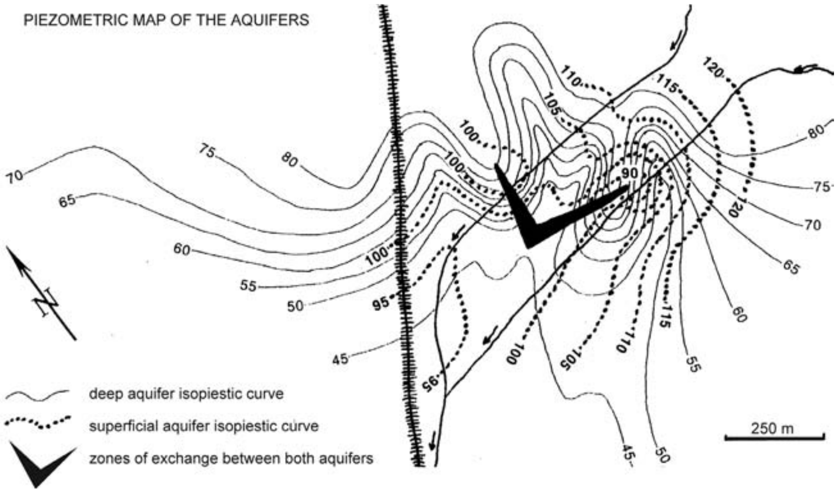

Figure 21 Piezometric map of the aquifers.

The superficial aquifer has a general east to west drainage, following the local drainage direction of the stream network. Its roof is located only a few meters below the natural ground surface.

The deep aquifer shows drainage toward the south, organized along several axes converging towards a single collector toward the southern spring (confirmed by tracer tests). The depth of its surface varies from 15 to 70 m.

Answer 2:

Two inter-aquifer exchange areas are revealed by the cartographic synthesis, and indicate local recharges of the deep aquifer by the shallow aquifer. These mixing zones are revealed by marked depressions in the shallow aquifer in the same location as piezometric domes in the deep aquifer.

These exchanges are locally caused by two complementary factors:

- on the one hand, deep wells that did not isolate the superficial aquifer put the two aquifers into contact;

- on the other hand, *per descensum* exchanges at the roof of ancient collapses of gypsum caves that decompressed the overlying terrain and increased their vertical permeability.

Problem #15—Prospection of an alluvial zone in order to implement a water well

A river and its accompanying aquifer are established in an alluvial zone, at the roof of a rocky substratum which also makes up the sides of the valley.

With the goal of exploiting the alluvial aquifer through a water well, geophysical prospection of the valley was undertaken, in order to specify the geometry and nature of the alluvial deposits and to determine the best location for the well.

The prospected site is partially shown on the joint figure, and the results of the electrical survey undertaken and given in the following table.

Question 1: Draw cross-sections along the lines AA′, BB′, and CC′, with the geologic units, taking into consideration the fact that the banks have a slope of around 40° below horizontal, and that the river is sunk 3 to 4 m into a practically planar alluvial plain.

Question 2: Select the most favorable sites for reconnaissance drilling, and justify your choice.

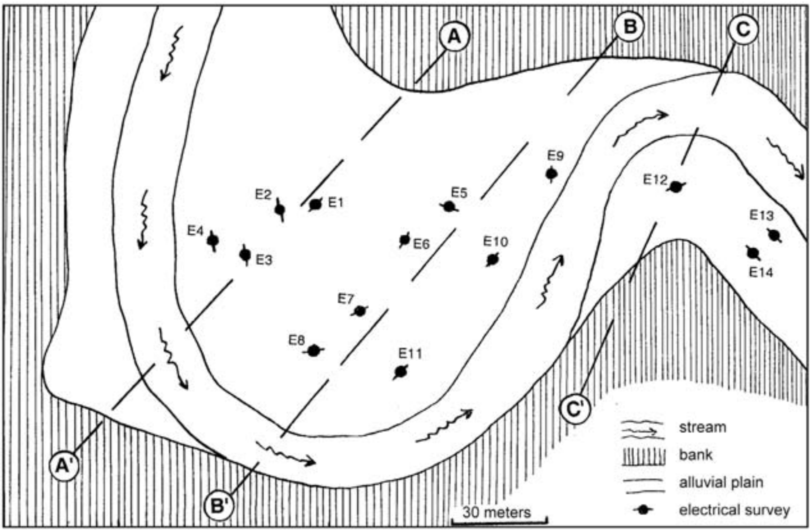

Figure 22 Location map for the electrical surveys.

Table 15 Result of electrical surveys.

Electrical survey	Resistivity (Ω·m)	Thickness (m)	Electrical survey	Resistivity (Ω·m)	Thickness (m)
E1	1 = 570 2 = 1,000 3 = 450	1 = 0.65 2 = 1.50	E2	1 = 290 2 = 870 3 = 150 4 = ∞	1 = 0.80 2 = 5.60 3 = 7.50
E3	1 = 330 2 = 1,900 3 = 150 4 = ∞	1 = 0.65 2 = 3.00 3 = 10.50	E4	1 = 130 2 = 400 3 = 150 4 = ∞	1 = 1.20 2 = 14.00 3 = 8.00
E5	1 = 185 2 = 1,800 3 = 190 4 = ∞	1 = 0.70 2 = 0.90 3 = 10.50	E6	1 = 140 2 = 500 3 = 110 4 = 1,000	1 = 0.60 2 = 1.60 3 = 4.80
E7	1 = 270 2 = 550 3 = 300 4 = 1,500	1 = 0.70 2 = 1.20 3 = 19.80	E8	1 = 750 2 = 1,500 3 = 100 4 = ∞	1 = 2.50 2 = 4.00 3 = 8.00
E9	1 = 190 2 = 1,330 3 = 290 4 = 2,600	1 = 0.70 2 = 1.40 3 = 14.40	E10	1 =140 2 = 430 3 = 150 4 = 3,000	1 = 1.10 2 = 4.50 3 = 8.00
E11	1 = 270 2 = 800 3 = 230 4 = ∞	1 = 0.65 2 = 5.20 3 = 14.00	E12	1 = 300 2 = 620 3 = 300 4 = ∞	1 = 0.90 2 = 1.90 3 = 12.50
E13	1 = 260 2 = 400 3 = 130 4 = 8,000	1 = 1.10 2 = 2.50 3 = 6.00	E14	1 = 225 2 = 450 3 = 70 4 = ∞	1 = 0.60 2 = 0.90 3 = 2.50

