# Chapter 5 Surface Waters and Groundwater in Karst

**Chapter** · March 2015

DOI: 10.1007/978-3-319-12850-4



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# Chapter 5
# Surface Waters and Groundwater in Karst

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## 5.1 Introduction

Karst is defined as a terrain, generally underlain by limestone or dolomite, in which the topography is chiefly formed by the dissolving of rock, and which is characterised by sinkholes, sinking streams, closed depressions, subterranean drainage and caves (Field 2002). A wide range of closed surface depressions, a well-developed underground drainage system and a strong interaction between circulation of surface water and groundwater typify karst. Due to very high infiltration rates, especially in bare karst, overland and surface flow is rare in comparison with non-karst terrains.

Carbonate rocks are more soluble than many other rocks. They are subject to a number of geomorphological processes. The processes involved in the weathering and erosion of carbonate rocks are many and diverse. The varied and often spectacular surface landforms are merely a guide to the presence of unpredictable conduits, fissures and cavities beneath the ground. But at the same time, these subsurface features can occur even where surface karstic landforms are completely absent. Diversity is considered as the main feature of karstic systems. They are known to change very fast over time and in space, so that an investigation of each system on its own is needed. Karstification is a continuous process governed by natural and man-made interventions.

In karst terrains, groundwater and surface water constitute a single dynamic system. The groundwater and surface water are hydraulically connected through

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Z. Stevanović (ed.), *Karst Aquifers – Characterization and Engineering*,
Professional Practice in Earth Sciences, DOI 10.1007/978-3-319-12850-4_5

numerous karst forms which facilitate and govern the exchange of water between the surface and subsurface (Katz et al. 1997). A complex underground conduit system, as well as interplay of pervious and impervious layers of karst massif are an inherent characteristic of many (practically all) karst systems. Groundwater and surface water exchange with both adjacent and distant aquifers through underground routes or inflows from surface streams, natural lakes and in recent time artificial reservoirs. Due to this reason, one of the almost inevitable characteristics of open streams, creeks and rivers in karst regions is that they either have partial water loss along their course or completely sink into the underground (Bonacci 1987).

de Marsily (1986) states that the study of the water cycle or hydrology in its wider sense is usually divided into three separate disciplines: meteorology, surface hydrology and hydrogeology or groundwater hydrology. What is difference, and what is identical in karst hydrology and hydrogeology? Usual definitions of hydrogeology and hydrology are UNESCO and WMO (1992): (1) hydrogeology is branch of geology, which deals with groundwater and especially its occurrence, while (2) hydrology is science that deals with the processes governing the land areas of the Earth and treats various phases of the hydrological cycle. From these definitions is hardly possible to strictly distinguish between the two scientific disciplines. In engineering practice, the division is grounded in argument that hydrology deals with surface water and hydrogeology with groundwater. However, strictly enforcing such division could have harmful consequences on the development of both sciences, especially in case of investigations of the karst water circulation. Synthesis of hydrogeological and hydrological approach could expedite progress in karst surface water–groundwater system understanding.

Hydrogeology generally deals with groundwater occurrence and circulation in aquifers. Aquifers are in turn geological units involved in transmission of quantities of water under ordinary hydraulic gradient. At the same time, interest of hydrology is mainly focused on water balance, which is basically accounting of the inflow to, outflow from and storage within a hydraulic unit such as a drainage basin or aquifer. Very often it is impossible and harmful to separate two above-mentioned approaches, but in practice it predominantly occurs.

Introductory part will be concluded with Atkinson's (1986) remark: "In soluble rock terrains, more than in most other terrains, the unexpected should always be expected".

## 5.2 Catchments in Karst

A catchment area (drainage basin or watershed) is the entire geographical area drained by any water body (spring, river, lake, aquifer, marsh, etc.). It is characterised by all run-off being conveyed to the same profile, outlet or the same water body zone.

Karst catchment represents complex water transport system in which heterogeneity of surface and underground karst forms, serving for flow circulation and storage, makes discovering and quantification of water through them difficult. Numerous and extremely different surface and underground karst forms make possible unexpected connections of water in karst medium space which changes in time. Changes of underground flow path during the time are caused by: (1) different recharges from different parts of surface area mainly caused by variable distribution of areal precipitation; (2) different groundwater levels (GWLs) in karst aquifers and their fast changes in time and space; (3) anthropogenic influences; and (4) exogenic and endogenic forces (Bonacci 2004).

The determination of the catchment boundaries and the catchment area is the starting point in all hydrological analyses and one of the essential data which serve as a basis for water resources protection, management, understanding and modelling of water circulation through karst massif. In karst landscape, the definition of catchment area and boundaries is a difficult and complex task, which very often remains unsolved (Bonacci 1987). The differences between the topographic and hydrological catchments in karst terrain are, as a rule, so large that data about the topographic catchment are useless in hydrological and hydrogeological analyses and water management practice. Determination of a karst catchment is an unreliable procedure due to unknown morphology of underground karst features (mainly karst conduits and characteristics of karst aquifers) and their connections with surface karst forms. The variability, in time and space, of karst aquifer as well as conduit parameters makes this process extremely sensible and complex.

**Box 5.1**

Herold et al. (2000) analysed the influence of tectonic structures on karst flow patterns in karstified limestones and aquitards in the Jura Mountains, Switzerland. In the early phase of karstification, fewer parts of the aquifer are oriented towards one spring, i.e. in this phase, there are a great number of springs with a small catchment area. As the hydrological activity increases, the respective catchment area of a spring becomes larger and deeper. Consequently, certain springs stop functioning, and the remaining active springs become larger and have a greater capacity (Bögli 1980). It is already evident in this phase that the catchment area of karst springs changes in time depending upon the water quantity and its altitude in the aquifer. This variability can be greater or smaller depending upon the local and regional geological and geomorphological conditions.

