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TITLE

GROUNDWATER FLOW IN HETEROGENEOUS MEDIA CONTAINING AQUITARDS

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Introduction

The rocks of the subsurface, because of the hydrogeological processes which they undergo have undergone since the beginning of their formation (diagenetic, tectonic and alteration processes), mainly represent heterogeneous systems in terms of physical properties, especially with regard to the characteristics of the network of discontinuities and interconnecting pores. From a hydrogeologic point of view, these kinds of heterogeneity often result in spatial variations of the hydraulic conductivity.

The groundwater flow, through the network of interconnected voids in the rocks, is governed by Richards' equation:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = S_S \frac{\partial h}{\partial t} + R$$

where:

k = hydraulic conductivity;

h = hydraulic head;

Ss = specific atorage;

t = time

R = sink / source term.

From this equation, the fundamental role played by distribution of permeability in the subsurface on the groundwater flow, both in steady flow and unsteady flow conditions is, therefore, clear. The effect yielded by the permeability variations on the groundwater flow have has been evaluated, especially through the development of numerical models (Tòth, 1963; Freeze and Witherspoon, 1967). As pointed out by Cherry et al. 2006, this is crucial for assessing the ability of the hydrogeological systems to counteract the migration of contaminants in groundwater.

Hence, a good understanding of the functioning mechanisms of the heterogeneous hydrogeological systems is essential in order to provide an effective planning tool aimed at the optimal management of groundwater resources.

Eaton and Bradbury (2003) and Eaton et al. (2007), emphasized the importance of the usage of sophisticated multilevel monitoring systems in accurate reconstructions of the flow patterns, especially in cases in which the subsurface is characterized by spatial permeability variations.

Nevertheless, the research based on the use of multilevel monitoring systems is still in its infancy. Perhaps because of their complexity, heterogeneous systems have been little studied so far. For these reasons, the present work aimed towards the refinement of knowledge regarding the hydrogeological functioning of such systems, with reference both to those in which the formations with low permeability are dominant, and to those in which the aquitards represent only a marginal component of the entire groundwater basin.

In greater detail, two articles have been yielded:

the first work, entitled "*Groundwater flow dynamics in heterogeneous sedimentary sequences. A study case in Southern Italy*", (Aquino et al., 2013), is under review at the journal Hydrological Processes;

the second work, entitled "*Role of the heterogeneity in dynamic groundwater flow systems. Experimental evidence in a carbonate aquifer (Southern Italy)*", (Aquino et al., 2013), is currently being submitted to an ISI journal.

Both works were developed on sedimentary successions outcropping near Longano (Isernia, Southern Italy).

With regard to the way in which the research was structured, due to the initial hydrogeological knowledge, it was not deemed appropriate to start the research by using the aforementioned sophisticated monitoring techniques. Hence, in both cases, the study was based primarily:

- ✓ on the reconstruction of the physical model for the subsurface through geological survey and/or the employment of geological and hydrogeological data drawn from the available scientific literature;
- ✓ direct observation of different hydrogeological parameters, such as hydraulic heads, spring discharges, stream flow, electrical conductivity and isotopic content (with respect $\delta^{18}O$) of the groundwater.

This approach has, however, allowed for the development of reasonable conceptual models concerning the functioning mechanisms for the investigated hydrogeological systems, broadening the spectrum of the predictable scenarios.

Groundwater flow dynamics in heterogeneous sedimentary sequences. A study case in Southern Italy

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ABSTRACT

The sedimentary sequences containing lithologic units with low permeability represent hydrogeologic systems which, as of now, have been little studied despite their diffusion worldwide. A hydrogeologic study, aimed to assess the main factors controlling the groundwater flow dynamics in such systems, has been carried out in Longano (Isernia, Southern Italy), on a sequence dominantly made up of shales and marls, surrounded by a carbonate aquifer, considered an important source of groundwater supply.

The analysis of the hydraulic heads, combined with the regimes of the springs and the electric conductivity (EC) of the groundwater, mainly reflect vertical and lateral heterogeneities of the media in terms of hydraulic properties. In particular, close to the carbonate relief, where clayey colluviums envelope discontinuous, receptive carbonate debris, the spring flows are controlled by contrasts of permeability and are separated from the deeper saturated, fissured bedrock.

Here, one-to-ten relationships in hydraulic heads, monitored in different piezometers, further uphold the crucial role played by the lateral contrasts of permeability in controlling the flow dynamics. In agreement with the stratigraphic information and the planimetric distribution of the hydraulic heads, the deeper part of the fissured media, in which the EC values are not influenced by seasonal recharge, could act as an aquitard. However, significant interactions with the nearby carbonate hydrostructure take place, as indicated by the isotopic content of the groundwater and confirmed by the variations of the stream flow, periodically gaining and losing.

Since the hydrogeologic functioning mechanisms of the heterogeneous sedimentary sequences behaving as aquitards have important implications concerning both the usage and the protection of groundwater resources, it follows the need to refine their knowledge through experimental activities.

KEY WORDS: Aquitard; Groundwater flow; Heterogeneity; Silico-clastic sequence.

INTRODUCTION

Aquitards are rocks which, do not usually allow the discharge of considerable amounts of groundwater. Therefore, they are not considered as economically usable sources of groundwater supply, and they are usually conferred only marginal importance (Cherry *et al.*, 2006). In addition, aquitards could lead to very complex groundwater flow schemes, especially within ~~the~~ heterogeneous sedimentary sequences (Freeze and Witherspoon, 1967; Eaton and Bradbury, 2003; Cherry *et al.*, 2006). It is probable that, considering these aspects, detailed studies regarding this kind of hydrogeological systems are, today, still relatively rare. However, aquitards can play an important role in the control of the groundwater regional circuits (Tóth, 1995), can restrict the recharge area for the adjacent aquifer systems (Cherry *et al.*, 2006), can yield very long change in hydraulic heads in response to the pumping well occurring in adjacent aquifers (Javandel and Witherspoon, 1969; Alley *et al.*, 2002; Eaton *et al.*, 2007) and could be able to protect the aquifer systems with respect to the chemical and biological pollution (Ponzini *et al.*, 1995; Cherry *et al.*, 2006).

In Italy, there are conspicuous volumes of heterogeneous sedimentary rocks, so far believed to be aquitards. A copious amount of these rocks is represented by Oligo-Miocenic silico-clastic sequences found in the Apennines. Some studies carried out in the Northern Apennines have demonstrated that the silico-clastic sequences could also behave like aquifers, allowing the discharge of high flow rates of groundwater (Gargini *et al.*, 2008; Vincenzi *et al.*, 2009), contrary to what was assumed before then (Pranzini, 1994; Gargini, 2000). Therefore, an adequate understanding of the role that aquitards play in flow dynamics is crucial in order to improve the management of groundwater supply. Considering their importance, in the light of the relative lack of knowledge, Neuman and Witherspoon (1969) emphasized the necessity to refine the methods of analyzing the field data regarding heterogeneous media containing aquitards.

In the Southern Apennines, detailed studies carried out on these silico-clastic rocks allowed for the observation of a rapid decrease of the hydraulic conductivity in relation to the depth (Petrella and Celico, 2009). However, a weathered, undetensioned, surficial horizon, about 20 m thick, shows values of the hydraulic conductivity comparable with the values estimated for the nearby carbonate aquifer (Celico, *et al.* 2006; Petrella *et al.*, 2007). Consequently, where the saturated zone of the carbonate aquifer adjoins this highly permeable horizon, the transfer of plentiful volumes of water between the two different systems could take place. Compatibly with this scenario, in a test site close to the town of Longano, it was demonstrated that the groundwater circulating through the Oligo-Miocenic silico-clastic sequence comes from the surrounding carbonate aquifer (Petrella and Celico, 2009). Moreover, the carbonate aquifer seems to be compartmentalized in a mosaic of sub-domains by means of a network of fault zones, acting as permeability barriers (Celico *et al.*, 2006). Between adjacent sub-structures, differences in hydraulic heads of several tens of meters were observed. Thus, complex hydraulic interactions between the compartmentalized carbonate aquifer system and the heterogeneous silico-clastic sequence are expected. Therefore, through several experimental field activities, the present work aims to broaden the spectrum of knowledge regarding the heterogeneous systems which contain aquitards. In particular, an attempt to outline the role played by the heterogeneity of the silico-clastic sequence on the groundwater flow dynamics has been made, having taken into account its relationship with nearby aquifer systems (in the study case, a carbonate hydrostructure).

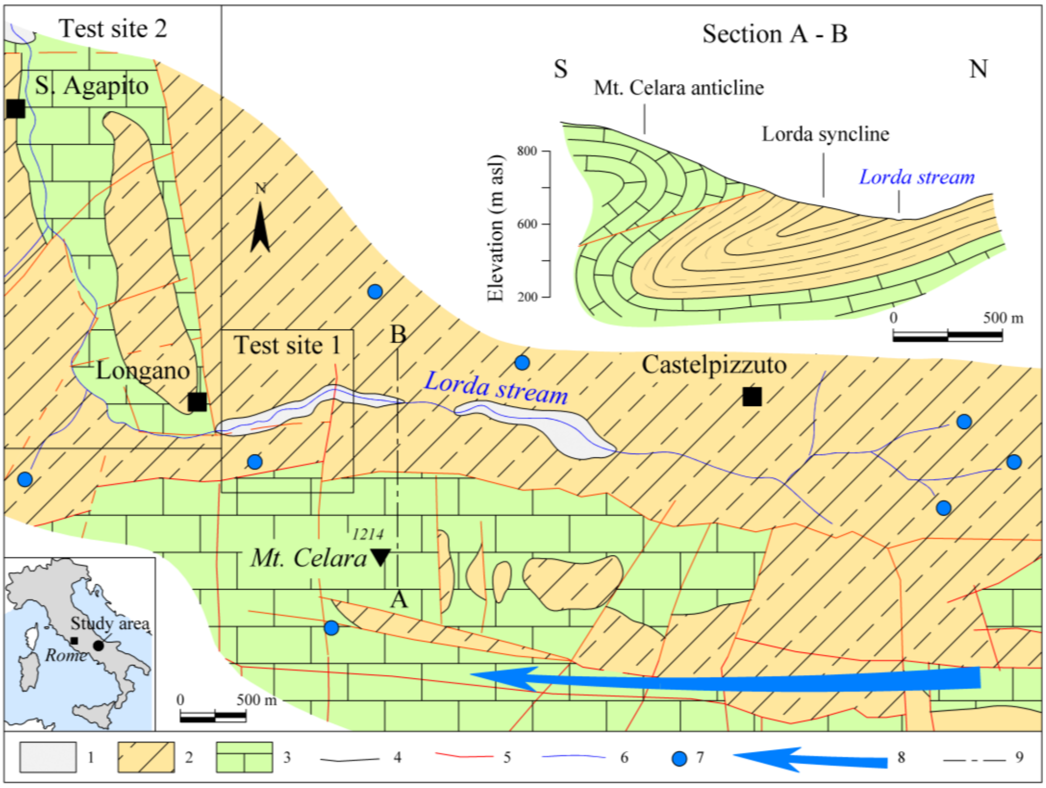

Figure 1: Study sites 1 and 2; simplified geologic map (from Carta geologica d'Italia, F. 161 – Isernia, simplified); geologic section (from De Corso et al., 1998, simplified). Legend: 1) Quaternary alluvial deposits; 2) Tertiary Silico-clastic sequence; 3) Mesozoic carbonate sequence; 4) Stratigraphic contact; 5) Fault; 6) Lorda stream; 7) Main spring; 8) Regional groundwater flow direction; 9) Trace of the geologic section A-B.

