Chapter 12
Management of Karst Groundwater Resources

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Abstract Karst aquifers are especially difficult to exploit, manage, and protect because of the extreme variability of their hydraulic properties which are almost impossible to determine at a local scale. Moreover, their functioning may be influenced by non-linearities and threshold effects. Considering long-term aquifer exploitation, karst system complexity does not allow for easy behavioral modeling, such as using the classical isochrone method for determining a protection zone. However, because karst aquifers may offer great storage capacity and high local hydraulic conductivity, high flow rates can be pumped from single sites, allowing for effective management of an aquifer. After outlining the main characteristics of karst aquifers, the management of their groundwater is examined from both quantity and quality viewpoints in order to highlight benefits and problems with this resource. Finally, some new avenues of research are proposed.

12.1 Introduction

Over the centuries, groundwater resources have not been well managed, regardless of whether or not they were karst aquifers. Since the end of the second millennium BCE, karst groundwater withdrawals were made at springs by means of water works and aqueducts as shown by archaeological remains in the Middle East (Bakalowicz et al. 2002). Some examples cited by archaeologists show that groundwater was also exploited from natural pits or from percolation in shallow caves.

Generally, the base flow of a spring is used for a town's water supply; however, when that resource becomes insufficient for the community, a new spring must be tapped. The development of the water supply of the city of Montpellier, France, is a

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good example of this exploitation of karst groundwater in Mediterranean regions. During the eighteenth century, when the town's wells yielded poor quality water, St-Clement Spring was captured and Henri Pitot built a 14-km long aqueduct (Aigrefeuille 1877) from the spring to the town. Initially, a flow rate of 25 L/s was captured but with the growing population, the aqueduct was extended during the nineteenth century to collect outflows from the Lez Spring, one of the most important karst springs in South of France. The total flow rate of the aqueduct was first doubled to 50 L/s, and then increased to 125 L/s in 1882, and to 250 L/s in 1899. The lowest natural base flow rate is approximately 350 L/s, hence not all the outflow is being captured.

For a long time, wells in karst areas were unusual because of the difficulty drilling in limestone which yielded low success rates. However, in areas where the epikarst is well developed and possesses shallow water storage, these waters are within easy reach of wells, and have been used since antiquity, for example, the limestone mountain in the dead cities of north-western Syria (Abdulkarim et al. 2003). The same extraction system was later developed in the karst plateaus of southern France. These examples correspond to what Collin (2004) calls the "gathering economy".

Water capture from karst aquifers changed with new drilling and pumping techniques, making groundwater easily accessible at depth. These techniques were only systematically used in karst since the 1950s, when the water needs considerably increased in western countries due to growing populations and related increased consumption, and the high water demand for agriculture. In addition, the blossoming tourist industry infrastructure demanded more water, especially in Mediterranean regions where often karst aquifers offered the only permanent water resource.

Initially, groundwater was exploited without a management plan, and usually without any knowledge of the functioning of the exploited aquifer. Frequently, an absence of competent management had (has) two serious consequences:

- A lowering of the water table, resulting in a seasonal, even permanent drying of wells, springs, and rivers, as observed in Southern Spain (Pulido Bosch et al. 1989) and in the Poitou – Charente Region in France (de Grissac et al. 1996) ;
- Diffusing pollution of groundwater mainly from agricultural activity or domestic waste water, or occasional salt water intrusion, which in some cases lead to the abandonment of the water resource.

This is what Collin (2004) terms "mining exploitation", i.e., a non-managed exploitation as it was practiced in Spain (Pulido Bosch et al. 1989). Managing karst groundwater should be sustainable and one approach is integrated water resource management (IWRM). Exploitation and protection are parts of an efficient IWRM in karst areas. Because of the distinct characteristics of karst aquifers, their delineation and boundary conditions require specific methodology, which is very different from that usually implemented in alluvium and fissured aquifers. If the correct methodology is not used, the consequences may be disastrous. Examples of drastic groundwater lowering, salt water intrusion, or heavy pollution are well documented (Pulido Bosch et al. 1989).

Aquifers contained with karstified bedrock are known to be problematic because of the considerable heterogeneity of its physical properties. For that reason, karst groundwater as a resource was not targeted while other more simple, predictable, porous, and fissured aquifers were developed and intensely exploited. The push for new water resources has lead to exploitation of karst groundwater, and the consequent need to improve knowledge about their functioning in order to benefit from them. Finally, there has been a movement to propose management approaches for optimizing the exploitation sustainably, and for managing the recharge area of the water resource to prevent or mitigate its pollution. This last aspect of karst aquifer management will be examined, incorporating both quality and quantity approaches which are in fact often related to each other. However, a short synthesis of karst aquifer properties will be introduced as a useful reference for the better understanding of karst groundwater management.

12.2 Main Characteristics of Karst Aquifers and Problems

The functional model of karst systems, shown in Fig. 12.1, is now well accepted by hydrogeologists (Bakalowicz 2005). The recharge area is the first component of a karst system (KS) to be considered. It may include both karst and non-karstic portions (non-carbonate formations), such as where river system is drained by swallow holes close to an impermeable – karst contact. When a KS includes a non-karstified rock, it is considered binary, recharged by both allogenic and autogenic recharge. When it is only karstified formations, it is a unary KS, recharged only by autogenic inputs. Allogenic recharge generally has concentrated inputs and supplies the rapid, concentrated flow inside the karst aquifer through wide conduits. This flow is an important source of pollutions and sediment to springs.

The karst aquifer itself is recharged through two very different modes: (1) A dispersed, diffuse-type infiltration, through cracks and narrow joints, which mainly occurs as a two-phase slow flow at the bottom of the epikarst; (2) A concentrated infiltration, which produces rapid flow through wide openings in the epikarst.