Figure 5.1 shows one relatively simple example of the GWL changes in karst aquifer. With number 1 is designated situation when the GWL is in minimum. Number 2 shows situation when the GWL is in average. Maximum GWL is designated with number 3. In this situation, the depressions in karst (mostly poljes in the karst) are flooded. Karst spring is designated with **A**. The swallow hole (ponor), **B**,

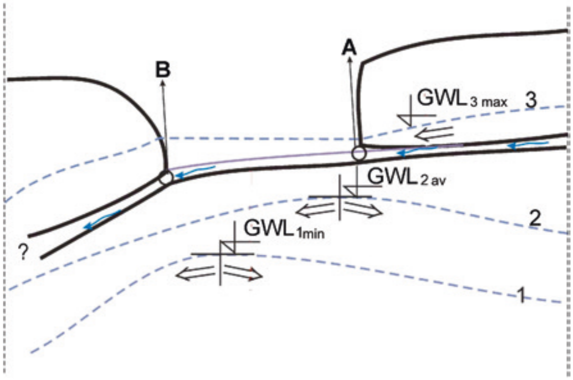



**Fig. 5.1** An example of the GWL changes in karst aquifer

during the flood can act as spring. In this case, it is an estavelle. Extremely large heterogeneities in geometric and hydraulic parameters exist in the vadose and phreatic zone. Boundary between these two zones is very fast changeable in time and space due fast raising and falling of the GWL in karst aquifers.

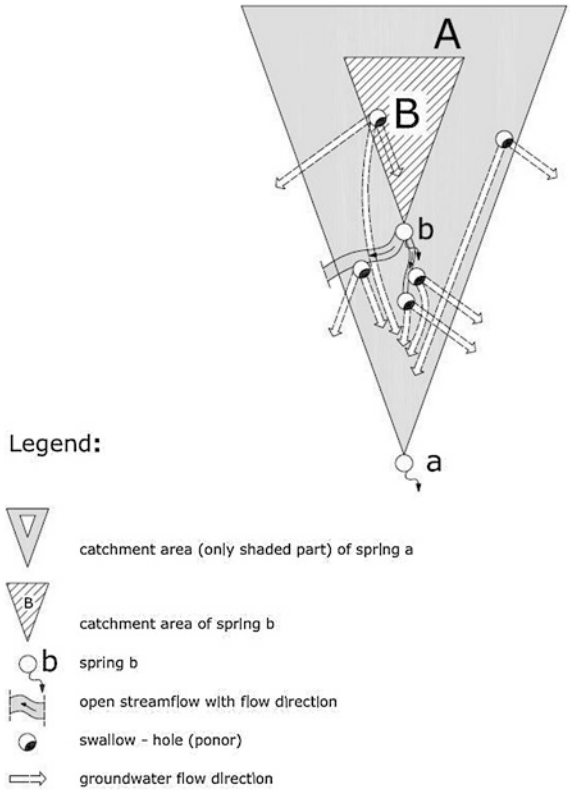
The full characterisation of the conduit network is the way to find accurate catchment in karst and to protect its water resources. In some situations at very high GWL (caused by intensive rainfall), generally, fossil and inactive underground karst conduits are activated, causing the redistribution of the catchment areas, i.e. overflow from one to other catchment (Roje-Bonacci and Bonacci 2013). Limited maximum outflow capacity of karst springs (Bonacci 2001a) and limited inflow capacity of swallow holes (ponors) cause overflow from one catchment to the other in large karst space.

Earthquakes may cause collapses of surface (mostly doline) and subsurface features (caves and large conduits) in karst areas. This can be reason of instantaneous changes of water circulation and redistribution of catchments. Especially in recent time anthropogenic actions in karst (inter-basin water transfer, dams and reservoirs, groundwater pumping, motorway and railway construction, etc.) strongly, suddenly and generally unpredictably affect natural hydrological and hydrogeological regime at the local and even large regional scale (Bonacci and Andrić 2010).

Figure 5.2 is an attempt to present schematically all possible relationships of water circulation between two karst springs (**a** and **b**) and their topographic catchment areas (**A** and **B**). Water from the spring, **b,** with catchment, **B,** can flow by surface stream to the catchment, **A,** or to any other catchment. Water sinking in the swallow hole located in the catchment, **B,** can reappear in the same catchment or in the catchment, **A,** as well as in any other catchment. Water sinking in swallow holes located in the catchment, **A,** can reappear in the same catchment or in any other catchment excluding the catchment, **B**.

Figure 5.3 represents seven possible relationships of water circulation between two karst springs (**a** and **b**) and their topographic catchment areas (**A** and **B**). It should be stressed that in reality there are much more possible combinations. These examples are given with the goal to point out on changes of catchment areas

**Fig. 5.2** Schematic presentation of all possible relationships of water circulation between two karst springs (*a* and *b*) and their topographic catchment areas (*A* and *B*)




depending on existence of different karst phenomena: (1) swallow hole; (2) open stream; and (3) losing stream. Hydrologic catchment areas are designated as, $\mathbf{A_a}$, and, $\mathbf{A_b}$, for springs, **a**, and, **b**, consequently.

Possible explanation of the GWL influence on the hydrological functioning of karst springs is given in Fig. 5.4. Explanation of the estavelle functioning and flooding of karst depression (mostly polje in karst) is given in Fig. 5.4a. If the spring **b** is at higher altitude than spring **a,** it can be intermittent, when the GWL in its topographic catchment is lower than spring **b** exit (Fig. 5.4a, b). Figure 5.4c presents how different geological setting (existence of low permeable rocks) influences on the hydrological functioning of the spring, **b**.

## 5.3 Karst Aquifers

Aquifer is rock formation that is able to retain large quantities of water (White 2002). The specific characteristic of karst aquifer is the existence of solutionally and by erosion generated and permanently enlarged karst voids of different