THE STUDY AREA

Two test sites were chosen, both located along a piece of the watershed of the Lorda stream, close to the town of Longano (Southern Apennine, Italy), where a Meso-Cenozoic sedimentary sequence crops out (Figure 1). The Mesozoic part of the sequence is made up mainly of carbonate rocks (dolostone and limestone), while the Cenozoic part is made up of a heterogeneous multilayer (marls, limestones, shales and siltstones; Bonardi *et al.*, 1988; De Corso *et al.*, 1998).

Close to the town of Longano, the tectonic style is defined by the anticline of the Monte Celara (Matese anticline), essentially made up of carbonate rocks, overthrusted on a folded silico-clastic sequence (Lorda syncline), whose hinge is approximately E – W trending with a Southward dipping axial surface (Figure 1).

Within the test site 1, the tectonic contact between the above-mentioned folds is detectable at 720 meters above sea level (m asl), on the left slope of the stream. The bottom of the watershed runs between 620 and 618 m asl, along the silico-clastic sequence. Strike slip and dip slip faults also characterize the tectonic style of the site (De Corso *et al.*, 1998). Further this, within the test site 2, the Lorda stream flows for about 4000 meters, between 618 and 405 m asl, on a uplifted portion of the Mesozoic carbonate rocks (Figure 1).

From a hydrogeologic point of view, the carbonate rocks form a fissured aquifer, subordinately karstified (Celico *et al.*, 2006). In particular, the Monte Celara massif represents a portion of a important aquifer, in which the regional groundwater flow is westward (Figure 1; Celico *et al.*, 2006). The results of ^{18}O and ^{2}H analyses, performed by Petrella and Celico (2009), suggest that the groundwater flowing through the silico-clastic sequence comes from the carbonate massif, but as the distance from it increases, so does the influence of the local infiltration.

MATERIALS AND METHODS

Geological and hydrogeological investigations

A geologic survey was carried out to refine the previous geological information and to outline an exhaustive stratigraphic and structural model of the site.

The hydrogeological investigations were performed by measuring hydraulic heads, spring discharges and stream flow. Slug tests were also performed in the two observation wells. In greater detail, the hydraulic heads were measured by means of a water level meter, in seven observation wells (P1, P2, P3, P4, P5, Pz1 and Pz2, fully screened, from 3 to 73 m deep, with diameters ranging between 0,06 m and 1,00 m; Table I), located in the test site 1 (Figure 2).

Table I: Main characteristics of the observation wells.

Parameters	P1	P2	P3	P4	P5	Pz1	Pz2
Depth (m)	70	55	25	45	50	3	15
Diameter (cm)	6	6	6	6	6	100	30

The monitoring was performed on a weekly basis: a) at the observation wells P1, P2, P3, P4 and P5, from February 2010 to September 2012; b) at the observation well Pz1, from December 2010 to July 2011; and c) at the observation well Pz2, from September 2010 to September 2011.

Two slug tests were carried out at the observation wells P3 and P4, in order to characterize the hydraulic property of the uppermost part of the hydrogeologic system. In each observation well, the test was performed, through the injection, by gravity, of 300 liters of water in 10 minutes in each observation well. The water levels were simultaneously observed with a water level meter and a pressure transducer, the latter located at the well bottom.

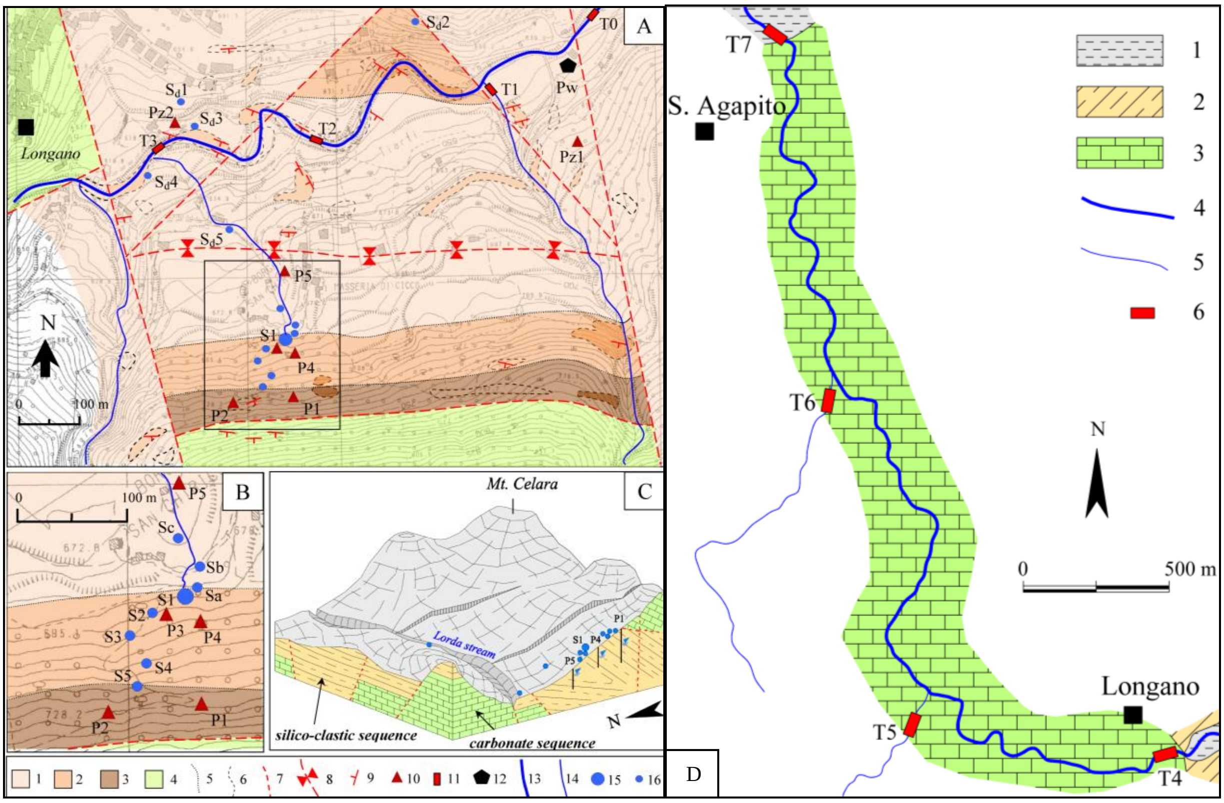

Figure 2: Geologic map of the test site 1, based on the geological survey (A); blow up of the area within the square, including the spring S1 (B); schematic structural configuration of the entire site 1 (C). Legend: 1) Frosolone Formation (shales) 2) Longano Formation (marls and clayey marls); 3) Cusano Formation (carbonate conglomerate); 4) Mesozoic sequence (limestone); 5) stratigraphic contact; 6) boundary of the outcrop of rock; 7) fault; 8) presumed trace of the axial surface of the fold; 9) orientation of the strata with dip angle ranging between 30° and 60°; 10) observation well; 11) measuring section of the stream flow; 12) Rainwater sampler; 13) Lorda stream; 14) runlet; 15) main spring 16) secondary spring. Test site 2 (D). Legend: 1) Quaternary alluvial deposits 2) Tertiary Silico-clastic sequence; 3) Mesozoic sequence (limestone and dolostone) 4) Lorda stream; 5) Runlet; 6) Measuring section.

The spring discharges were observed on a weekly basis, from February 2010 to September 2011. However, during this period, the flow rate was measured only for the spring S1. When the flow rate of the spring S1 was higher than 60 l/s, it was not possible to carry out the measurements. With regard to the remaining springs (S3, S4, S5, Sa, Sb, Sc, S_d1, S_d2, S_d3, S_d4, S_d5; Figures 2A and B), since very scarce volumes flowed, throughout a relatively extended and irregular ground surface, only a rough estimate of the flow rate could be made. Therefore, the measurements were carried out just a few times, during the high flow period (February 2010 and March 2011). Moreover, in the site 1, along the riverbanks, during the high flow period, many springs tended, during the period of observation, to form seepage faces, continuing for tens of meters, for which the flow rate was not estimable. However, in several cases, the springs became inaccessible due to the overgrowth of vegetation (e.g. springs S_d3, S_d4, S_d5).

The flow of Lorda stream was monitored in three measuring sections (T0, T2 and T3) within the test site 1 (Figure 2A), and in two measuring sections (T4 and T7), within the test site 2 (Figure 2D).

In the site 1, the stream flow monitoring was carried out on a weekly basis, from April 2010 to September 2011, while in the site 2, the monitoring was done on the same basis, from April 2004 to March 2005. The flow rate was also measured for the three runlets (measuring sections, T1, in the test site 1; T5 and T6 in the test site 2; Figures 2A and 2D) which flow into the main stream current. Measurements were carried out by means of a current meter.

Electrical Conductivity measurements

Electric conductivity (EC) measurements were carried out in the field, by means of a multi-parametric probe.

EC profiles were performed in the wells P4 and P5, in April 2011, while a monitoring of EC, on an hourly basis, was carried out in P4, at bottom well, from April 2011 to September 2011.

The EC was also measured for springs S1, S2, S3, Sa, Sb, Sc, S_d1 and at measuring sections T0, T2 and T3, in the Lorda stream, on a weekly basis, from July 2010 to September 2011.

Isotopic analyses

Groundwater and spring water samples for stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) analyses were collected in the observation wells and for the springs S1, S2, and S4. The water samples were collected in 50 ml polyethylene bottles.

The analytical precision was ±0.1‰ for $\delta^{18}O$, and ±1‰ for $\delta^{2}H$. The compositions of $\delta^{18}O$ and $\delta^{2}H$ are reported in δ‰ vs. V-SMOW standard. The analyses were carried out at the Laboratorio di Geochimica Isotopica of the University of Parma, Italy.

RESULTS

Geologic setting

By means of the geological survey, several geologic units were recognized in the field, within test site 1. Observed stratigraphically from bottom to top, they can be described as follows (Figure 2):

- massive marly conglomerates with fragments of Pectinidies (Cusano Formation);
- marls with Orbulines (Longano Formation);
- alternations of shales, marls, and siltstones (Frosolone Formation).

In particular, with regard to the left slope of the watershed, the above-mentioned geologic units are South-dipping. The Cusano Formation, which is the basal unit of the silico-clastic sequence, rests geometrically above the younger Longano Formation. This evidence indicates that, on the left slope of the watershed, the stratigraphic polarity of the sequence is reversed and the younger rocks are encountered moving northward. Additionally, along the bottom of the watershed, the Longano Formation is detectable and South-dipping.