The epikarst is a vital component of karst aquifer because it forms the interface between the aquifer, soil, plant cover, and human activities, and is a key to distributing infiltrating waters (Bakalowicz 2004). It plays a major role in the development of conduits by determining whether solution processes are either close to the surface or at depth. It retains and mitigates pollution, particularly diffuse events, and delays recharge to the phreatic zone and consequently the recession of spring discharge. For these reasons, epikarst is considered a major cornerstone by methods assessing the vulnerability of karst aquifers (Doerfliger et al. 1999; Zwahlen 2005).

The main practical consequences of the complexity of flow in karst aquifers are the:

- *Exploitation of the resource*. Drilling a well for water utilization using a pumping station can be risky due to the very high heterogeneity of bedrock permeability,

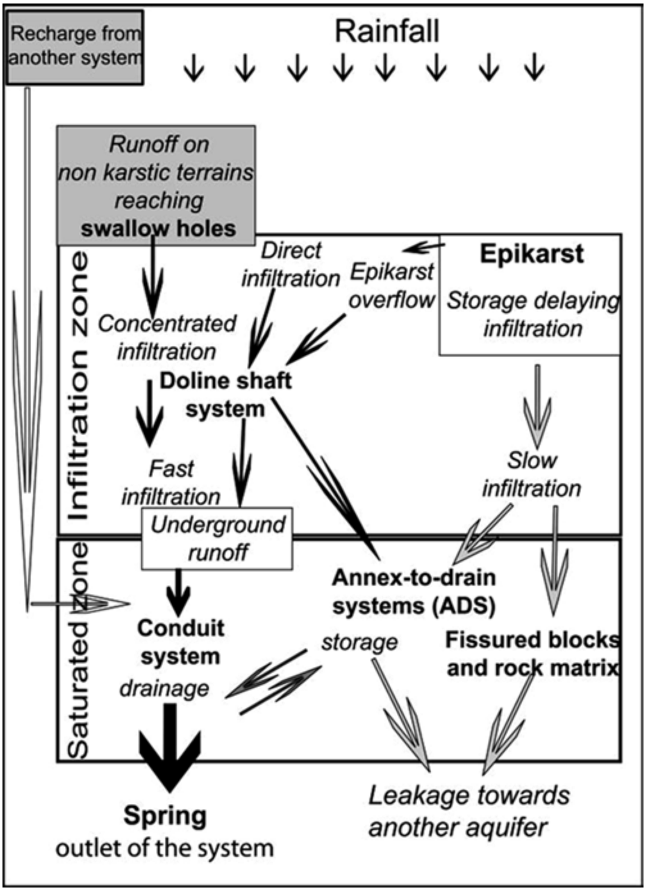

Fig. 12.1 The synthesis of the functioning of karst systems. Functions are written in italic, major components in bold

especially as the effects of pumping can impact wells located at several kilometres away without impacting closer ones.

- *Protection of the resource*. The determination of protection zones for wells often considers the whole recharge area as vulnerable, which imposes severe constraints on landuse for a large area surrounding the well. Moreover, the recharge area is often only estimated, and its limits are not well delineated, while the protection measures may appear inadequate.

The uniqueness of karst systems compared to other aquifers consists of the development of different, separated hydrologic components:

- Those draining the aquifer (conduits and open joints organized in a drainage system or "karst network"), where groundwater flows quickly, between 50 and several hundred meters per hour, as shown by tracing tests;

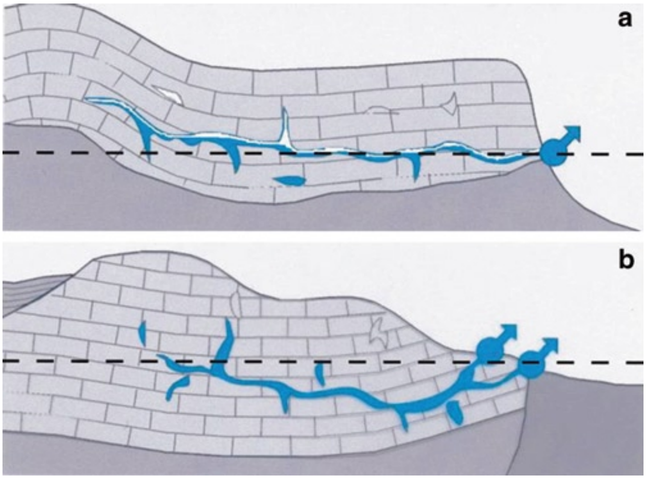

Fig. 12.2 Jura-type (**a**) and Vaucluse-type (**b**) karst aquifers. The cross sections show the conduit system with respect to the relative spring elevation represented by the dashed line and the development of potential storage below the spring level (from Marsaud (1997a))

- Those storing groundwater (porous matrix, or matrix blocks (Kiraly 1998), and karst cavities, the annex-to-drain systems (ADS) (Mangin 1994) which have poor hydraulic connections with the conduit system, allowing exchanges between them and the conduits, dependent on water head conditions and head losses.

Because storage and drainage are separate, it is especially important to know their respective part in the comprehensive functioning of karst systems and to be able to locate well sites while taking these two components into consideration. Moreover, knowledge of the position of the conduit system is absolutely essential. Marsaud (1997a) considers two organization types in karst aquifers (Fig. 12.2):

- *Jura-type systems*, where the conduits develop in the epiphreatic zone, i.e., in the zone of seasonal variation of the groundwater table. Flow in the main conduits, at least in some parts, may be surface-free flow. Water withdrawals from such karst systems by pumping at the spring or the well in the main conduit are controlled by the natural lowest discharge occurring during the low stage season; the exploitation flow rate cannot exceed the natural discharge of the conduit. The water reserves potentially developed around or below the conduits cannot be exploited by pumping.
- *Vaucluse-type systems*, where the conduits develop at depth in the phreatic zone. The flow in the conduits always occurs under confined conditions, where there is a permanent connection of the storage components through the conduit systems. Pumping in a conduit or in a storage area allows a significant drawdown controlled by the water head in the conduit. The extraction flow rate may be much higher than the natural flow at the spring by withdrawing water from storage due to the conduit connections pulling water from other storage sites.