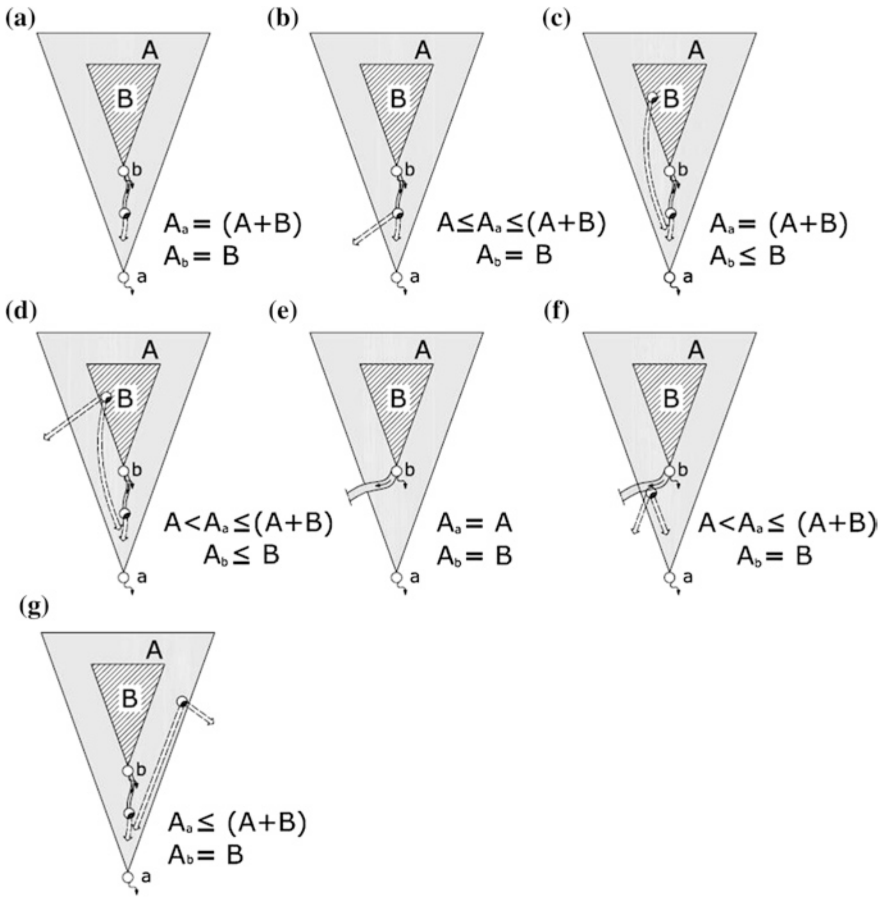



**Fig. 5.3** Seven possible relationships of water circulation between two karst springs (*a* and *b*) and their topographic catchment areas (*A* and *B*) shoved in Fig. 5.2

dimensions. Circulation of groundwater in karst aquifers is quite different from water circulation in other non-karstic-type aquifers. In karst aquifers, water is being collected in networks of interconnected cracks, caverns and channels. The extremely enhanced heterogeneity of karst aquifers is caused by multiple porosity and anisotropy (Ford and Williams 2007).

Karst aquifer triple permeability (matrix, fissures and fractures and conduits) results in its heterogeneity and anisotropy. Water flowing through karst aquifer continuously dissolves surrounding rocks and spreads the dimensions of preferable voids. Process of karstification is temporal variable and relatively rapid in comparison with common geological processes. Each karst aquifer has specific hydrogeological, hydrological and hydraulic characteristics. There are three different types of karst aquifer: (1) only with large karst conduits; (2) only with narrow karst joints; and (3) system combined of highly developed and interconnected

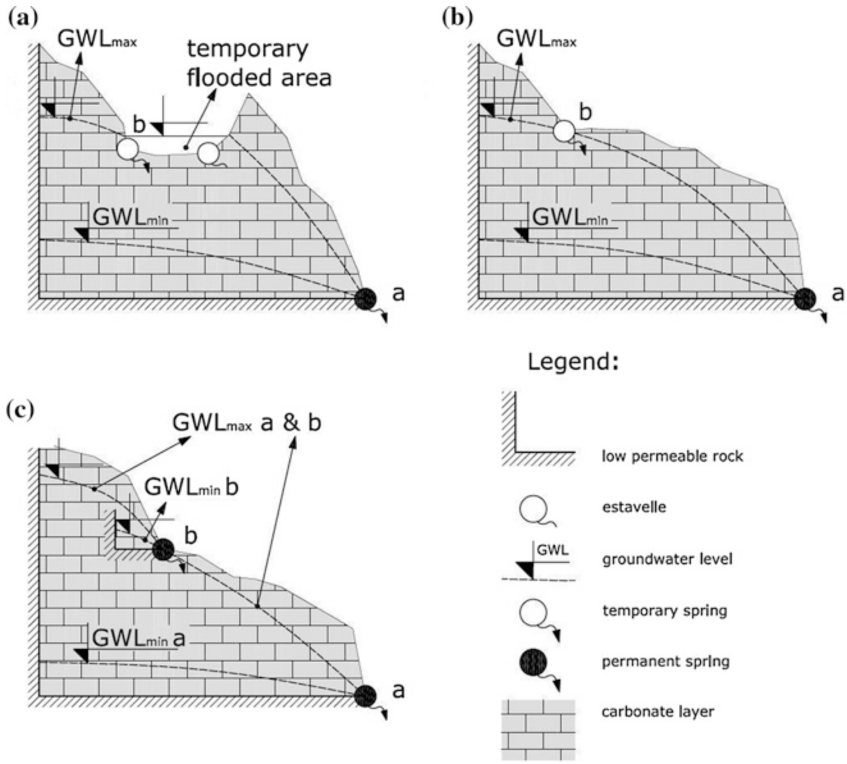



**Fig. 5.4** Explanation of the GWL influence on the hydrological functioning of karst springs

large karst conduits and narrow karst fissures (Bonacci 1993). In karst aquifer, generally, it is not possible to define representative elementary volume, as it is case in other non-karstic aquifers.

Due to generally unknown spatial distribution of the karst conduit network and interplay between high and low permeable layers, the hydraulic conductivity of karst aquifers is extremely anisotropic and heterogeneous. The conduit porosity of karst aquifer ranges from solutionally widened joints and bedding planes with apertures of about 1 cm to large and irregularly shaped channels many metres in diameter.

Karst aquifers are generally continuous. However, numerous subsurface morphologic features in karst massive (caves, jamas, fractures, faults, impermeable layers, karst conduits, etc.) strongly influence the continuity of the aquifer, so that an aquifer commonly does not function as a continuum in a catchment especially during periods of abrupt groundwater rise. One of the most important characteristics of karst aquifers is the high degree of heterogeneity in their hydraulic properties. Karst aquifers can be very deep (hundreds of metres) with endless cracks, fractures, joints, bedding planes and conduits serving as groundwater pathways. In karst aquifer investigations, problem is that subsurface water is highly heterogeneous in terms of location of conduits, location of vertically moving water and flow velocities. Karst aquifers are some of the most complex and difficult systems to decipher. The highly heterogeneous nature of karst aquifers leads to the inability to predict groundwater flow direction and travel times. For karst aquifers' investigation, special challenge represents existence of concurrent fast turbulent flow through large karst conduits and slow, diffuse laminar flow through small karst fissures, joints, cracks and bedding plains. There exists a significant and permanently present interaction between these two types of flow.

Great variability of surface and underground karst forms, interplay of pervious and impervious layers as well as fast and large range of the GWL rising and decreasing in karst massif creates practically endless possibilities of contact between two or more karst aquifers which can belong and feed to different karst water bodies. In last about hundred years and especially in recent time, anthropogenic influences created new and very fast redistribution of surface water and groundwater in karst areas, which had caused changes of connections between aquifers of neighbouring (in some cases distant) karst springs and/or other water bodies (Bonacci 2004). De Waele (2008) explained the case of the Su Gologone karst springs influenced by the different water level in reservoir which is located downstream of them. Milanović (1986) found that the submergence of the karst spring zone of the Trebišnjica River (Dinaric karst of Bosnia and Herzegovina) affects the dynamic and emptying of the karst aquifer, which causes the redistribution of catchments of many karst springs.