At site scale, this evidence is compatible with a fold (Lorda syncline), whose overturned limb is represented by the Southern part of the site, while the axial surface is South-dipping, in agreement with the findings of De Corso *et al.* (1998). Furthermore, several important tectonic contacts with a transcurrent and / or a normal component of the slip were also detected. These faults can be perceived where the interface between two different geologic units cuts through the strike lines of the layers forming the sequences. As a result, in the North-Western part of the study site, a morpho-structural high made up of Mesozoic carbonate rocks, located at the right side of the stream current, is surrounded by the younger silico-clastic sequence (Figures 3 and 4). Thus, the bottom of the watershed is represented by the silico-clastic rocks, with the exception of the North-Western part of the site, where the Mesozoic carbonate rocks are outcropping (Figures 3 and 4). Here, it is possible to infer that the deeper position of the carbonate rocks below the silico-clastic sequence takes place as the distance from the relief progressively increases, by means of a series of normal faults (Figure 2C). The morphological contacts between the carbonate reliefs and the silico-clastic sequence are characterized by escarpments which yield accumulation of pebbles of limestones, along with clayey colluviums due to the weathering of shales and marls. With regard to site 2, the geological survey had the singular aim to verify the presence of the carbonate rocks along the portion of the talweg between the measuring sections T4 and T7 (Figure 2D).

Hydrogeological features

When carrying out the slug tests in the wells P3 and P4, the injection of 300 L of water in 10 minutes did not cause any variation of the hydraulic heads, indicating that, locally, the system is highly permeable.

The seasonal variations in hydraulic heads were up to 20 meters in P1 and P2, while in the remaining wells were of just several meters (Figure 3).

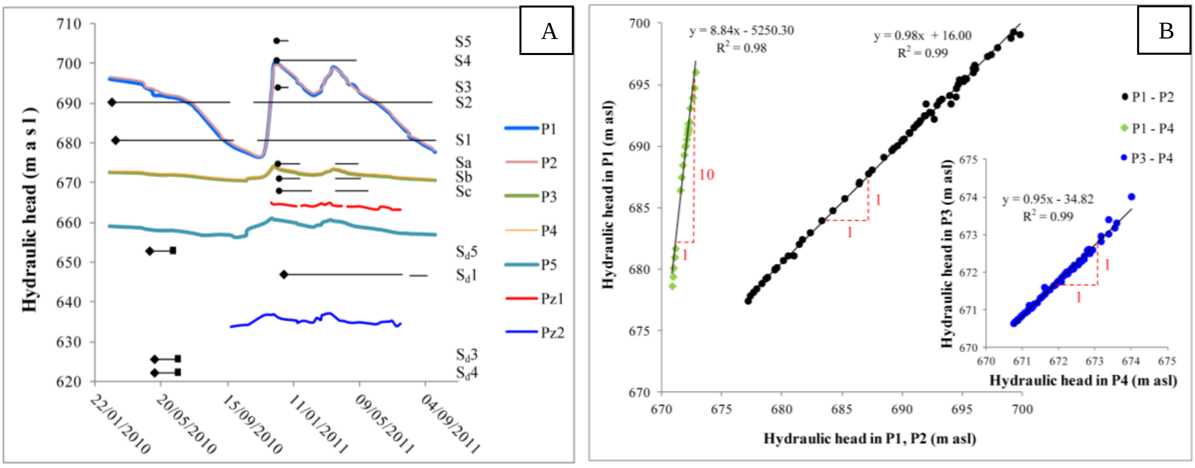

Figure 3: Hydraulic head fluctuations in the wells (A). The bars show when the springs flow out. The rhomb shows the beginning of the observation period; the circle shows that the observation started when the temporary spring began to flow out; the square shows the end of the observation due to inaccessibility. The spring S_d2 is at the same elevation of the spring Sa. Correlations between the hydraulic heads relative to three pairs of wells (P1-P2, P1-P4 and P3-P4), showing very high correlation coefficients (> 0.98). For the pair P1-P4 only the recession period has been considered (B).

The hydraulic heads observed in P1 and P2 are well correlated (Figure 5 and Table II), as are the hydraulic heads observed in P3 and P4 (Figure 5 and Table II).

Table II: Coefficients of correlation between wells.

	P2	P3	P4	P5	Pz1	Pz2
P1	0.998	0.859	0.908	0.635	0.530	0.368
P2		0.839	0.892	0.608	0.507	0.347
P3			0.990	0.828	0.767	0.580
P4				0.819	0.556	0.525
P5					0.768	0.675
Pz1						0.652

Conversely, due to the disturbance yielded by the effective infiltration during the high flow period, non-synchronous head fluctuations between the hydraulic heads, measured in P1 (or P2) and P3 (or P4), cause relatively low correlations (circa 0.9; Table II). However, during the recession periods, without the mentioned disturbance, the correlation coefficient between P1 (or P2), and P3 (or P4) increases (e.g., for the pair P1-P4, R^2 = 0.982; Figure 5), but only during the recession period.

Concerning the correlations, a one-to-one relationship exists for the pairs P1-P2 and P3-P4, while a one-to-ten relationship exists for the pair P1-P4 (Figure 3).

The springs S1, S2 and S_d1 flowed for the most of the year (Figure 3). However, the flow rate of the spring S1 ranged between several hundreds l/s and 0 l/s, while for S2 and S_d1 it ranged between 2 l/s and 0 l/s (Table III). The remaining springs (S3, S4, S5, Sa, Sb, Sc and; Figure 2) discharged for much shorter time intervals (Figure 3) with a flow rate lower than 0.1 l/s (Table III).

The Lorda stream is perennial, ranging between 150 l/s during the low flow periods, and more than 850 l/s, during the high flow periods; above the value of 850 l/s, it was not possible to carry out the measurements (Figure 4A). Variations in flow rates were detected along the riverbed for two pieces, respectively interposed between sections T0 and T2 and sections T2 and T3 (Figure 4A). In particular, for each the differences in flow rates varied, from positive to negative and vice versa (Figure 4A).

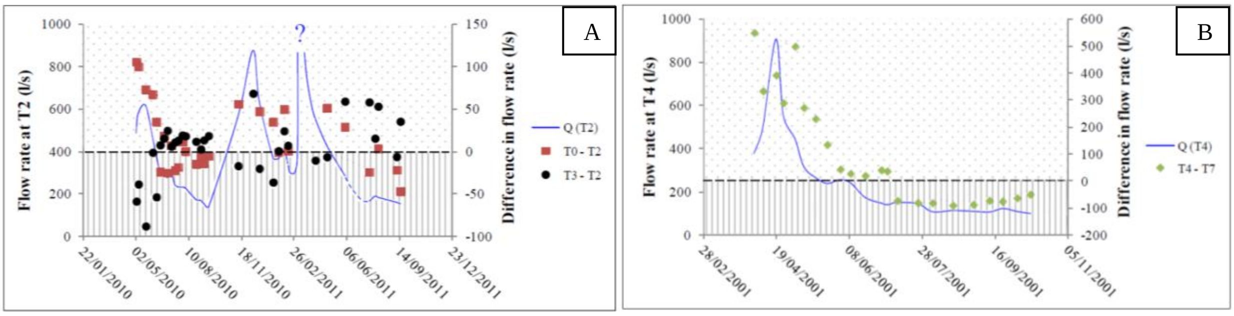

Figure 4: Differences in flow rates between the measuring sections T2 and T0 (red square) and between the measuring sections T3 and T2 (black circle), along the Lorda stream, in test site 1 (A). Above the dark dashed line the stream is gaining, while below the stream in leaking. The label Q is referred as fluvial regime in the measuring section T2. The interrogative point indicates that above the value of 850 l/s the flow rate was not measurable. Differences in flow rates between the measuring sections T4 and T7 (green rhomb), in the test site 2 (B). Above the dark dashed line the stream is gaining, while below the stream in leaking. The label Q (blue line) is referred as fluvial regime in the measuring section T4.

With regard to the test site 2, variations in flow rate, between the measuring sections T4 and T7, were observed throughout the year (Figure 4B). In greater detail, during the high flow period, an increase of the flow rate was observed as to the downstream flow, while a decrease was observed during the low flow period (Figure 4B).

Table III: Maximum values of flow rates of the springs.

Spring	S1	S2	S3	S4	S5	Sa	Sb	Sc	S_d1	S_d2	S_d3	S_d4	S_d5
Flow rate (l/s)	> 50.0	< 0.2	< 1.0	< 1.0	< 1.0	< 0.1	< 0.1	< 5.0	< 0.5	< 0.1	< 1.0	< 0.5	< 0.1

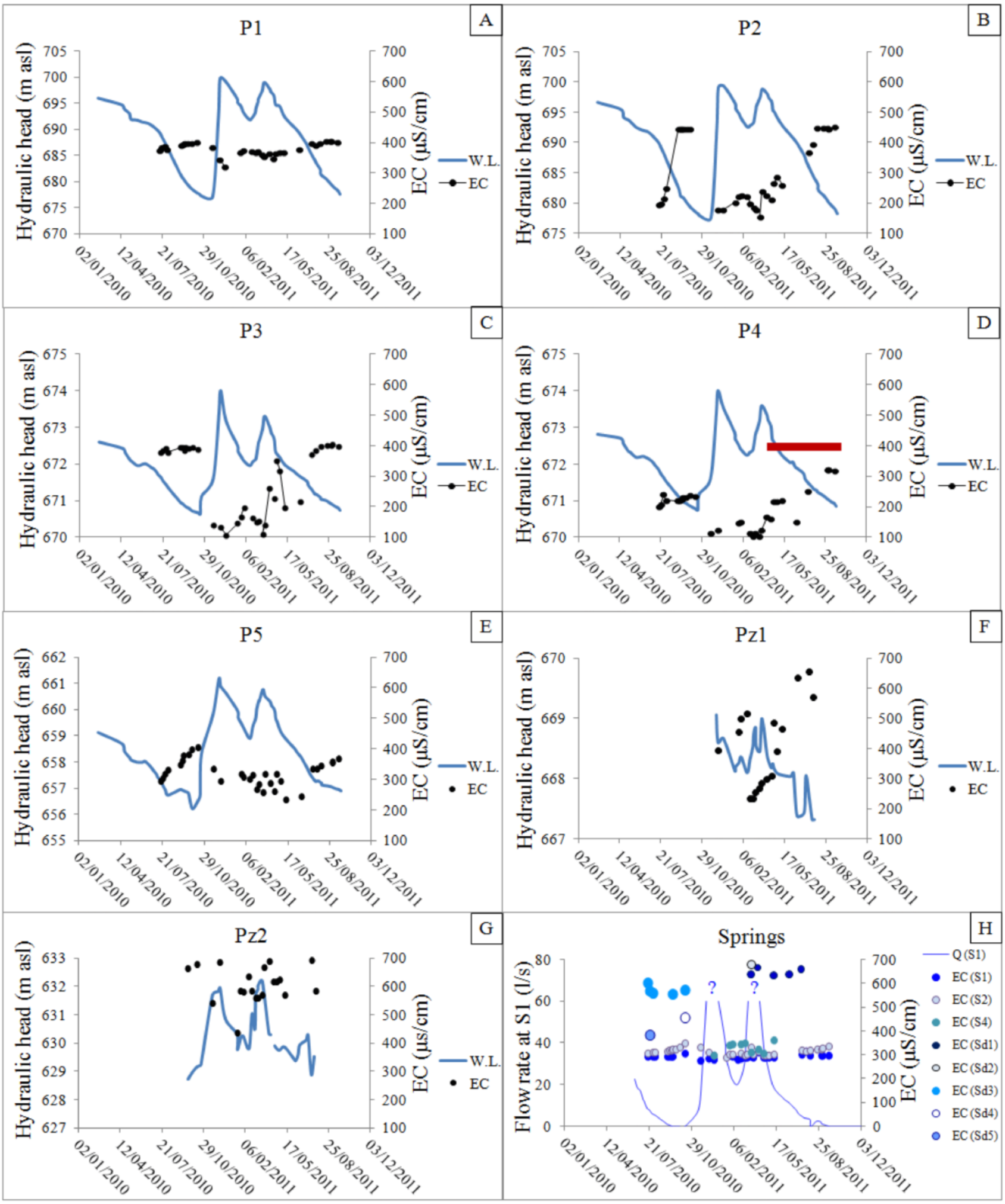

Figure 5: Groundwater EC versus hydraulic heads for the observation wells and for the springs S1, S2, S4, S_d1, S_d3, S_d3, S_d4 and S_d5. The red bar, in figure 5D, indicates the value of EC recorded, on a hourly basis, at the bottom of the well P4. The label W.L. is referred as groundwater level through the time in each observation well. The label Q is referred as spring regime of S1. The interrogative point indicates that above the value of 60 l/s the flow rate of the spring S1 was not measurable.