12.3 Quantity Management of Karst Groundwater Resource

Due to the complexity and the variety of karst aquifers, the management plan of the groundwater resource has to be created on a case-by-case basis. No uniform "road map", considering all the possible situations, exists for defining such a development and management plan. In the following sections, some guidelines will be outlined.

12.3.1 Active Management

Spring discharge is most often highly variable, due to seasonal changes in recharge. The ratio between minimum and maximum daily flow commonly varies from 1:4 to 1:100. In some cases, ratios occur up to 1:10,000 (Marsaud 1997a), which means that the base flow is too low to satisfy the water demand of a sizeable community. While the seasonally variable resource of a river may be regulated by resorting to artificial storage in dam reservoirs, the natural groundwater storage of a karst aquifer may be used for regulating the total withdrawals during base flow stage. Pumping aims at emptying more storage space, which will be recharged during the next rainy season. The best site for pumping is generally close to the main spring, directly in the main conduit, with the condition that its vertical development allows a significant drawdown, i.e., a Vaucluse-type conduit which drains up the whole phreatic zone, or at least a large part.

To do so requires knowledge of the aquifer resource, its seasonal variability, and storage capacity (dynamic storage in natural conditions), but also requires monitoring all withdrawals. Therefore, groundwater resources can be managed in the same way as a bank account; inputs and outputs are permanently monitored. Groundwater storage (savings) is used for regulating the total discharge, spring flow, and withdrawals. If storage is large enough, the theoretical total permanent withdrawal could be the mean annual discharge of the spring. In fact, European regulations require permanent flow in rivers fed by springs, the so-called "saved discharge", so that part of the pumped groundwater must be discharged into the river bed downstream from the spring.

12.3.2 Evaluation of Resource and Reserves

Depending on the storage capacity value and on the length of duration of the season without recharge, it is possible to calculate the discharge which can be extracted from the reserves in addition to the natural discharge. Mangin (1974) proposed a method for evaluating the renewable storage of karst aquifers from the analysis of the spring hydrograph (Bakalowicz 2005; Ford and Williams 1989). Below is the example of the spring hydrograph of Fontaine de Vaucluse, France, for the 1997 hydrological year (Fig. 12.3).

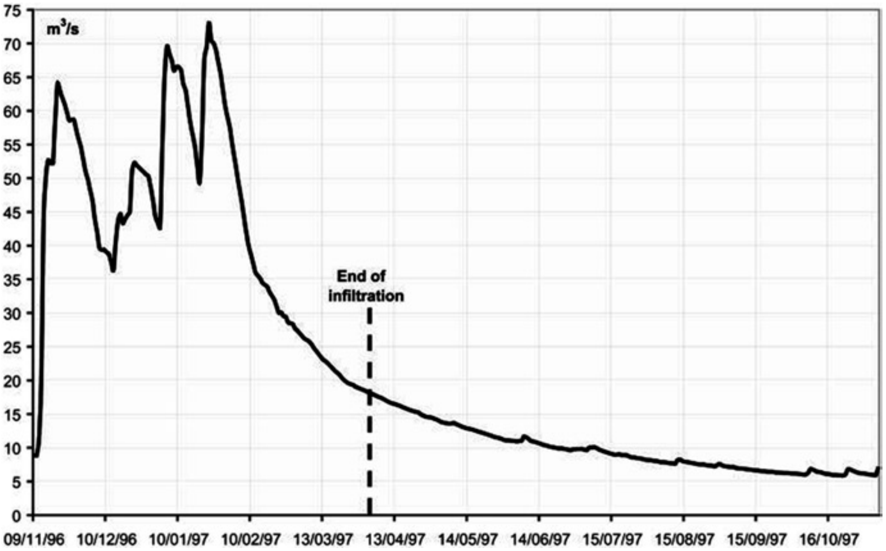

Fig. 12.3 Spring hydrograph of Fontaine de Vaucluse for the 1997 hydrological year

The characteristics of the recession of Vaucluse spring for the 1997 hydrological year (Fig. 12.3) are given in Table 12.1. Of importance are the characteristics of the phreatic zone, where most of the exploitable groundwater is stored. The dynamic storage, given by integrating the base flow hydrograph, according to Maillet's formula, is the volume of reserves in the phreatic zone which flows at the beginning of the base flow stage; it is an approach of calculating the lowest actual volume stored in the phreatic zone.

Drainage of the phreatic zone is quite fast ($\alpha = 0.0065$ day^{-1}) due to the highly karstified nature of the reservoir. The dynamic storage is important, with 359 million m^3, of which 226 million m^3 remains stored at the end of infiltration, which can be considered the beginning of the base flow stage. These 226 million m^3 of groundwater form the renewable storage which can be considered for extraction in the active management of the resource.

From the hydrodynamic characteristics of the infiltration and phreatic zones, Mangin proposed a classification method of karst aquifers, recently discussed and modified by El-Hakim and Bakalowicz (2007). The classification (Fig. 12.4) considers two indices, one related to the infiltration i, the infiltration delay between 0 and 1, and the second, k, related to the phreatic storage. The higher the i index, the slower the recharge flow to groundwater.