**Box 5.2**

Figure 5.5 represents an attempt to schematically expose all possible relationships between the aquifers of two karst springs, **a** and **b,** showed in Figs. 5.2 and 5.3. In Fig. 5.5a, b, two aquifers are not connected. The spring acts as intermittent when the $GWL_{min}$ is lower than spring exit. In Fig. 5.5c, d exists overflow from the aquifer of the spring **a** to the aquifer of the spring **b** and vice versa, respectively. Figure 5.5e presents overflow of groundwater from both analysed springs in any other catchments. Overflow appears only after heavy precipitations and generally last short time (maximum few days after the rainfall termination). Figure 5.5f represents existence of underground connection between two analysed springs. It can last different time during the year depending on relationship between the GWLs. Figure 5.5g shows case when groundwater from aquifer of the spring, **b,** emerges on the surface and by this way feeds aquifer of the spring, **a**. Example given in Fig. 5.5h shows possibilities of existence overflow as well as underground contacts between the aquifers of two analysed springs. It is obvious that in reality exist more different cases.

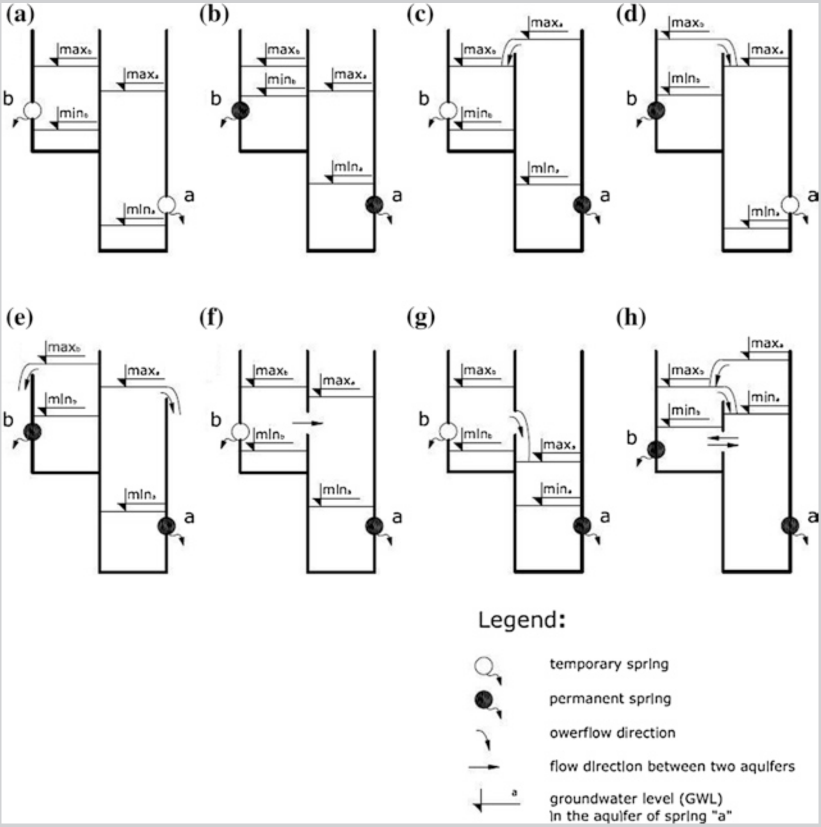



**Fig. 5.5** Schematic presentation of all possible relationships between the aquifers of two karst springs, *a* and *b*

Underground flow direction is controlled by the GWL in neighbouring aquifers. As it is previously stressed, the GWLs in karst are extremely variable in time and space, as well as in different parts of them. Shape of the GWL in karst aquifer strongly depends on spatial distribution of intensive precipitation in analysed catchment. The catchment area of karst spring can be larger than 100 $km^2$, while cells of intensive precipitations (which cause fast GWL rising) are rarely larger of 5–10 $km^2$. It means that the GWL rising exists in only one part of the catchment area of the karst aquifer (Eagleson 1970; Dahlström 1986). For each case of intensive precipitation, it can be different part of the aquifer.

Figure 5.6 schematically presents connection between two neighbouring karst spring aquifers. Discharge from the spring **b** aquifer to the spring **a** aquifer, $Q_{a-b}$, depends on dimension of area through which groundwater flow, hydrogeological and hydraulic characteristics of this area and slope of the groundwater piezometric

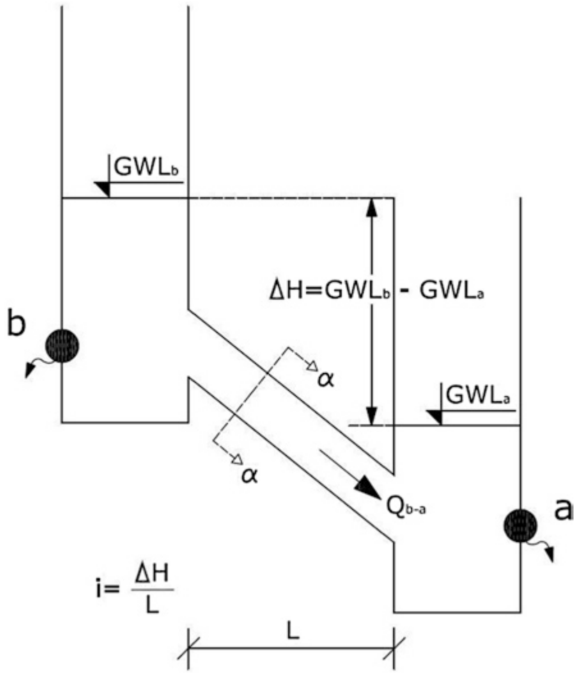



**Fig. 5.6** Schematic presentation of connection between two neighbouring karst spring aquifers

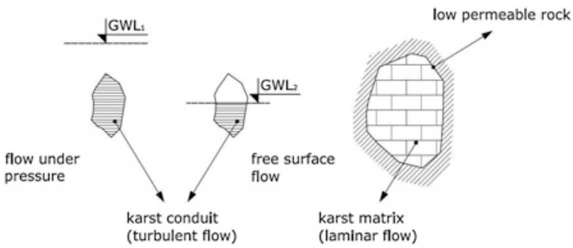



**Fig. 5.7** Three possible type of flow in karst underground

line, **i**. Figure 5.7 presents three possible type of flow: (1) flow under pressure in karst conduit; (2) flow with free surface in karst conduit; and (3) flow through karst matrix. In most cases, all three types of flow exist at the same time what depends on structure of contact area and appearance of large karst underground features in it. Along a karst conduit, the shape and diameter of its cross section can vary significantly. Because of this flow in one part of the same conduit can be partly under pressure, while in the other part can be with the free surface. These characteristics strongly influenced on the groundwater travel time to the spring or residence time in the aquifer. They can vary from few hours (if a large conduit flow prevails) to decades (if there are only small karst joints).