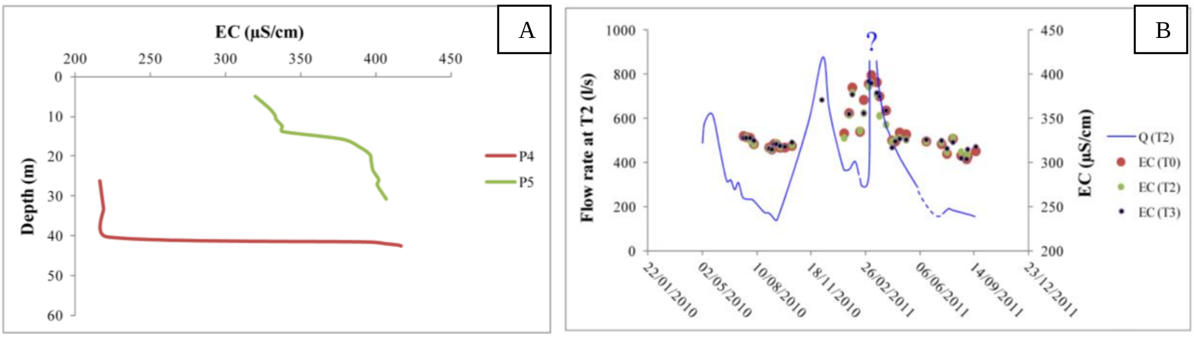

Figure 6: EC profiles, measured with respect to the ground surface, in the observation wells P4 and P5 (A). Electric conductivity recorded in the Lorda stream (B). The label Q is referred as fluvial regime in the measuring section T2. Dates are given in day/month/year

Electrical Conductivity measurements

The electric conductivity (EC) of the groundwater collected in the observation wells (just below the water level) and at the springs (Figure 5), changed over time in different ways:

1. in the wells P1, P2, P3, P4, P5 and Pz1, an anti-correlation between the EC and the hydraulic heads exists; the maximum EC values are associated with the low flow periods (Figures 8, A to F);
2. in both P1 and P2, the maximum EC value was reached when the groundwater level went below 680 m asl (Figures 8A and B); however, in P1, the seasonal fluctuations of the EC were much less amplified, as they were for the springs S1, S2, S4 (Figure 5H);
3. for the monitoring points closer to the carbonate massif (wells P1, P2, P3, P4, P5 and springs S1, S2, S4; Figure 2), the maximum EC values, recorded during the low flow periods, are close to 400 µS/cm (Figures 5, A to E, and Figure 8H); moreover, during the last low flow period, the highest values of the EC were recorded in August;
4. for the monitoring points located farther from the nearby carbonate massif (wells Pz1, Pz2 and springs S_d1, S_d2, S_d3, S_d4, S_d5; Figure 2), the EC tends to be higher; in particular, for Pz1, during the last low flow period, the EC exceeded 400 µS/cm much earlier (in April rather than August) and the highest value recorded is circa 650 µS/cm (Figure 5F); for the well Pz2 and the springs S_d1, S_d2, S_d3, S_d4, S_d5, the highest EC is higher than 400 µS/cm, throughout the observation period (Figures 5G and H).

Two EC profiles were carried out during the recession period. In the well P4, in April 2011, an abrupt contrast in EC was observed close to the well bottom (Figure 6A). In particular, 20 m below the groundwater level, the EC changed very quickly from 400 µS/cm to 216 µS/cm (Figure 5D). The discontinuity in EC in the well P4, is further confirmed by comparing the EC measured on an hourly basis at the well bottom (from May 2011 to September 2011), with the EC measured, on a weekly basis, just below the groundwater level (Figure 5D).

A vertical discontinuity was also found in the well P5; the EC was 320 µS/cm, until 20 m below the groundwater level, in June 2011, while, below this depth, it increased abruptly at 400 µS/cm and remained nearly constant until the well bottom (30 m below the groundwater level; Figure 6A).

Differently from the groundwater collected from the observation wells P1, P2, P3, P4, P5, Pz1, the stream water does not show a reverse correlation between EC and flow rates.

In fact, during the recession periods, the stream EC is around the value of 310 µS/cm (Figure 6B), while EC peaks (400 µS/cm) have been recorded during the period influenced by precipitations (Figure 6B).

Isotopic content

The isotopic content of groundwater and spring water is plotted in a $\delta^{18}O$ vs $\delta^{2}H$ diagram (Figure 7). Since the samples are distributed between the global meteoric water line (GMWL; $\delta^{2}H=8\delta^{18}O+10$; Craig, 1961), the eastern Mediterranean meteoric water line ($\delta^{2}H=8\delta^{18}O+22$; Gat and Carmi, 1970), and the local meteoric water line ($\delta^{2}H=8.2\delta^{18}O+15.2$; Petrella *et al.*, 2009) (Figure 11), the meteoric origin of the groundwater can be inferred.

The isotopic content of groundwater varies over time, but no significant differences (variations were lower than the 2σ error of the analyses) are observed between the isotopic signature of the water samples collected at the observation well P1 and at the springs S1 and S2 (Figure 7, Table IV). Instead, the signature of the remaining observation points changes in a range which is greater than the 2σ error of the analysis (Figure 7, Table IV).

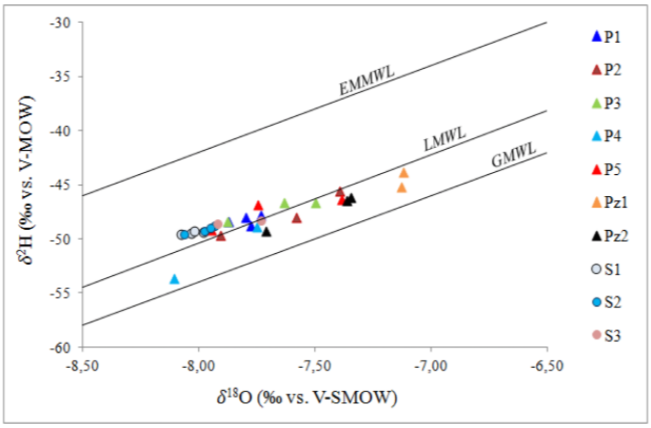

Figure 7: $\delta^{18}O$ vs $\delta^{2}H$ diagram for the groundwater samples (triangles and circles). LMWL: local meteoric water line (Petrella et al., 2009) referred to the rain water collected in the sampler Pw showed in Figure 2; GMWL: global meteoric water line (Craig, 1961); EMMWL: Eastern Mediterranean meteoric water line (Gat & Carmi, 1970).

DISCUSSION

Expected hydrogeological scheme

Based on the field evidence, close to the carbonate relief, accumulations of carbonate, pebbly debris and clay colluviums form an heterogeneous surficial horizon, which capes the silico-clastic bedrock.

Based on the previous hydrogeological knowledge regarding a much wider area (Petrella and Celico, 2009), the underlying silico-clastic bedrock is supposed to be characterized by:

- an upper portion, reasonably more permeable, being subject to a minor lithostatic load and a more intense weathering;
- a deeper portion, reasonably less permeable, being subject to an increasing lithostatic load with the depth, in absence of weathering.

Further this, in every natural system where topographic gradients exist and different lithotipes crop out, due to the alteration processes involving the rocks, we can expect similar scenario.

Since the heterogeneity, in terms of lithologic and physic characteristics, can reflect significant lateral and vertical contrasts of permeability of the subsurface for a wide range of hydrological systems, it follows its great importance with respect to the usage of the groundwater resources.

Therefore, in a wide perspective, the main objectives of this study are as follows:

a) experimental verification of the preliminary model for the subsurface outlined above;
b) understanding of the control that the contrasts of permeability can exercise over experimentally observed hydrological dynamics; previa verifica sperimentale …
c) understanding of the functioning mechanisms of such heterogeneous hydrogeologic systems, usually considered to be aquitards, taking also into account the hydraulic relationship with nearby aquifer systems (in the case study, the carbonate hydrostructure).

To hydrogeological functioning of this type of systems has been schematized distinguishing a conceptual model at local and site scale, as to put in evidence the factors that can play a significant role when changing the observation volume.

The hydrogeological model at local scale

Based on the comparison between the water levels and the position of the active and dry springs (Figure 4), we can observe that:

- ✓ mostly, the water levels are significantly lower than the active springs (Figure 8A);
- ✓ in some cases, the water levels are significantly higher that the dry springs; (Figure 8B).

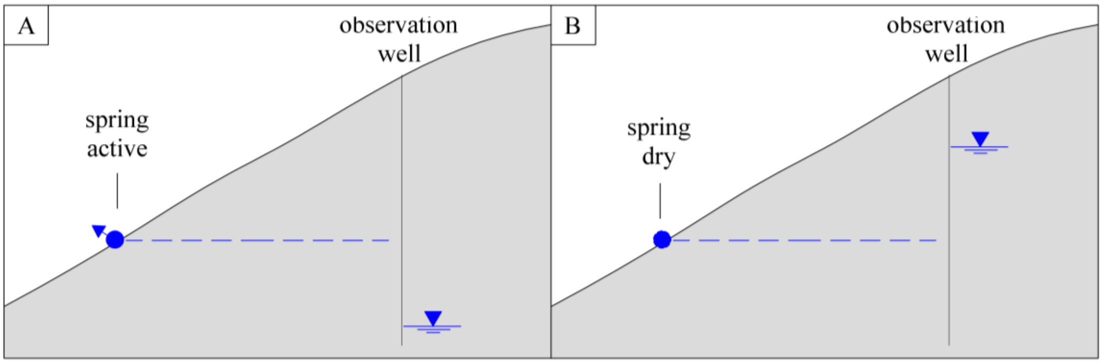

Figure 8: Schematic representation of relationships between hydraulic head in some observation wells and elevation of some springs. The label W.L. indicates groundwater level.