The k index, named regulating power (Mangin 1994), is the mean residence time, calculated by dividing the highest observed dynamic storage (m^3) by the mean annual transit volume in m^3/year (El-Hakim and Bakalowicz 2007). Most classical karst systems show that their regulating power is less than 1 year.

Table 12.1 Main characteristics of the recession of Vaucluse spring hydrograph during the 1997 hydrological year. They were calculated according to Mangin's method (Ford and Williams 1989)

Discharge at t_0 (23 Jan 1997)	73 m^3/s
Discharge at end of recession (6 Nov 1997)	6.9 m^3/s
α (low stage coefficient)	0.0065 day^{-1}
epsilon (coefficient of infiltration heterogeneity)	0.06 day^{-1}
Discharge of the phreatic zone at time $t=0$	27 m^3/s
t_i (infiltration duration)	70 days
Q_0 (Q max at time $t=0$, the beginning of the flood)	73 m^3/s
q_0 (infiltration discharge at $t=0$)	46 m^3/s
eta (mean infiltration "velocity")	0.0143 day^{-1}
i (infiltration delay)	0.87
Nash criterion (quality of the simulation)	97.71
Dynamic storage	359 million m^3
Remaining dynamic storage at t_i	226 million m^3
Volume of infiltration	71 million m^3

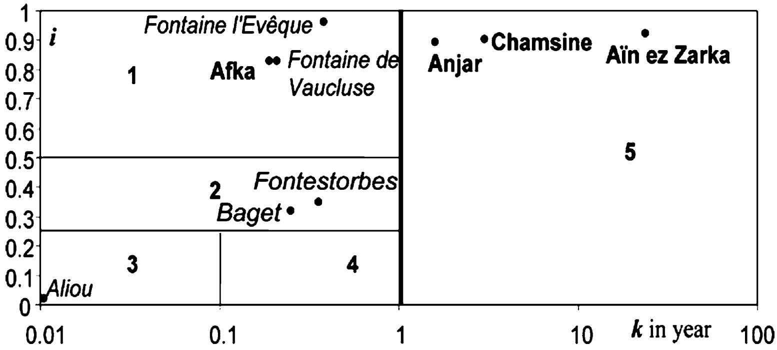

Fig. 12.4 Classification of karst systems from the recession analysis, accounting for karst systems with very large dynamic storage, corresponding to very long residence times (El-Hakim and Bakalowicz 2007)

The classification considers five domains, named 1–5 (Fig. 12.4), with the following characteristics:

1. $k<0.5$ and $i>0.5$: The domain of complex karst systems, very extensive and made up of several sub-systems;
2. $k<0.5$ and $0.25<i<0.5$: Systems where karst conduits are more developed in their upper regions than those closer to the spring, and characterized by a delayed recharge because of either non-karstic terrains, snow, or sediment cover;
3. $k<0.1$ and $0<i<0.25$: Intensely karstified systems in both the infiltration and phreatic zones, with a well developed conduit system directly connected to the spring;

4. $0.1 < k < 0.5$ and $0.1 < i < 0.25$: Systems with a well karstified infiltration zone and an extensive conduit network ending in a flooded phreatic zone;
5. $k > 1$ and $i > 0$ (in fact i should be > 0.5): Systems with a deep phreatic zone, partly or totally confined underneath impermeable sediments, and largely karstified during previous karstification phases. These karst systems named "non-functional karst systems" (13) which possess a large storage capacity due to a complex drainage structure partly or totally flooded are responsible for very long, multi-year, or secular residence times. However, the paleo-conduit networks existing in their phreatic zone remain partly functional.

From the exploitation and management viewpoint, the most useful aquifers are those of domains 1 and 5, with k values exceeding 0.1. Aquifers of karst systems classified in domain 2 may have limited utility, but only if the storage capacity is large enough to allow the regulation of the exploitation flow rate.

12.3.3 Modeling Aquifer Functioning for Managing the Resource

There have been many attempts to model the functioning of karst aquifers and conferences were specifically dedicated to this important issue (Palmer et al. 1999; Ford and Williams 1989). In managing karst groundwater resources, it is essential to predict the evolution of the spring flow and storage depending of rainfall and outflow. Modeling is then a necessary tool for predicting water levels and spring flow rate. However, when compared to porous and fractured aquifers, karst aquifers present a complexity which makes them difficult to model, such as the huge heterogeneity of the hydraulic characteristics, non-linearities and threshold effects, and the location of the conduit system. In a recent paper presenting a model for simulating the spring hydrograph of Fontaine de Vaucluse and predicting them by modeling (Fleury et al. 2007a), different types of models were presented in a short and very useful analysis.

Two types of models were used:

1. Physical or mathematical models, where heterogeneity may be taken into account by introducing several levels of porosity or permeability, such as in dual porosity models, and sometimes conduits. These models need huge amounts of data and are too complicated to be used for managing groundwater resources. Moreover, distributed models like MODFLOW are not adapted to simulate karst aquifer functioning because spatial heterogeneity is so large that it is impossible to obtain the necessary data.
2. Lumped or rainfall – runoff models, which consider that the aquifer functions as a set of reservoirs, whose characteristics are either obtained from spring hydrograph analysis.

All lumped models are particularly well suited to simulate spring hydrographs from rainfall, for instance at a daily time scale. Black-box or grey-box models, based on deconvolution or a simple or even complex transfer function, use either the time series analysis as proposed by Box and Jenkins (Mangin 1984) or neural networks. Among all the lumped models, the reservoir models are especially interesting because they give a rough representation of the aquifer whose behavior is broken up into several parts identified with its main components. However, they can be used only on the condition that the input function and the system functioning itself are stationary. This is true if the rainfall time series is not concerned with a drastic climate change, or if the system was not subject to physical changes, e.g., plugging or deplugging of conduits, high rate pumping. A reservoir model was developed using the Vensim© simulator in order to simulate spring hydrographs of some French karst springs, such as Fontaine de Vaucluse (Fleury et al. 2007a) and the Lez Spring (Fleury et al. 2009) on a daily time series for several years.