Answer 1:

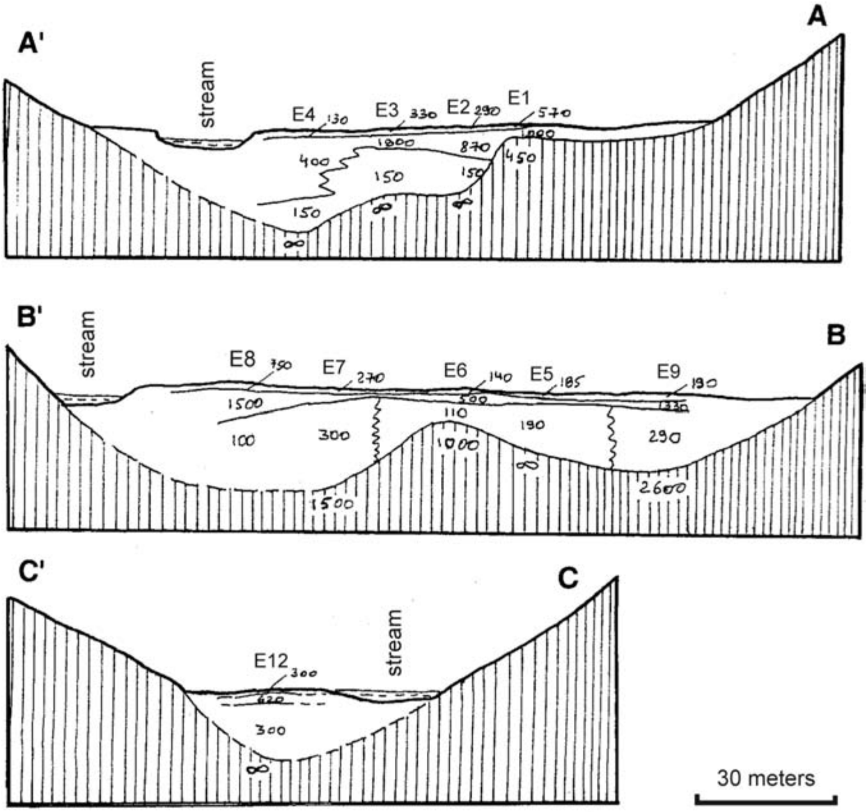

Figure 23 Geologic cross-sections, considering that the high resistivities measured at depth correspond to the roof of the rocky substratum.

Answer 2:

The location of a reconnaissance well is dictated by the following factors:

- a maximum thickness of alluvial deposits in order to draw on the entire thickness of the aquifer. The search must focus on the more deeply channeled axis revealed by the cross-sections (E4 in AA′; E7-E8 in BB′; E12 in CC′);
- mostly gravelly terrain, in order to benefit from the highest permeability. Under the rocky surface silt, the high resistivities probably correspond to unsaturated terrain. Further on and in the meander of the river, the alluvium offers distinctly higher resistivities along the deeper channel

(300 to 400 mS·cm^{-1}) than upstream (150 to 290 mS·cm^{-1}), which can correspond to rockier terrain with little matrix.

Given the geometry of the area and the characteristics revealed by the geophysical survey, the most favorable site in the area would be in the zone of the E7 and E8 electrical surveys (BB′ cross-section). Two reconnaissance wells did, in fact, reveal an alluvial thickness of 15 to 20 m, and mostly rocky facies beyond the first three meters. The aquifer was then exploited near the E7 electrical survey.

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About the Book

Water is indispensable to life and the human body cannot do without it for more than two days. While historically it was freely available and plentiful, potable water is becoming a more and more a scarce commodity, and increasing unequally distributed. The 20th century saw the transition from water gathering to water cultivation. The 21st Century will need to address a basic challenge: how to provide clean water to the 7 billion people on Earth. Water, a necessity for life but also a force of destruction, is present on Earth in all three of its phases. It is caught up in an endless cycle, a part of which takes place below ground. Hydrogeology is the science of groundwater. It is a new field requiring a multidisciplinary approach and involving many other sciences: surface hydrology, climatology, geology, geography, physics, chemistry, biology, etc.

This book takes a broad view, considers water as a single entity, and presents many examples illustrating the variety of existing hydrogeological problems and the diverse scientific, technical, and social approaches used in resolving them.

The book is intended primarily for students of Earth Sciences, Environmental Sciences and Physical Geography. It will also be useful to all players involved in water-related issues: hydrogeologists, geologists, soil scientists, agronomists, civil engineers, or developers.

About the Authors

Éric Gilli is a karstologist. Formerly a consultant in Nice, he is now a professor at the University of Paris 8 in the Geography department. Part of his research interests concern karst aquifers and submarine karstic springs.

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About the Translator

Chloé Fandel is an undergraduate studying Geological Sciences at Brown University in Providence, RI (class of 2012), with a particular interest in environmental science and education. She is a dual French-American citizen, with ties to Nice and Boston. This is her first translation.

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