Figure 5.8 is schematized cross section through karst massif which connected Prespa and Ohrid Lakes (Macedonia, Greece and Albania). The Prespa Lake does

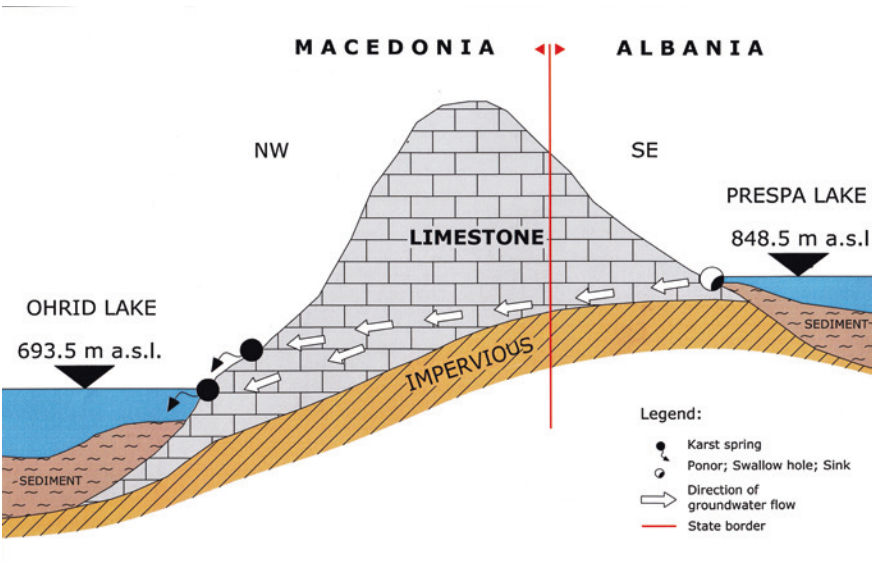



**Fig. 5.8** Schematized cross section through karst massif which connected Prespa and Ohrid Lakes (Macedonia, Greece and Albania)

not have surface outflow. The waters from it outflow through karst underground massif into the Ohrid Lake (Popovska and Bonacci 2007).

For karstified rocks, the hydraulic conductivity depends on the density and aperture of the joints existing in karst matrix. Fractures may either seal with time or increase in aperture as a consequence of natural or anthropogenic actions. Hydraulic conductivity **K** of karst massive varies in range $10^{-4}$–$10^{-1}$ m/s and generally decrease with depth (Perrin et al. 2011).

**Box 5.3**

Using Dupuit's assumption, Bonacci (2001b) determined hydraulic conductivity **K** in the karst massif around the Ombla Spring (Croatia). In relatively small area of about 50 km$^2$, the values of the hydraulic conductivity ranged from $0.702 \times 10^{-3}$ to $26.414 \times 10^{-3}$ m s$^{-1}$ during 262 h of measurement. Changes in values of **K** in both time and space can be attributed to differences in the position of investigated pairs of piezometers, their connection with main karst conduits, their GWLs and differences in development of karstification process in the analysed karst massif. These points to a significant influence of the time and space scale effect upon the results obtained by investigations and measurements in karst. Another analysis leads to conclusion that piezometric relations in karst aquifer are more uniform during the descent than during rising of the GWL. The rising phase is relatively short and lasts 5–10 % of the year. During this time all processes are rapid, flow is mostly turbulent and more non-homogenous than during descending phase (Bonacci and Roje-Bonacci 2000).

## 5.4 Karst Springs

Karst spring can be defined as a discrete place where groundwater flows naturally from the hydrologically active fissures of the karst mass onto the land surface or into a body of surface water. Generally, spring is formed where groundwater table intersects with the earth's surface or groundwater rises to the surface through rock faults, fractures or depressions. Lehmann (1932) mentioned the karst-hydrological contrast expressed by the presence of numerous places through which the water sinks into the karstified mass, whereas there are relatively few karst springs.

Hydrological characteristic of karst springs, especially their minimum and maximum values, can be very different in comparison with same characteristics of non-karst springs. Water surfacing from the karst springs can be considered as groundwater contribution in a large scale (Rimmer and Salingar 2006). It may not actually depend on the surface area on the catchment but is a function of total subsurface area contributing to groundwater flow.

Karst morphology and water pathways within the karst massif feeding the karst springs change with altitude and outflow capacity. Due to very special and complex underground and surface karst forms, which control surface water and groundwater behaviour, there are very different cases of karst springs. As discussed in Chap. 3 in literature, there are many classifications, systematisations and/or definitions of karst springs from different points of view (Bögli 1980; Bonacci 1987; Smart and Worthington 2004) in accordance with different scientific disciplines (hydrology, hydrogeology, geomorphology, geochemistry, geography, etc.). No one of them is so many-sided that would be able to clearly explain their complex functioning.

Karst springs can be perennial (permanent) or intermittent (temporary, ephemeral or seasonal). From perennial spring, stream flows above land throughout the whole year, while from the intermittent ones flows at irregular intervals related to seasonal variations in rainfall. The intermittent spring falls dry several times or most of the year. Seasonal ones act only during a certain (wet or rainy) seasons while ephemeral springs are active only for a short time as a consequence of intensive precipitation. Intermittent springs are very often in karst areas. They flowing at irregular intervals related to seasonal variations in rainfall, which control the GWL. In many cases, ephemeral karst springs are active for a short time (few days or even hours) after intensive precipitation. Rhythmic (ebb and flow) springs are special kind of intermittent springs, which appear exclusively in karstified terrains (Bonacci and Bojanić 1991).