12.3.4 Different Types of Approaches for Capturing Groundwater

Karst groundwater may be exploited generally from sites not located in the conduit system. Possible sites are represented on a schematic diagram of karst system (Fig. 12.5). Pumping directly in the spring (site 1, Fig. 12.5) is possible if the spring is largely open and if the conduit is of the Vaucluse type, in order to lower as much as possible, the water table to draw down the reserve.

When the aquifer is of Vaucluse type, it may be more effective to pump from a well intersecting the drain at a depth lower than that of the spring (site 2, Fig. 12.5).

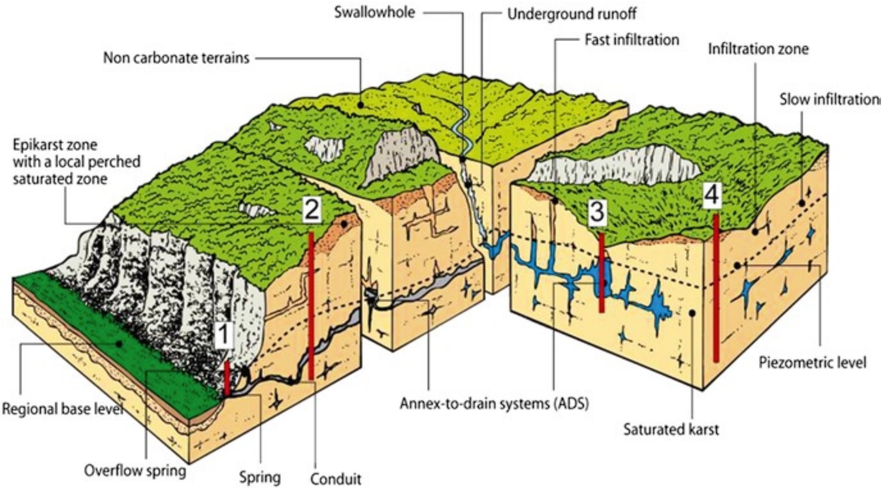

Fig. 12.5 Schematic representation of karst system (modified from 12) with the four different positions of pumping sites. *1* pumping directly in the spring. *2* pumping in (one of) the main conduit(s). *3* pumping in an annex-to-drain system (ADS). *4* pumping in a matrix block

The main difficulty is to locate the conduit from the surface. Geophysical methods are generally ineffective at revealing conduits or voids at depths more than 30 m (Al-Fares et al. 2002). When the conduit is accessible, it can be located by means of magnetic positioning, with a magnet and a proton magnetometer. This method was used for positioning boreholes intersecting a conduit at depths up to 300 m below the surface (see the case study). Pumping rates may be very high, limited by the highest possible drawdown.

When the well reaches an ADS (site 3, Fig. 12.5), usually by chance, the extraction efficiency is maximal in a Vaucluse-type aquifer, because the main conduit provides hydraulic continuity between all storage sites within the phreatic zone because it is located within confined conditions. However, in Jura-type aquifers, there is little hydraulic continuity between conduits; the ADS reached by the well acts as a local reservoir where storage is only supplemented when water levels are higher in the adjacent conduit. Then, the pumping rate may be temporarily higher than the natural flow in the conduit, because the natural flow is augmented by the volume withdrawn from the ADS. However, the volume of ADS, which is a small part of the dynamic storage of the whole aquifer, cannot be evaluated by means other than long-duration pumping tests (several weeks or even months (Marsaud 1997b)).

When the well does not reach a conduit or an ADS, statistically the most common situation (site 4, Fig. 12.5), the scenario does not favor a high pumping rate. Generally, the resource cannot be exploited from such sites. However, in some cases, especially in aquifers with a shallow water table, karst features are well developed in the phreatic zone so that the wells may intersect many enlarged joints which allow viable pumping rates. Under such situations, well fields may be developed, allowing the extraction of significant water quantities, comparable to those of alluvium aquifers. At Wadi Jilo, South Lebanon, a field of five wells in karstified upper cretaceous limestone are pumped at approximately 4 hm^3/year, i.e., 100 m^3/h for each well, suggesting relatively high hydraulic conductivity for the local aquifer (Mroueh 1997).

12.3.5 The Question of Interpreting Pumping Tests

Despite the fact that the assumptions behind the application of different models used to analyze pumping test data are not pertinent to karst aquifers (Al-Fares et al. 2002), most hydrogeologists still calculate hydraulic conductivity and storability. Those results can only be considered as general estimates, whose accuracy remains generally unknown. Moreover, these tests are often conducted over only a few days, which is too short a time to assess the effects of drawdown in a poorly transmissive medium. These results tend to be more indicative of conditions in the immediate vicinity of the well or around the conduit, if intersected by the well. From some recent tests undertaken in France by BRGM (Ladouche et al. 2006), it appears that several weeks or, better still, a few months of pumping at a rate in the same order of magnitude as the spring is the most informative method. For the moment, no numerical method of interpretation has been developed for interpreting pumping test in karst aquifers under high pumping rates over long periods.

12.3.6 Underground Dams

In highly developed karst aquifers, especially in binary KS, conduits drain most of water during a rainy season. Consequently, the storage may be trivial while the resource may be important, but great seasonal variation makes it unusable. Chinese engineers created underground reservoirs by damming conduits, either partially or totally (Bakalowicz et al. 1993). They observed that it is more efficient to build the dam inside the large conduit, not at the outlet itself because leakages occur in the shallow zone, where joints are mechanically open by the decompression occurring on the valley sides within the first 10 m below the ground surface. In South China, at Muzhu Dong, a dam completely sealing a conduit (Fig. 12.6) allowing storage of more than 3 million m^3 is used during the dry season for irrigation and water supply.