This evidence indicates that the flow system associated with the springs is physically separated by the saturated zone crossed by the wells. This is further confirmed by the absorption of the spring water by the surficial rocks just downgradient of S2. In fact, as indicated by the gurgling of the spring water flowing downward, an unsaturated zone is interposed between the spring and the saturated zone intercepted by the wells P3 and P4 (Figure 9).

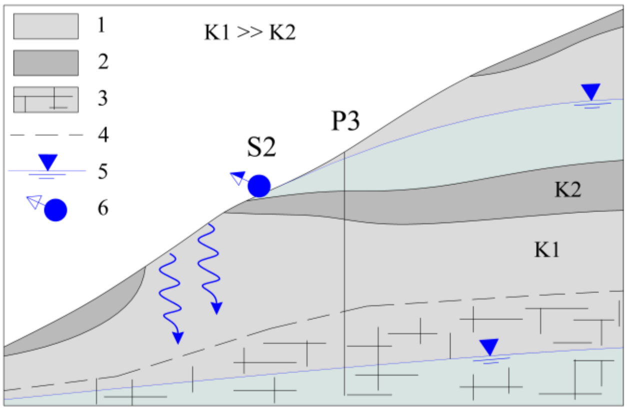

Figure 9: Schematic representation of the relationship between the perched groundwater and the deeper water table. The arrows show the percolation of water which yields the gurgling within the unsaturated zone. Legend: 1) talus 2) clayey colluviums; 3) fissured bedrock; 4) limit between the surficial heterogeneous horizon and the fissured bedrock; 5) piezometric profile; 6) secondary spring.

Despite this, previous investigations (Petrella and Celico, 2009) demonstrated that both S1- and P1-water come from the nearby carbonate aquifer. The whole scenario is consistent with the known compartmentalization of the carbonate aquifer, compatibly with the fault zones found in the carbonate aquifer (Figures 1 and 2). As a matter of fact, taking into consideration the findings of Celico et al. (2006), concentrated head losses take place within a low-permeability fault core, interposed between two compartments:

- ✓ one located upgradient of the fault core, feeding the springs;

✓ one located downgradient of the fault core, feeding the deeper saturated subsurface.

The isotopic data confirm the higher elevation the alimentation zone which feeds the springs (Figure 10).

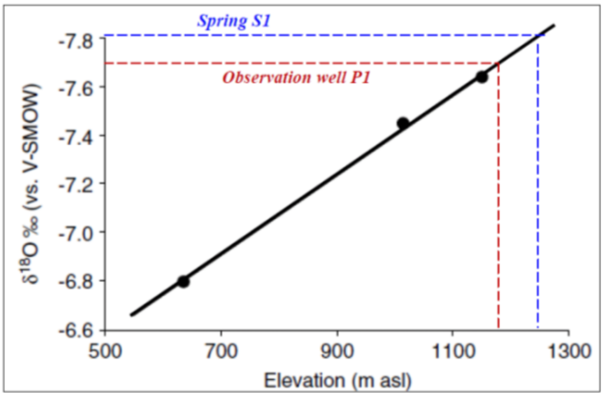

Figure 10: Correlation between the groundwater isotopic content and the mean elevation of its recharge area (from Petrella & Celico, 2009, modified).

This conceptual model (Figure 11) has a general validity in cases of transfer of groundwater between two heterogeneous hydrostructures. It could explain, for the fed hydrostructure, the origin of two distinct flow systems separated by an unsaturated zone.

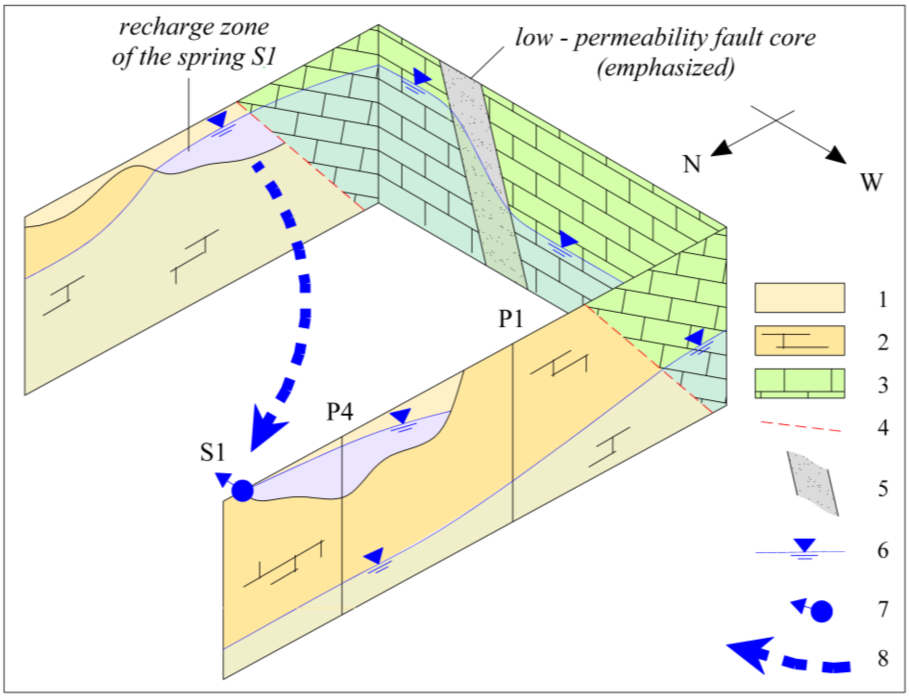

Figure 11: Conceptual model explaining the relationship between the compartmentalized carbonate aquifer and the silico-clastic sequence. Legend: 1) Surficial horizon including high permeable talus and clayey colluviums; 2) silico-clastic sequence; 3) carbonate aquifer; 4) fault; 5) low-permeability fault zone; 6) piezometric profile; 7) main spring; 8) groundwater flow direction within the surficial horizon.

Porous surficial horizon

Close to the carbonate relief, the surficial horizon is made up of discontinuous debris, due to the alteration of the carbonate rocks, enveloped by clayey colluviums, due to the alteration of the silico-clastic rocks. Therefore, it is reasonable to expect that the springs are controlled by the amount and distribution of the carbonate debris in the subsurface. Analyzing the spring regimes in more detail (Figure 12), it is possible to observe that ephemeral springs are located lower than more copious and durable spring flows. This anomalous behavior can schematically be explained with the conceptual model showed in Figure 16, in which it is possible to observe that several springs can flow only when the groundwater level exceeds a specific threshold.

On the whole, lateral and vertical contrasts of permeability, can control the number, the spatial distribution, the flow rate, and the discharge duration of the springs, with important implication on the usage of the groundwater for human purposes.

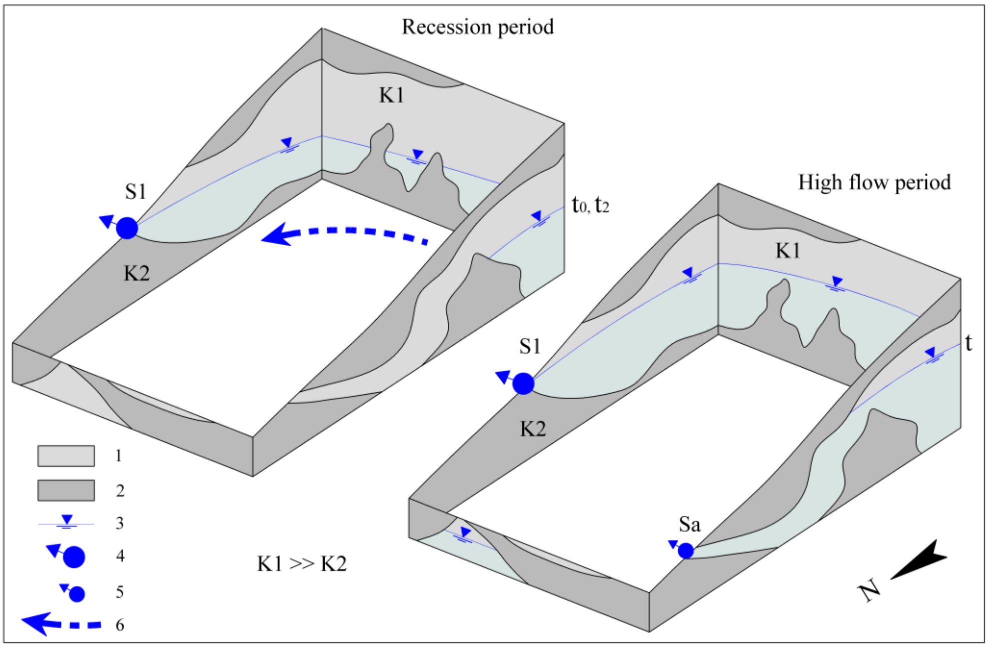

Figure 12: Conceptual model explaining the activation mechanism of several springs. Legend: 1) talus 2) clayey colluviums; 3) piezometric profile; 4) main spring; 5) secondary spring; 6) groundwater flow direction.

Fissured bedrock

Taking into consideration the piezometers P1 and P2, close to the carbonate massif, it is possible to observe as follows:

- ✓ based on the stratigraphic evidence, the interface between the conglomeratic unit and the underlying clayey-marly unit, is crossed by the piezometers (Figure 13A);

  since the conglomeratic unit is characterized by a lattice of open voids is supposed to be highly permeable, while the clayey-marly unit, resting geometrically below, can be more preserved by the weathering and is supposed to have low permeability;

- ✓ during the high flow periods, the rapid change of the hydraulic heads through the conglomeratic unit is compatible with the high hydraulic conductivity of the media, according with Javandel and Witherspoon (1969) and Bear (1987);
- ✓ one-to-one relationship in hydraulic heads between P1 and P2 (Figure 13A) also indicate homogeneity of the media in terms of hydraulic properties;
- ✓ furthermore, an anti-correlation between the hydraulic heads with the EC values exists, indicating an effective influence of the seasonal recharge, compatibly with the high receptivity of the conglomeratic unit;
- ✓ the maximum values of 400 – 450 µS/cm are reached during the low-flow periods, when the water levels go below the elevation of 680 m asl, in the clayey-marly unit; here, the stability of higher EC values could reflect less active groundwater flow circuits, according with the supposed low permeability of the media;
- ✓ hence, the wide fluctuations in hydraulic head, quite similar to those observed in the carbonate massif (several tens of meters; e.g., Celico *et al.*, 2006), leads to consider the conglomeratic unit as part of the carbonate aquifer, and can be explained with the barrier effect yielded by the clayey marls and shales, which partially impedes the groundwater flow;
- ✓ as a result, the main component of the groundwater flow within the conglomeratic unit is westwards, in agreement with that observed in the carbonate aquifer (Figure 1; Celico *et al.*, 2006).