Andreo et al. (2009) and Ravbar and Goldscheider (2009) distinguish the following three zones of contribution and connection between karst aquifer and karst springs: (1) inner; (2) intermediate; and (3) lower. In response to hydrogeological and hydrological settings, parts of an aquifer can either permanently or temporary contribute to the spring. The inner zone comprises parts of the system that always contribute and the connection is sure and direct to the spring. The outer zone comprises the morphologically uplifted part of the system that contributes only a small portion of the total amount (less than 1 %). It could comprise part of the aquifer system that temporarily contributes to the spring. The intermediate zone is located between nearer inner and further outer zone. It represents transition between them.

Due to fact that water discharging from the karst springs integrates the signal of geological and hydrological processes over large spatial areas and long periods of time, they are an indirect source of information (Manga 2001). By using a variety of techniques and approaches (for example: isotopic tracers, water chemistry, discharge, water temperature, electrical conductivity, etc.), it is possible to determine the mean-residence time of water, infer the spatial pattern and extent of groundwater flow or estimate basin-scale hydraulic properties. All previously mentioned in combination with dense and continuous monitoring of the GWL can help in determination of karst springs catchments.

The amount of water that flows from a spring depends on several factors but mostly from the rainfall on its catchment as well as size of the spring recharge catchment. Other factors are given as: (1) the size of caverns within rocks; (2) the hydraulic characteristics of aquifer soil; (3) the water pressure in the aquifer; and (4) the size and shape of spring exit.

Human intervention, especially construction of dams and reservoirs as well as interbasin water transfers can introduce instantaneous and distinct changes in the volume of discharge from a spring and especially in changes of its extreme discharges (minimum and maximum). For example, increased groundwater withdrawals can reduce the hydraulic pressure in an aquifer, causing water levels to decline and spring flows to decrease. The increasing in the natural GWL, caused by the reservoir's construction, can lead to formation of new springs or increasing of the spring characteristic discharges (minimum, mean or maximum) (Bonacci and Jelin 1988).

## 5.5 Karst Ponors

Ponor, swallow hole or sinkhole can be defined as a hole or opening in the bottom or side of a depression where a surface stream or lake flows either partly or completely underground into the karst groundwater system, and/or as a hole in the bottom or side of a closed depression, through which water passes to an underground channel (Field 2002). Ponors are situated commonly close to the terminus of a polje. The following classification of ponors from a morphological viewpoint is given by Milanović (1981): (1) large pits and caves; (2) large fissures and caverns; (3) system of narrow fissures; and (4) alluvial ponors. Practically, all underground phenomena (jamas, karst conduits, caves and even bedding planes) can take over the function of ponors. Jamas most commonly function as ponors and present a pathway for fast and direct contact of the surface water with the karst underground.

Estavelles belong to a special type of ponors and/or springs. They have a double hydrological function. In one period, they operate as ponors. This happens generally in the dry period of the year, when the GWL in the surrounding karst massif is situated under their surface openings. In the wet period of the year when the GWL are high, they functioning as springs (Bonacci 1987).

Figure 5.9 gives a schematic explanation of a ponor swallow capacity, $_{\mathbf{P}}\mathbf{Q_O}$, (in $m^3/s$) as a function of a water level, **H** in a flooded karst area (mostly karst polje). When the flow in the main karst channel is not under pressure, **(H < H*)**, a ponor's discharge curve has a form indicated in Fig. 5.9 as, ($_PQ_O = f\ (H{-}H_1)$). When the flow in the main karst channel comes under pressure, **(H > H*)**, the discharge curve changes suddenly (point **H***, **Q*** in Fig. 5.9). Then the ponor swallow capacity depends exclusively upon the difference, $\Delta\mathbf{H_3}$, between the water level in the polje, **H**, and the level of the spring exit, $H_3$. In this case, the equation for the ponor discharge curve is given as:

$$_PQ_O = c \times A \times ((2 \times g \times (H{-}H_3))^{0.5} \tag{5.1}$$

where

| | |
|---|---|
| **c** | is the discharge coefficient (usually ranging between 0.7 and 0.9), |
| **A** | is the average cross-sectional area of the main channel in $m^2$, |
| **g** | is the acceleration of gravity in m $s^{-2}$, |
| ($\Delta H_3 = H{-}H_3$) | the dimension of difference given in metres |

If there is a large cave system in the karst massif that is never completely filled with water, that is, if flow under pressure does not exist all the way up to the spring level, then the difference between water levels, $\Delta\mathbf{H_2}$ is less than $\Delta\mathbf{H_3}$, and the discharge coefficient $\mathbf{c_2}$ is different from $\mathbf{c_3}$. In general, $\mathbf{c_3}$ exceeds $\mathbf{c_2}$.

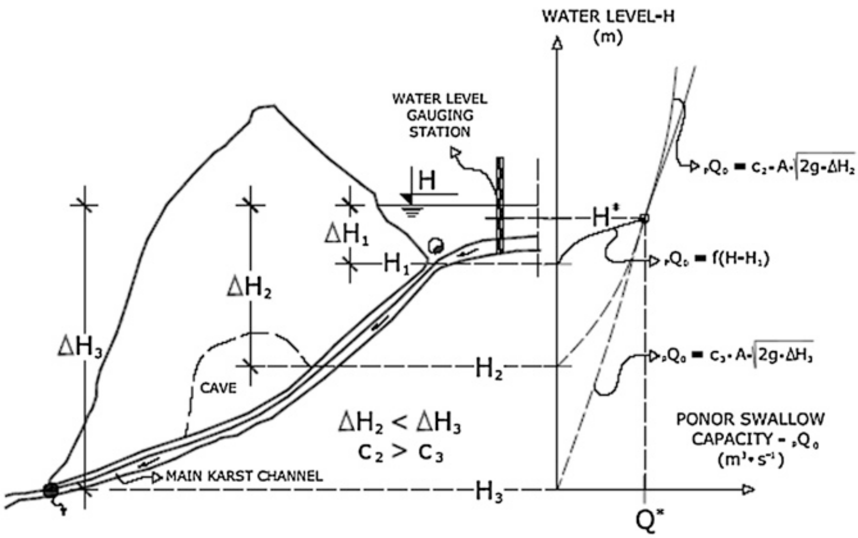



**Fig. 5.9** Schematic explanation of a ponor swallow capacity

This explanation is valid for the case where the ponor swallow capacity is not under influence of the GWL in the adjacent karst massif. When the GWL (**$H_{GWL}$**) is higher than the water level (**H**), the ponor acts as an estavelle. When the GWL, (**$H_{GWL}$**), is lower than water level (**H**), the ponor swallows water and its capacity depends upon the difference ($\Delta \boldsymbol{H} = \boldsymbol{H} - \boldsymbol{H}_{GWL}$) (Bonacci 2013).