Milanovic (2000) provides several interesting examples of underground dams partially or completely sealing karst conduits in China. In order to avoid overpressure behind the dam, overflows are developed by enlarging fractures or pumping stations may pump directly into the flooded conduit from a natural pit. Some of these dams are also developed for producing electricity via an underground waterfall.

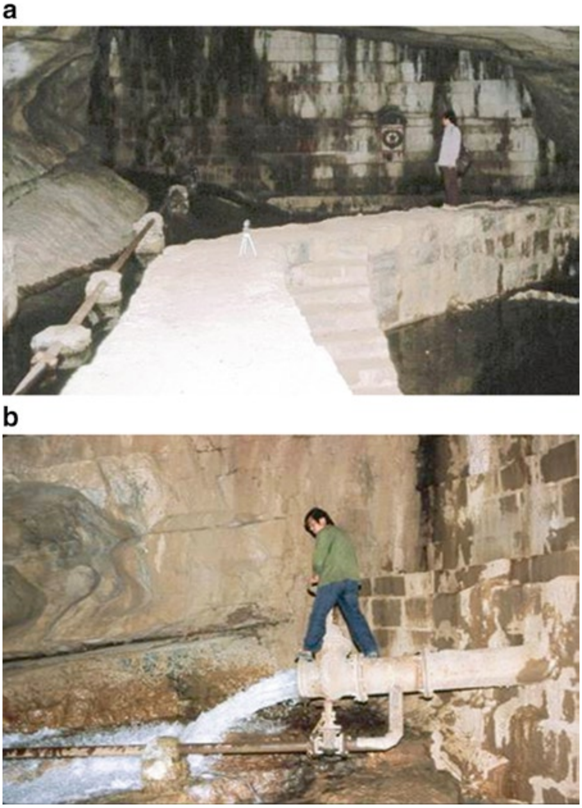

Fig. 12.6 Underground dam in Muzhu Dong Cave, Guizhou Province, China

12.3.7 Enhanced Recharge and Proactive Management

Managed Aquifer Recharge (MAR) is an emerging sustainable technique that to date has been successful in community, economic, and political spheres and is expected to solve many water resource supply and management problems, especially in the semi-arid and arid regions. Where karst aquifers are highly sensitive to overexploitation and seawater intrusion (Fleury et al. 2007b), the use of MAR could be helpful for augmenting storage in the aquifer by injecting excess water from local rivers during the rainy season, the result of which may even improve the quality of groundwater. MAR techniques (Dillon 2005) may present interesting possibilities for karst aquifers which offer exploitable groundwater resources, especially those in Mediterranean areas (Margat 2008). However, the technique has only been used in Australia (Vanderzalm et al. 2009), and there are a few similar pilot projects conducted in the USA and elsewhere.

The main difficulty in applying MAR, which is being presently explored (Daher 2010; Bakalowicz et al. 2008), is the selection of an appropriate site and method of injection. The direct injection through wells is probably not the best approach because, according to what was previously shown from pumping tests, if the injection is done directly into a conduit, water will be quickly flow away and will not be stored. It seems that the best method could be to inject water in the infiltration zone, in areas where it will not quickly reach the phreatic zone. When this method is refined, it will allow for more proactive management of karst aquifers.

12.3.8 Non-conventional Resources and Karst Aquifers

In order to satisfy the increasing demand for water, the search continues for new sources. When all known natural resources are already exploited, non-conventional resources are then considered by stakeholders. Desalinated water, treated water (Parizek 2007), and submarine groundwater discharge (SGD) are the three main non-conventional resources, in addition to reducing leakage and water conservation.

Some desalination plants in Spain (Pulido Bosch et al. 2007) prefer to pump brackish groundwater from coastal aquifers rather than sea water. Some pumping sites use groundwater from karst aquifers. However, with increasing costs of energy for desalination, an alternative may be to directly capture the fresh water of SGD from karst submarine springs (KSS). The frequent occurrence of KSS's along the Mediterranean coast has been well known since antiquity. However, only recently have they been considered as a potential, non-conventional resource that may satisfy increasing water needs. Several studies reported that KSS's along the Mediterranean coast may discharge several million to billion m^3 per year (Khawlie et al. 2000; Ayoub et al. 2002). However, the methods of those evaluations did not seem reliable and more detailed studies were undertaken in order to measure or at least evaluate the SGD from Mediterranean KSS's and to determine their origin and the reason for their particular abundance in the Mediterranean basin.

Recent investigations (Fleury 2005; Arfib et al. 2006; Cavalera et al. 2006; El-Hajj 2008; Al Charideh 2007) show that the flow rate of fresh water from KSS's had been greatly exaggerated due to the inappropriate methods and often these springs discharge brackish water during base flow. Moreover, Fleury (2005) in France, Fleury et al. (2008) in Spain, and El-Hajj (2008) in Lebanon, have shown that slight modifications in the natural as well as artificial conditions of discharge at the spring may contribute to uncontrolled intrusion of sea water. In addition, pumping at an on-shore well, even at a low rate, may stimulate sea water inflow into open conduits far inland from the coast. The reversal of flow at a permanent submarine spring was caused by an onshore pumping test at Chekka Spring in Lebanon (El-Hajj 2008).

As a consequence, coastal karst aquifers appear as particularly sensitive to every human action; therefore, their utilization must be undertaken with great caution. Detailed knowledge of their functioning, seasonal behavior, and relationships with sea water is the prerequisite to any management plan. It is necessary to reconstruct the recent evolution of the regional geology with the objective to determine the effects of the changes of the sea level. The dire need for this knowledge is shown in the Messinian crisis of salinity in the Mediterranean Basin (Rouchy et al. 2006).