Taking into consideration the piezometers P3, P4 and P5, located farer from the carbonate massif, it is possible to observe as follows:

- o the results of the slug tests indicate that the uppermost part of the saturated, fissured media is highly receptive;
- o one-to-one relationship in hydraulic heads between P3 and P4 (Figure 13B) also indicate homogeneity of the media in terms of hydraulic properties;
- o further this, the anti-correlation between the hydraulic heads with the EC values indicates a significant influence of the fresh water due to the seasonal recharge episodes;
- o however, vertical EC profiles highlight a vertical discontinuity (Figures 6A and 5D); as a matter of fact, the deeper part of the media is characterized by higher EC values (> 400 µS/cm) and does not undergo the influence of the recharge episodes (Figure 5D), indicating less active groundwater flow circuits, in agreement with previous findings

(Petrella *et al.*, 2009; Petrella and Celico, 2013).

On the whole, the field evidence suggest that the more weathered, upper part of the fissured media, also subject to a lesser lithostatic load and intensive weathering, is more permeable than the deeper rocks, according with Petrella and Celico (2009). They found, for a more extended nearby area, that whatever is the dominant lithotype of the silico-clastic sequence, an abrupt decrease in hydraulic conductivity occur only after about 20 m from the ground surface.

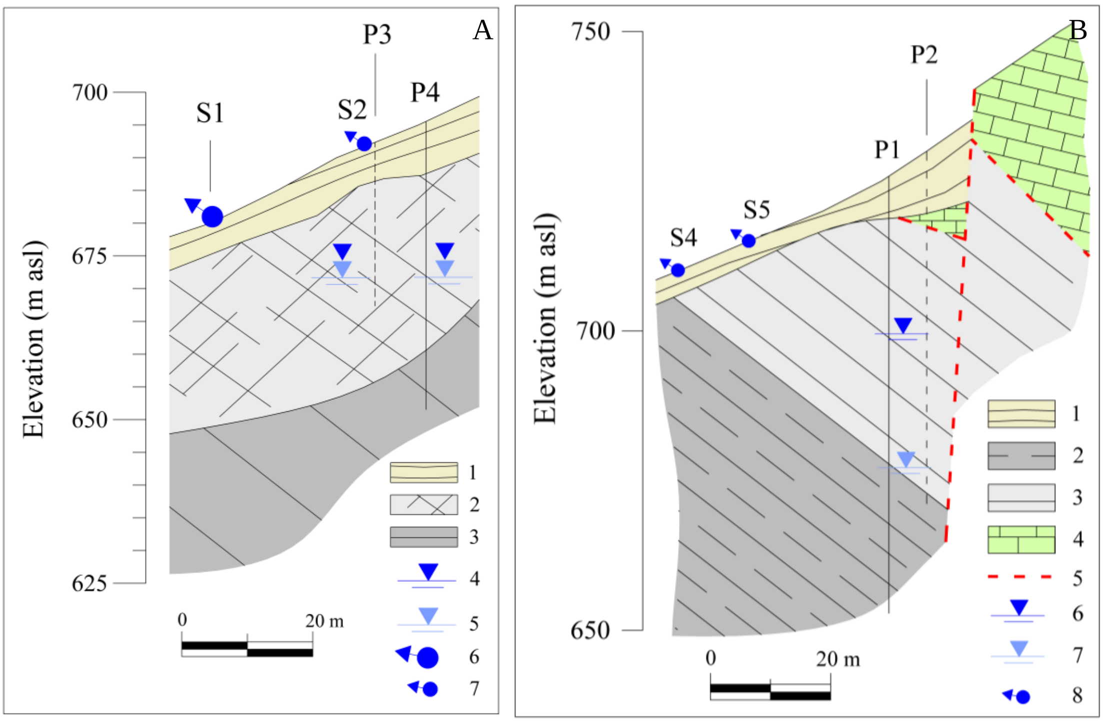

Figure 13: Hydrostructural scheme for the media intercepted by the wells P3 and P4 (A). Legend: 1) surficial heterogeneous horizon; 2) weathered part of the silico-clastic sequence Frosolone Formation (shales). Hydrostructural scheme for the media intercepted by the wells P1 and P2 (B). Legend: 1) surficial heterogeneous horizon; 2) Longano Formation (marls and clayey marls); 3) Cusano Formation (carbonate conglomerate); 4) Mesozoic sequence (limestone); 5) fault; 6) highest groundwater level; 7) lowest groundwater level; 8) secondary spring.

In addition, between P1 and P2 and between P3 and P4, despite one-to-one relationships in hydraulic heads (Figure 3B), were found:

- ✓ differences in EC values, indicating fluxes along which different degrees of mineralization or dilution of the groundwater take place;
- ✓ differences in $\delta^{18}O$ values, indicating fluxes which come from different portions of the same feeding carbonate hydrostructure.

Consequently, the groundwater flow patterns can be complex and undergo periodical modifications, despite the local homogeneity of the media in terms of hydraulic properties.

Hydrogeological model at site scale

According with De Corso et al., (1998), due to the doubling of the stratigraphic sequence the subsurface is mainly made up of shales, supposed to act as an aquitard.

As is shown below aims (i) to verify whether this hypothesis is experimentally supported and / or (ii) if significant interactions with the nearby carbonate hydrostructure take place.

<u>The Southern sector</u>

When comparing the hydraulic head fluctuations in the wells P3 and P4 with those measured in the wells P1 and P2, a one-to-ten relationship (Figure 3B) indicates a significant lateral heterogeneity in terms of hydraulic conductivity of the silico-clastic bedrock. In different words, according with Javandel and Witherspoon (1969) and Bear (1987), the fluctuations in hydraulic heads in P1 and P2 do not transmit with the same amplitude through the less permeable clayey-marly horizon acting as an aquitard, according to the section in Figure 14. Despite this, copious fluxes across this aquitard as the $\delta^{18}O$ values of the groundwater collected downgradient, in P3, P4 and P5, indicate the carbonate massif as the main feeding source.

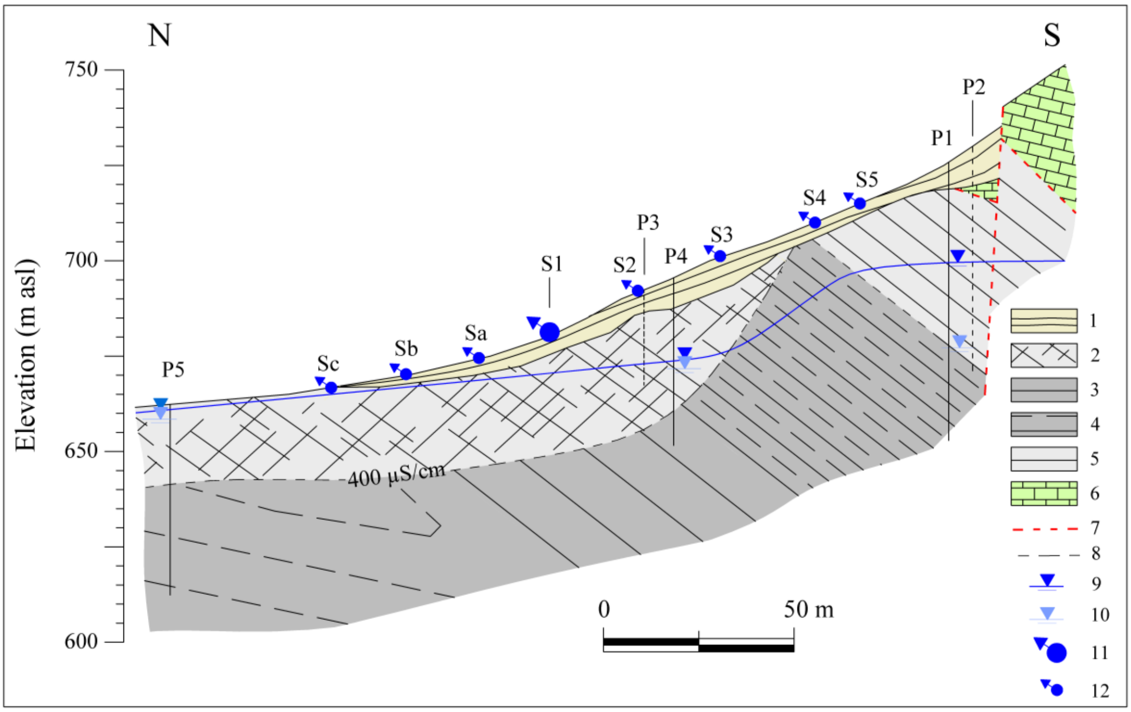

Figure 14: Hydrogeologic model of the study site 1. The feeding of the springs by means of the carbonate aquifer is explained by the conceptual scheme shown in the figure 11. Legend: 1) surficial heterogeneous horizon; 2) weathered part of the silico-clastic sequence; 3) Frosolone Formation (shales); 4) Longano Formation (marls and clayey marls); 5) Cusano Formation (carbonate conglomerate); 6) Mesozoic sequence (limestone); 7) fault; 8) contour line associated with EC = 400 µS/cm); 9) highest groundwater level; 10) lowest groundwater level; 11) main spring; 12) secondary spring.

On the whole, in terms of EC, the entire system is composed by three parts. In the porous surficial horizon the groundwater flowing through the pebbly carbonate debris maintains values about 300 µS/cm throughout the year.

In the silico-clastic rocks the groundwater tends to pass 400 µS/cm. However, the upper, highly receptive part of the fissured media is periodically influenced by the fresh water associated with recharge episodes. On the contrary, in the deeper, less permeable part of the fissured media, the groundwater has stably high EC values.

The Northern sector

With increase of the distance from the carbonate massif the weathered horizon is represented by a clayey soil and a generalized rise of the EC values takes place for both the groundwater (Pz1 and Pz2; Figure 2A) and spring water (S_d1, S_d2, S_d3, S_d4, S_d5; Figure 2A).

The mean elevation of the riverbed was constantly lower than the nearby hydraulic heads, indicating that the stream current is partly fed by the highly conductive groundwater. Despite this, just a few peaks of about 400 µS/cm were recorded when copious spring flows are distributed along the riverbanks during the high flow periods. Mostly, the highly conductive fluxes are lower, since they do not significantly influence the stream water, indicating that the core of the Lorda syncline, dominantly made up of shales, has a low bulk permeability. This is further confirmed by the significant difference between the mean elevation of the riverbed (about 620 m asl) and the high hydraulic head measurable upgradient of the Lorda syncline, in the carbonate massif (about 700 m asl).

The hydrogeologic functioning of the silico-clastic sequence can be refined analyzing the flow rate of the stream current. In fact, despite the higher hydraulic head in the nearby wells, the stream was alternatively gaining and losing. Therefore, the groundwater flowing within the silico-clastic sequence can not be the only source feeding the stream. Despite the bulk low permeability of the silico-clastic sequence there must be elements acting as source and sink, alternatively. The hypnotized conceptual model assumes interconnections between the stream and the deep carbonate aquifer, through open fractures and/or damage zones associated with tectonic discontinuities (Figure 2), and (ii) that the hydraulic head in the carbonate bedrock fluctuates up and down, periodically, with respect to the elevation of the stream.

This model is in agreement with the measurements made directly in the test site 2, where the Lorda stream is superimposed on carbonates rocks. Here, the stream was still losing and gaining, indicating that the groundwater table of the carbonate aquifer periodically interacts with the riverbed (Figure 4B).