## 5.6 Karst Open Streamflows

Flow regime in open streamflows in karst depends mostly upon the interaction between the groundwater and the surface water (Bonacci 1987). The GWL in karst greatly depends upon the effective porosity of the matrix, while groundwater connections between different parts of karst massive as well as some open streamflows depend on the existence, features and dimensions of karst conduits. Some of these conduits recharge, while some drain off water from the rivers in karst. Generally, recharging or drainage depends on the GWL. The influence of karst differs from one streamflow to another, and therefore general conclusions should be carefully drawn.

Open streamflows in karst very often disappear underground a number of times and emerge again in different karst springs, usually under a different name. Sinking, losing and underground streams are frequent karst phenomena. Their occurrence in karst terrains is more the rule than the exception. Such streamflows are more typical, significant and relatively frequent karst phenomena than is reflected in their treatment in the karst literature (e.g. Hess et al. 1989; Yuan 1991; Bonacci 1999; Potié et al. 2005; Bonacci and Andrić 2008; Prelovšek et al. 2008; Cavalera and Gilli 2009; Bonacci and Andrić 2010; Bonacci et al. 2013). A synonym for a sinking and losing stream is an *influent stream*. Such streams have an integral function in karst hydrology and hydrogeology.

A losing streamflow can be defined as an open streamflow that loses water as it flows downstream. A losing streamflow is a surface stream that contributes water to the karst groundwater system in localised areas. It has cracks in its bed that allow water to seep into the groundwater. These losses can be massive in particular river sections, whereas in others they are small and difficult or even impossible to observe without performing especially precise measurements. Losing streams segments are important groundwater recharge zones for underlying karst aquifers. The water level in a losing stream is higher than the GWL, as opposed to the water level in a gaining stream which is lower than the GWL. Due to very rapid rise and fall of the GWLs in karst terrains, some losing rivers or their losing stretches can intermittently act as gaining streams. Figure 5.10 presents an attempt at the conceptualisation of losing streamflows. Water infiltrated from these sections can either flow in another catchment or can reappear in the downstream reaches of same river (at the spring, **B** in Fig. 5.10b).

Occasionally, permanent water courses flow beyond the GWL, even for 50 m or more. Bonacci (1987, 1999) called these river sections “suspended” or “perched”.

A sinking surface streamflow can be defined as a surface river or stream flowing onto or over karst that then disappears completely underground through a swallow hole (ponor or sinkhole) and which may or may not rise again and flow as a resurgent surface river or stream. Infiltration from sinking streams into the karst groundwater

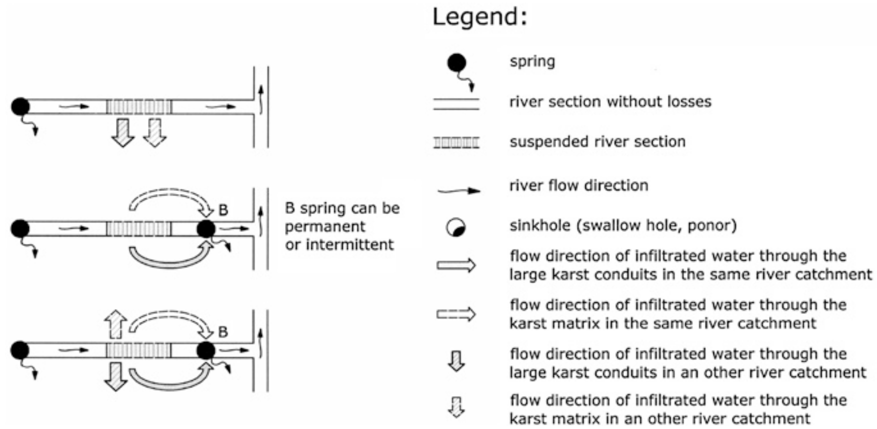



**Fig. 5.10** An attempt for the conceptualisation of losing streamflows

system is the most rapid form of recharge for carbonate aquifers (Hess et al. 1989). Sinking streams represent the most direct access to the sensitive and highly vulnerable karst groundwater system. The unique nature of sinking rivers is their development and evolution of conduit flow routes and caves through soluble rocks. The evolution of most of the world's largest and most significant karst caves and springs is formed as a consequence of large volumes of concentrated recharge from sinking rivers (Ray 2005). Figure 5.11 presents an attempt at the conceptualisation of sinking streamflows. Sinking stream can reappear at the surface through a typically large karst spring (Fig. 5.11a) though there are some cases when it reappears through many permanent and intermittent karst springs dissipated over a large area.

Underground or subterranean streamflows are subsurface karst passages that have the main characteristics of open rivers or streams. In an underground streamflow, water flows through caves, caverns, karst conduits and large galleries in the karst underground. The karst underground system provides access to fragments of the abandoned conduit system, which have hydraulic geometries comparable, though not identical, to those of surface rivers or streams.

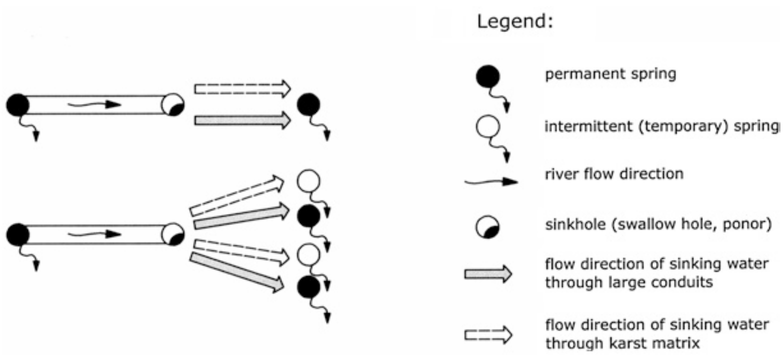



**Fig. 5.11** An attempt for the conceptualisation of sinking streamflows

**Box. 5.4**

Figure 5.12 is the map of the Disu underground stream system in China, which has a catchment area of 1,004 km$^2$ (Yuan 1991). The system has a total length of 241.1 km and includes a main conduit that is 57.2 km long and 12 tributaries. The Disu underground system is the longest identified subterranean stream in China. In the upstream section, it is about 100 m in depth, with karst conduits usually in a simple fissure-shape, from several metres to 30 m wide, and ten to tens of metres high. The average hydraulic gradient is about 12 %. At the middle and lower reaches, it is 30–50 m below the bottom of the valleys. The cross section of the conduit here varies between 145 and 184 m$^2$, and the average hydraulic gradient is 1 %. Discharges at the exit of the Disu underground river vary from the minimum 4.03 m$^3$ s$^{-1}$ in dry season to the maximum 544.9 m$^3$ s$^{-1}$ (Yuan 1991).