The Fleury (2005), Fleury et al. (2007b), and El-Hajj (2008) studies focused on the possibility of capturing fresh water from KSS. Where SGD occurs offshore directly from a limestone formation, KSS's work generally in the same way as an onshore spring. Their discharge is highly seasonal, and overflow springs may work during floods, when the water head increases in the conduit system (Rouchy et al. 2006; Fleury et al. 2007b). However, the submarine overflow springs appear deeper than the main springs, while other overflow springs may also occur onshore. The evaluation of their discharge by different methods shows that earlier estimates were 10 or 20 times the actual values, which thereby reduced their economic significance. Moreover, the very important seasonal change in hydraulic head in the conduits and the occurrence of conduits open to the sea at different depths would create conditions favorable to natural sea water intrusion, potentially far inland. The situation may worsen if a pumping well is installed directly in a major drain. Because the sea water intrusion and the resulting mixing change considerably with hydrological conditions, the SGD water presents a wide range of salinity from 0% during floods to consisting of >60% sea water. Generally, such values suggest that KSS's cannot be considered as a future alternate non-conventional resource in coastal zones, despite the claim that their discharge might be considerable.

12.3.9 A Case Study: Lez Spring, France

Detailed studies using appropriate methodology and permanent monitoring can allow the sustainable use of karst groundwater. The best example is from Lez Spring, which was bought by the city of Montpellier, in Southern France. This spring was tapped during the nineteenth century to supply Montpellier and its suburbs by way of a 16 km long aqueduct. Until the 1960s, only natural base flow, around 300 L/s, was withdrawn. In 1969, a pumping station installed in the spring itself extracted

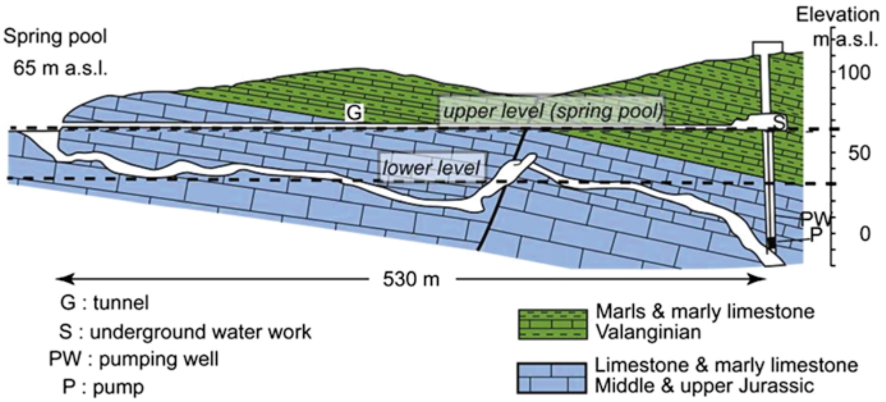

Fig. 12.7 Cross section of the Lez spring, with the main conduit, the pumping station and the upper and lower groundwater levels (source: Bakalowicz (2006))

~600 L/s, with a drawdown of 8 m. The pumps could not be placed deeper because of the shape of the conduit.

With increasing population and corresponding water demand, two conflicting projects arose during the 1970s. The first proposal was to supply Montpellier area with water from the Rhône River, which was already partly utilized for irrigation via a canal. However, the water was polluted by chemicals and hydrocarbons from the industrial zones of the city of Lyon, and needed special treatment to allow its use. The second project supported by several hydrogeological studies and proposed by Avias (1995), showed that the Lez Spring Aquifer was not recharged by concentrated infiltration from the main rivers and its storage capacity is large enough to allow a pumping rate ~1,500 L/s. These two projects involved different technical and economic approaches. After a long dispute, augmenting the city's water supply using the aquifer was the proposal finally chosen by the municipality. Thirty years of extraction without overuse shows that the chosen solution and the management method worked perfectly thanks to accurate knowledge of the aquifer characteristics.

Since 1980, four wells were installed 500 m upstream of the spring, crossing the main conduit 75 m below the spring level, i.e., at −10 m below sea level. The extraction flow rate is on an average 1,300 L/s (41 million m^3/year), with a maximum of 1,500 L/s, while the mean inter-annual flow rate is around 2,250 L/s, with a range of 40 and 90 million m^3/year (1981–2003). The new pumping station and the conditions of withdrawal were designed after detailed studies (Avias 1995; Bakalowicz 2006), have been controlled and modeled (Fleury et al. 2009) and are strictly defined by regulations. Thanks to the monitoring network, no overexploitation and pollution has occurred. Figure 12.7 shows a cross section of the spring area, with the pumping station and the upper and lower groundwater levels.

Lez Spring is neither the first nor the most important pumping site exploiting a karst aquifer with increases seasonally in withdrawals. Many Mediterranean cities use karst groundwater resources for their water needs. Damascus, probably the largest city to do so, uses two large karst aquifers (Kattan 1997). The main spring at

Figeh is pumped at a rate ~3.5 m^3/s. However, increasing demand and the erratic recharge in a semi-arid environment make its exploitation a difficult challenge.

However, there are two approaches for the use and management of regional water resources that are in direct opposition to one another. The exploitation of surface waters requires building reservoirs for regulating their natural flow and canals for transferring water. However, when groundwater is available, especially from a karst aquifer, it may also an important flow, often does not require canals due to its pre-existing conduit system (particularly when close to the spring), can have potentially huge reserves, and allows the natural control of withdrawals temporarily larger than the natural flow.