CONCLUSIONS

The present work was aimed at understanding the main controlling factors which govern the dynamics of groundwater flow in heterogeneous sedimentary sequences.

In the presence of morphological reliefs and non-uniformity of the lithotypes outcropping (in the specific case, carbonate rocks and silico-clastic rocks), the alteration processes confer both lateral and vertical heterogeneities in terms of hydraulic properties to natural systems.

Based on the analysis and comparison of spring discharges, hydraulic heads, slug tests and monitoring of EC values of groundwater, significantly contrasts of permeability, which characterize the sedimentary sequence, according with the findings of Petrella and Celico (2009) have been found.

It is also remarkable the role played by the contrasts of permeability in governing the observed flow dynamics, for both (i) the perched groundwater system, which feeds the springs, and (ii) the deeper saturated system, crossed by piezometers.

Furthermore, the analysis of hydrogeological parameters, combined with the stratigraphic evidence at a site scale, confirms the dominant behavior similar to that of an aquitard for the silico-clastic sequence. Despite this, as confirmed by isotopic data and the periodical variations in flow rate of the stream current, the hydraulic interactions with the nearby carbonate hydrostructure are significant, possibly due to the network of structural discontinuities pervading the entire silico-clastic sequence at a site scale.

On the whole, with the exception of the surficial weathered horizon, the silico-clastic sequence substantially acts as an aquitard but, maybe due to the network of tectonic discontinuities, its functioning mechanisms also depend from the hydrogeologic dynamics in the nearby hydrastructure.

From these aspects, we can infer the important implications, concerning both the usage and the protection of groundwater resources. The low-permeability sedimentary sequences, despite being considered of little practical and scientific interest, allow for the improvement of the management of groundwater resources. It follows the need to further refine the knowledge about their hydrogeologic functioning through experimental activities, in accordance with Neuman and Witherspoon (1969).

Given the worldwide diffusion of the heterogeneous sedimentary sequences, conceptual functioning models here outlined have a vast margin of applicability.

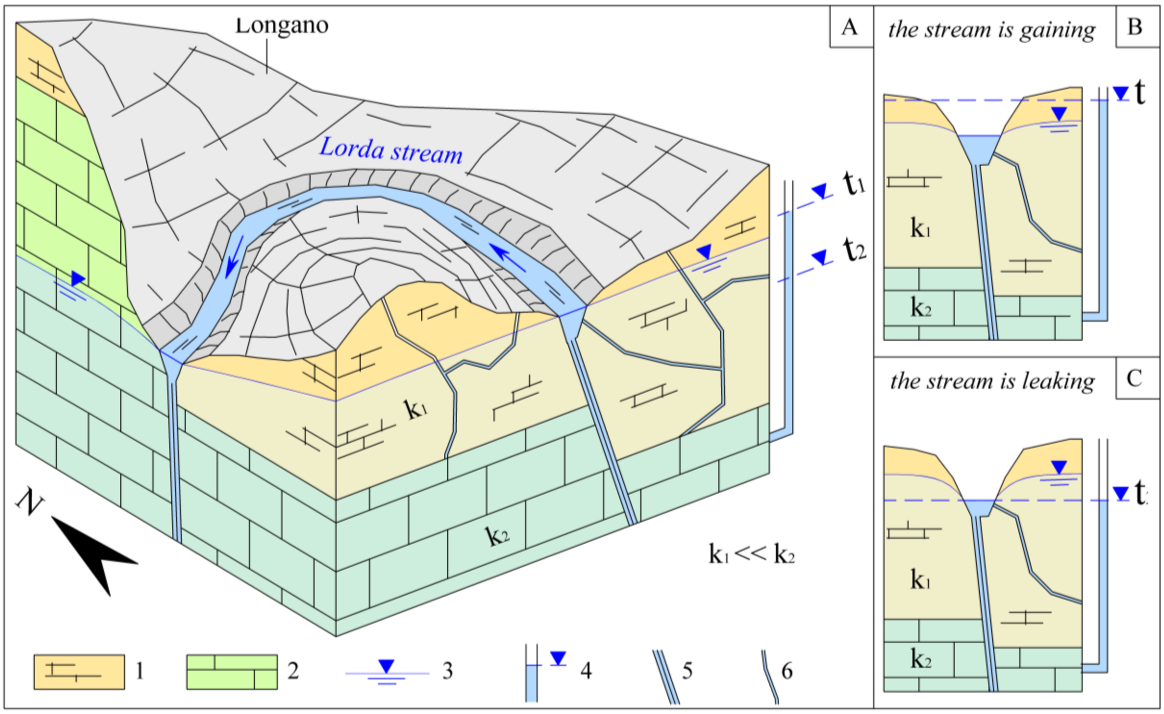

Figure 15: Hydrostructural model for the North – Western part of the study site 1 (A); conceptual functioning model (B and C). At the time t_1, the hydraulic head in the carbonate aquifer is higher of the stream current level, causing the injection of groundwater toward the riverbed (the stream is gaining). At the time t_2, the decrease of the hydraulic head in the carbonate aquifer causes the vacuuming of the riverbed (the stream is leaking). Legend: 1) Tertiary Silico-clastic sequence; 2) Mesozoic sequence (limestone); 3) groundwater level associated with the phreatic profile (within the carbonate aquifer or within the silico-clastic sequence); 4) hypothetical piezometer connected with the deeper carbonate aquifer and the relative potentiometric profile; 5) fault zone connecting the carbonate aquifer and the stream current; 6) open fracture connecting the carbonate aquifer and the stream current.

ACKNOWLEDGEMENTS

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Role of the heterogeneity in dynamic groundwater flow systems
Experimental evidence in a carbonate aquifer (Southern Italy)

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ABSTRACT

Hydrogeological systems are usually represented by heterogeneous media, in terms of physical and hydraulic properties, due to the geologic processes which the rocks continuously undergo since their formation.

The carbonate hydrostructure of Acqua dei Faggi (Isernia, Southern Italy) is configured as a compartmentalized, fissured aquifer, by means of a network of variously oriented, low-permeability fault cores. The effect that this conceptual model exerts on the configuration of the potential field, in ideal conditions of steady flow, was evaluated by means of the finite difference method, for different values of permeability ratios. As the contrasts of permeability increase, a generalized enhancement of the downward and upward vertical flow arises, leading to the compartmentalization of the major flow system in smaller sub-basins. However, unlike what happens in case of steady flow, the experimental observations suggest that in dynamic scenario, the heterogeneity of the subsurface can significantly influence the functioning mechanism of the flow system, especially in case of weak permeability contrasts. Despite the substantial uniformity in terms of distribution of the pluvial recharge, a significant diversification in variation of the hydraulic heads is observable during both the recharge and discharge episodes. The analysis of the hydraulic heads measured along the regional groundwater flow direction indicates that the subsequent continuous modifications of the potential field configuration may themselves constitute an important concause controlling the dynamic behavior of the hydrogeologic system.

Keywords: aquitard, carbonate hydro-structure; sub-basin; hydraulic head; groundwater flow, heterogeneity

INTRODUCTION

Geologic setting

The study site is located in Acqua dei Faggi (Isernia, Southern Italy; Figure 1), where the subsurface is made up of an heterogeneous Meso-Cenozoic sedimentary succession (Bonardi et al., 1988; De Corso et al., 1998). Despite the lithological heterogeneity characterizing the entire sequence, a macroscopic discontinuity can be recognized between two main chronostratigraphic units. About 600 m of carbonate rocks (limestones, dolostones and, subordinately, marls) characterize the Mesozoic unit, while about 200 m of silico-clastic rocks (siltstones, clayey marls and shales) form the Oligo-Miocenic unit (De Corso et al., 1998). The outcropping rocks are uniformly covered by a pyroclastic soil (Celico et al., 2010).

Due to the intense past tectonic phases, thrusts and folds caused the thickening of the sequence and the overlaying of the older rocks upon younger rocks. In more detail, in the site of Acqua dei Faggi, the antiform fold of M. Celara anticline (Mesozoic carbonate rocks) overthrusts on the sinform fold of the Lorda syncline (Oligo-Miocenic silico-clastic rocks) (Figure 1; De Corso et al, 1998). Normal and transcurrent faults contribute to the amplification of both the structural complexity and the degree of fracturation of the entire sedimentary sequence.

Hydrogeologic setting

From a hydrogeologic point of view, the carbonate succession (Mesozoic limestones and dolostones) identifies a regional groundwater basin, several hundreds meters thick, which is highly permeable mainly by fessuration and subordinately by karsification. The main groundwater flow direction is north-westward (Figure 1; Celico et al., 2006).

With regard to the Miocenic part of the sequence, it has been observed that, whatever the local dominant lithotipe may be (arenaceous siltstones or shales), a rapid decrease in hydraulic conductivity exists as the depth increases (Petrella and Celico, 2009). Only a surficial horizon about 20 – 25 m thick has an hydraulic conductivity comparable with that observed for the carbonate aquifer (10^{-6} m/s; Celico et al., 2006; Petrella et al., 2007). Therefore, a significant transfer of groundwater could be subordinated to this thin surficial horizon, while the deeper part of the Oligo-Miocenic silico-clastic rocks could significantly impede the flow of groundwater. Because of the high hydraulic conductivity of the carbonate rocks, the gradient of the water table is very small (about $3,5*10^{-2}$; Celico et al., 2006). Furthermore, no karst channels seem to influence the response of the aquifer system with respect to the rainfall. This is in agreement with the presence of the pyroclastic soil (Figure 2). In fact, the latter guarantees a uniform distribution of the effective infiltration, allowing for a homogeneous dissolution of the rock mass through the entire fracture system (Celico et al., 2010). Despite the fact that the karst channels do not significantly influence the aquifer behavior, jagged spring hydrographs during the recharge periods suggest that the aquifer system is characterized by low values of effective porosity, which is mainly controlled by the development of the network of fractures. However, field evidence indicates that it is often possible to find variations in effective porosity also due to different degree of karsification and fissuring (Petrella et al., 2007 and 2008; Petrella et al., 2009; Celico et al., 2010; Petrella & Celico, 2013). As a matter of fact, usually, an epikarst zone, up to 10 m thick, identifies the uppermost part of the aquifer system (Figure 2). Nevertheless, this zone is well connected with the underlying fissured media, since the formation of perched groundwater is not detectable (Petrella et al., 2007).