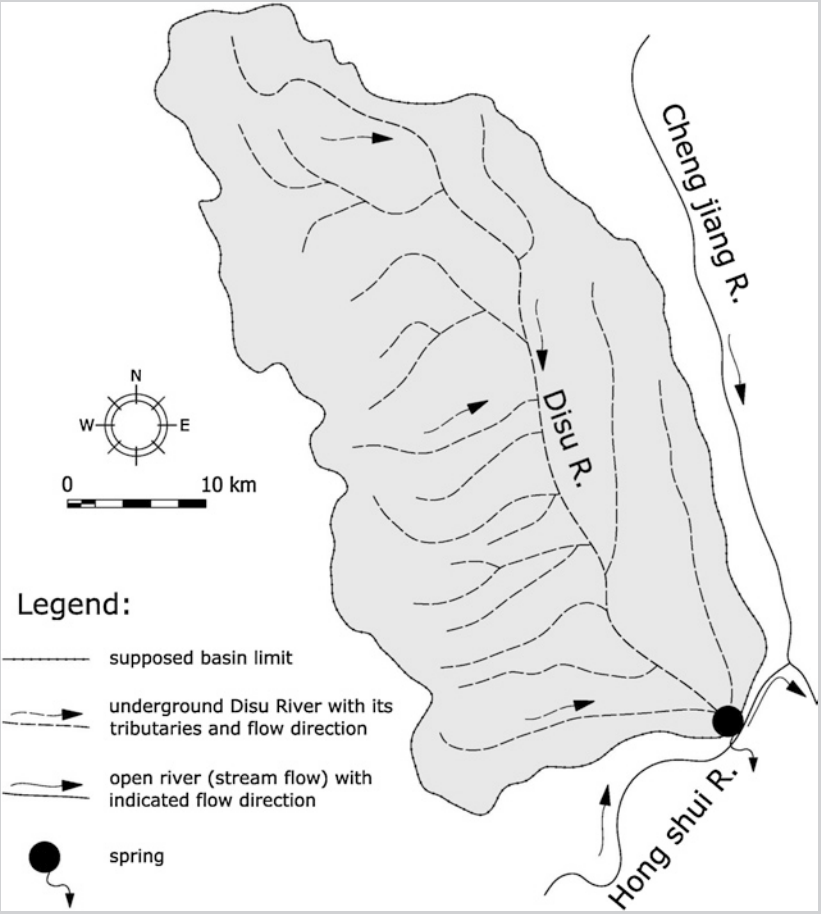



**Fig. 5.12** Map of the Disu (China) underground stream system (Yuan 1991)

Through sinking and losing streamflows, contaminants can quickly enter the karst groundwater, with little or no filtration. This can cause the rapid and extensive pollution of a downstream water body and can have a negative impact on the surrounding environment.

## 5.7 Piezometers as a Crucial Source of Information in Karst

The piezometer boreholes represent an exceptionally important source of information of a wide range, necessary for all types of investigations related to the regime of water circulation in karst. One of the main goals of the GWL measurements in karst massif is determination of the hydraulic head, which underlies the interpretation of groundwater flow, the quantification of aquifer properties and the calibration of flow models (Post and von Asmuth 2013). The measurements of the GWL as well as many other parameters (e.g. water temperature, chemical composition and electrical conductivity) in piezometers are crucial:

(1) for investigating the permeability structure of carbonate aquifers and the behaviour of groundwater in this complex system (Bonacci and Roje-Bonacci 2012);
(2) to understand interplay between surface waters and groundwater;
(3) to define changes of catchment area and boundaries during the time as a consequence of the GWL variation;
(4) to establish groundwater flow patterns;
(5) to determine the response of an aquifer to stresses such as pumping or recharging;
(6) to understand impact of grout curtains on groundwater behaviour;
(7) to identify hydrogeological units.

The changes in the GWL as well as other measured water parameters can clearly explain the characteristics of the medium in which the process of the water flow takes place. They have made it possible to explain numerous “mysteries” in the karst and realise that there are no “miracles” in the karst regions related to the water circulation (Bonacci 1988).

For all investigations in karst, of special importance is to have at disposal continuously measured the GWL in dense network of deep piezometers. In practice, this prerequisite is very rare fulfilled, not only due to high price of project, but mostly due to complexity and troubles in determination of suitable position of piezometers. According to data from the literature (Drogue 1980; Bonacci 1999; Bonacci and Roje-Bonacci 2000; Worthington 2003), only every second piezometer provides the necessary information on the water circulation in karst and aquifer characteristics. At least half of them are drilled in impermeable, compact or less permeable parts of the karst massif in which all dynamic processes of water flow are very slow.

**Box 5.5**

- The probability of intersecting a major karst conduit during the drilling of one piezometer is small. Worthington (2003) estimated that it is between 0.37 and 7.5 %.
- Yuan (1986) reported the fact that from a wells had been excavated in the Malian valley, Waxian country, Gaungxi province (China), only two yield satisfactory results, giving a discharge of 190 and 33 $l\ s^{-1}$ under 5 m drawdown. The discharges from the other seven are smaller than 0.5 $l\ s^{-1}$ with a drawdown of more than 5 m. The distance between the wells was of the order of magnitude of 100 m.
- Studying geometry of the karst aquifer over 1,000 $m^2$ experimental area in the vicinity of Montpellier, France, Drogue (1980) made continual measurements of the GWL and water temperature at 19 piezometers. This study showed that the GWL in piezometers, which were close to one another (less than 10 m), responded differently to rainfall in the catchment, mainly because of varying connections with the main karst conduits, subsurface karst features and karst springs. The GWL in piezometers connected to small fissures reacts much more slowly than in piezometers connected to main karst conduit and/or spring.

A piezometer represents a window open onto the inner side of the karst massif. The question of whether this window will be really wide open or just slightly open depends upon ability and skill of the researcher more than on the application of modern technology (Bonacci and Roje-Bonacci 2012).

Reliable GWL measurements are fundamental to all hydrogeological investigations. Post and von Asmuth (2013) worn that the measurement of the hydraulic head is not as trivial as simply lowering a measurement tape down to the water level in a borehole. Their paper aims to provide quantitative guidance on the likely sources of error and when these can be expected to become important.

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