12.4 Quality Management of Karst Groundwater Resource

In porous and fissured aquifers, which when considered at an appropriate scale, can be delineated into homogeneous, protection zones using isochrones, i.e., lines corresponding to equal transit time to the spring or well captured for water supply. According to national or regional regulations, the 40-day or 50-day isochrone represents the upper limit of the protection zone. It is considered that a residence time of 40–50 days is sufficient for eliminating all pathogenic bacteria and to control the arrival of pollutants.

In karst, the presence of surface features, well connected to conduits and zones of preferential flow up to several tens of kilometres in length, would oblige the consideration of the whole recharge area, comprising even the non-karst regions. Until recently, such an approach led stakeholders to an impasse and scientists to look for a more appropriate method (Doerfliger et al. 1999; Zwahlen 2005). The issue is that many karst systems are large, from several tens or hundreds of km^2, hence it is impossible to impose strict conditions in terms of planning and control of human activities in such an area.

A final issue is how to determine the vulnerability of a karst system. This chapter will not give a detailed description of the different methods proposed by the European Action COST 620 (Petelet-Giraud et al. 2000) and subsequent individual karst research efforts. They are somewhat identical in their approach, so briefly presented here is the RISKE method (Petelet-Giraud et al. 2000) which was developed following the EPIK method (Doerfliger et al. 1999); because EPIK requires too many data, and is impossible or too expensive to collect for large karst systems.

Vulnerability mapping methods are inspired by the DRASTIC method (Aller et al. 1987). DRASTIC was developed by the US Environment Protection Agency for assessing the intrinsic vulnerability of groundwater to pollution. It is based on numerical counting of parameters considered for vulnerability mapping (depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone media, and hydraulic conductivity). Instead of these parameters, some of which are not important in karst, the RISKE method has five criteria:

- Reservoir rock (R),
- Infiltration potential (I), only function of the terrain slope,

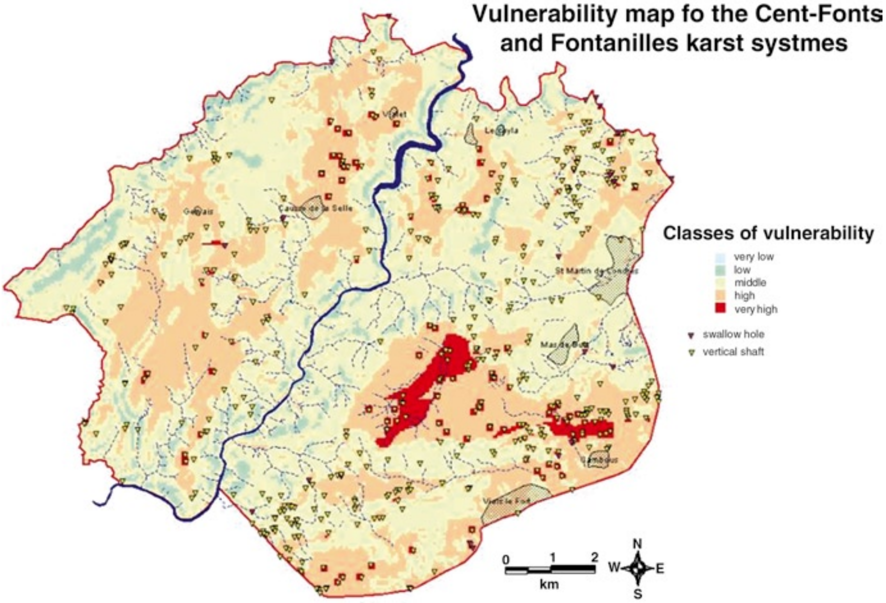

Fig. 12.8 Vulnerability map of Cent-Fonts and Fontanilles karst systems north of Montpellier. Areas in red are the most vulnerable to pollution while those in light blue are the least vulnerable (from Petelet-Giraud et al. 2000)

- Soil (S), often grouped together with the epikarst (E), and
- Development and behavior of karst (K).

Some of the criteria are obtained directly from existing documents: Geological map for R, topographical map for I, soil map for S. The epikarst E is mapped from field observations and a karst database. The karst behavior is determined for the whole system from literature and field observations. A synthetic map is finally built by allocating at each mesh or points of the grid a value of vulnerability calculated by:

$$V = a * R + b * I + c * S + d * K + e * E$$

V is the vulnerability in the considered mesh, and a, b, c, d, and e are coefficients of the considered criteria R, I, S, K, and E. These coefficients are rated according to the importance of each criterion, and must be tested for each study site. The experience shows that epikarst together with soil is certainly the most important criterion in mitigating pollution, either diffuse or concentrated. The final map describing the vulnerability of groundwater resource is one component to be considered during the process of creating resource protection zones. Figure 12.8 presents an example of vulnerability map using the RISKE method on two karst systems north of Montpellier, France (Petelet-Giraud et al. 2000). Areas in red and pink are the most vulnerable so that particular protection measures must be taken in order to protect the groundwater resource in those locales.

12.5 Conclusions

On a practical level, karst aquifers often provide an important groundwater resource. They can be highly productive, with rapid discharge through conduits and large cavities, though these are difficult, if not impossible, to locate from the surface. The complex evolution of karst due to changes in base level, particularly in Mediterranean regions, may give them a large storage capacity which is the key for long term withdrawals at high pumping rates, if combined with well informed regulation.

Methods now exist for karst systems that are very different to those used for porous aquifers, allowing the exploitation, management, and protection of karst water resources. Examples show that the exploitation must be based on the analysis of aquifer functioning and monitoring in the vicinity of the spring. However, the exchange of experiences comparable to what was done in Europe for the protection of karst resources is absolutely necessary for improving the methods and adapting the regulations to this complex medium, that is karst.

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