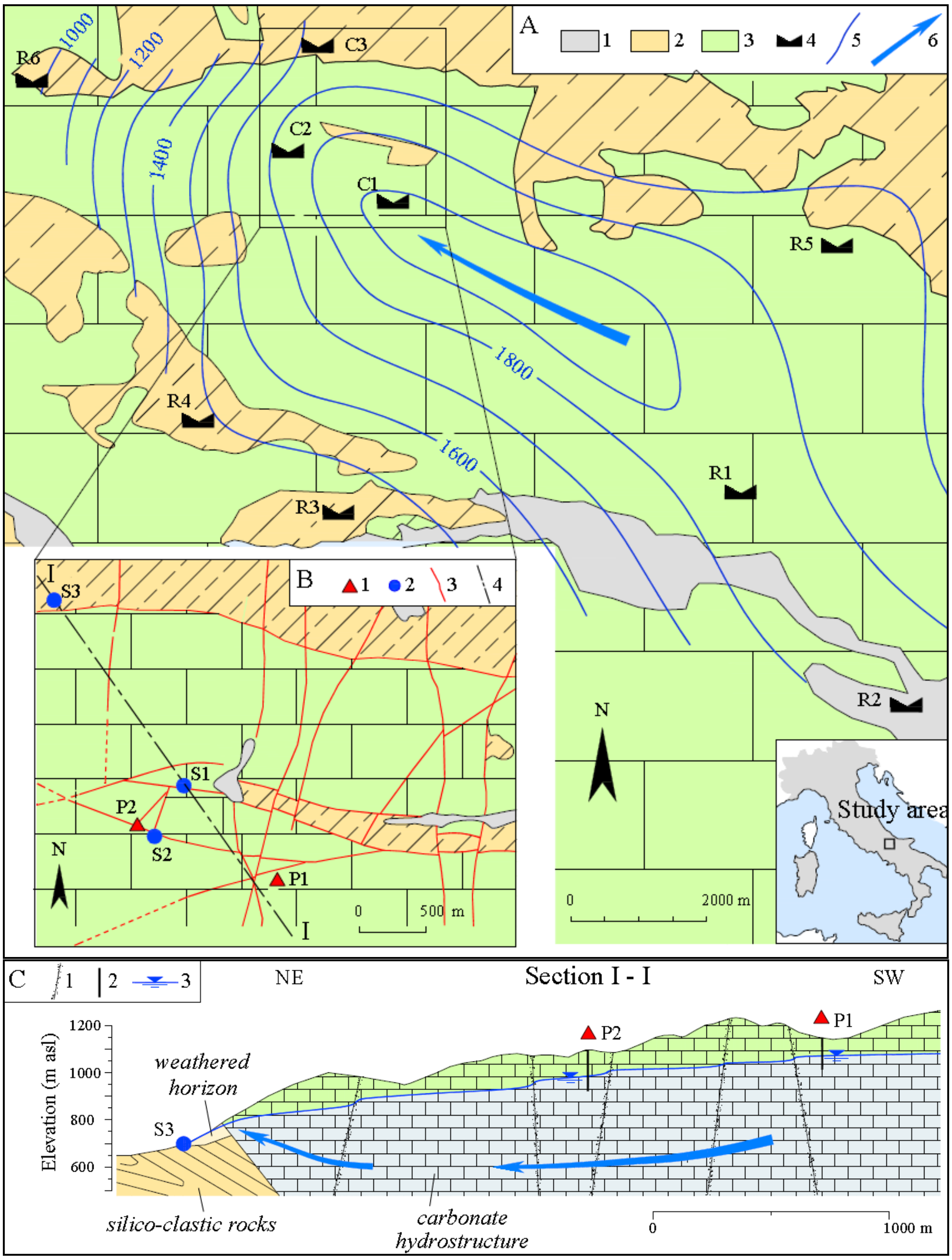

Figure 1: (A) Simplified geologic map of the area including the study site (from from De Corso et al., 1998, simplified; Legend: 1 - Quaternary alluvial deposits; 2 - Tertiary Silico-clastic unit; 3 - Mesozoic carbonate unit; 4 - rain gauge; 5 - isohyetal line; 6 - Regional groundwater flow direction). (B) Simplified geologic map of the study site (from De Corso et al., 1998, simplified; Legend: 1 - observation well; 2 - spring; 3 - tectonic discontinuity; 4 - trace of the hydrogeologic section). (C) Hydrogeologic section (from Celico et al., 2006, modified; legend: 1 - low-permeability fault core; 2 - observation well; 3 - groundwater level.

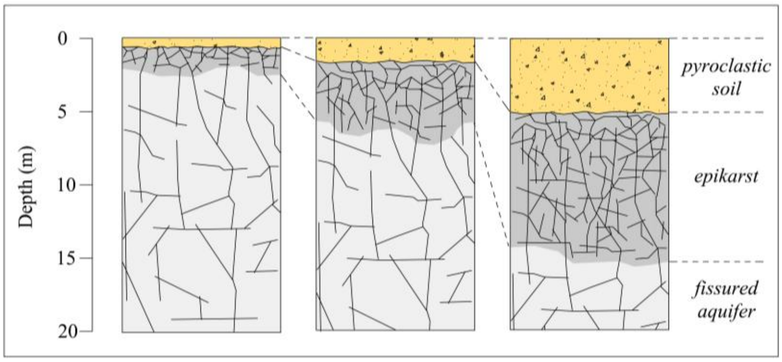

Figure 2: Physical characterization of the subsurface in Acqua dei Faggi (from Celico et al., 2010, simplified).

Field evidence indicated that the carbonate aquifer is also characterized by lateral heterogeneity in terms of hydraulic conductivity. In fact:

- during the recession periods, despite the interdependence detectable between the hydraulic heads measured in two piezometers (located along the regional groundwater flow direction; Celico et al., 2006), it is not possible to observe a "one-to-one" relationship between them; further this, the decrease of the hydraulic head measured up-gradient is slower than that measured down-gradient, suggesting a lateral heterogeneity of the sub-surface in terms of hydraulic properties;
- broad differences in hydraulic heads measured between different piezometers are not compatible with the small hydraulic gradients expected for such an highly permeable aquifer. Rather, significant differences in hydraulic heads could be explained with the presence of rock masses acting as permeability barriers interposed between the observation wells;
- these permeability barriers, in the case study, are represented by some tectonic discontinuities (Celico et al., 2006), identified between the observation wells. In fact, mainly due to mineral precipitation and/or grain-size reduction, the fault cores could be characterized by lower porosity and permeability with respect to the adjacent protolith (e.g. Chester and Logan, 1986; Antonellini and Aydin, 1994), in agreement with some findings of calcite-filled cataclasite in Acqua dei Faggi. The results of Lugeon tests corroborate this interpretation (Celico et al., 2006);
- where the investigated low-permeability fault zones intercept the ground surface, the activation of seasonal and temporary springs (e.g. Figure 3) further confirms the buffering yielded on the groundwater flow (Celico et al., 2006; Petrella et al., 2007; Petrella et al., 2009).
- Low values of hydraulic conductivity could be subordinated to very thin cores within the fault zones. In fact, the Figure 3 shows the hydraulic gradient measured, during the

recession period, between two piezometers which across a dipping fault zone (Celico et al., 2006). The abrupt increase in hydraulic gradient below 990 m asl indicates the presence of a low permeability fault core. However, the last part of the curve shows an abrupt decrease of the hydraulic gradient, indicating that the portion of the fault zone acting as an aquitard is just a few meters thick.

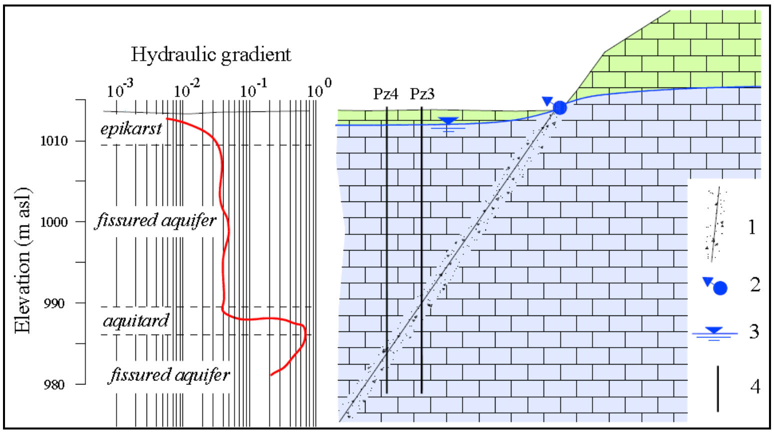

Figure 3: Evolution of the hydraulic gradient between two piezometers crossing a dipping fault zone (from Celico et al., 2006, simplified). Legend: 1) low-permeability fault core; 2) spring; 3) phreatic level; 4) observation well.

On the whole, the carbonate aquifer of Acqua dei Faggi is configured as a groundwater basin compartmentalized in smaller sub-structures, by means of variously oriented aquitards.

Expected functioning mechanisms

In such kind of hydrogeological system, the following general considerations can be developed. For each sub-structure, given a specific inflow (groundwater coming from the up-gradient part of the groundwater basin plus the local infiltration), the velocity in raising or lowering of the water table mainly depends on:

- ✓ the physical and geometrical properties of the rock masses characterizing the sub-structure (e.g. effective porosity and volume);
- ✓ the physical and geometrical properties of the aquitards which bound the sub-structure (e.g. thickness, integrity, permeability);
- ✓ the orientation of the of the aquitards with respect to the local groundwater flow direction.

It follows that during the recharge and discharge episodes, the water table configuration could continuously undergo drastic modifications.

Due to the heterogeneity of the media, a non-uniform rebalancing of the hydraulic heads takes place and leads to transient conditions within the less permeable portions of the system (Javandel and Whiderspoon, 1969; Freeze, 1971; Cedergren, 1989; Bear, 1987). Furthermore, also depending on the air-pressure head of the unsaturated rocks (Freeze, 1971; Lam and Freudlund, 1984; Lam et al., 1987), the advancing phreatic surface can move rapidly through the highly permeable media but it slows down within the less permeable media (Freeze, 1971). In other words, the heterogeneities of the subsurface could yield variations through time of the groundwater flow patterns for which the aquitards play an important regulatory function.

In addition, because of the seasonal fluctuations of the water table, the uppermost part of the flow system could periodically undergo further modifications (i) if a discontinuous epikarst becomes part of the flow region, determining new vertical contrasts of permeability and (ii) if seasonal or temporary springs are activated, determining new intermediate discharge points, toward which the flow lines tend to converge.

On the whole, in a dynamic system, mainly due to the permeability variations of the subsurface, we can expect that the groundwater flow patterns are continuously variable through time. However, in such a scenario, the modifications of the flow system could become an important concause of the observed hydrogeologic dynamics. In the following sub-sections, based on experimental observations, a conceptual functioning model for the heterogeneous groundwater basin of Acqua dei Faggi is outlined.

MATERIAL AND METHODS

Experimental observations

The hydraulic heads were measured in two observation wells P1 and P2, (130 and 170 m deep, respectively), fully screened, located 1100 m apart, along the regional direction of the groundwater flow (Figure 1). The monitoring was carried out on a weekly basis, from April 2005 to December 2005, and on a hourly basis, from January 2006 to April 2009. The heads were recorded with pressure transducers and standard water level measurements. The discharge of the spring was monitored weekly from April 2005 to March 2007 by means of a current meter.

The rainfall was monitored (i) with a rain gauge (R5 in Figure 1A), located at 1050 m a.s.l., from April 2005 to April 2009, on a hourly basis, and (ii) with three rain gauges (C1, C2 and C3 in Figure 1A), located at 1940, 1730 and 1620 m asl, respectively, from January 2006 to December 2011, on a monthly basis.

Data collected from January 1973 to 1999, relative to the rain gauges R1, R2, R3, R4, R5 and R6 distributed in broadest area (Figure 1A) have also been used. Based on the mean values of rainfall, the isohyetal contour lines have been constructed by means of linear interpolation (Figure 1A).

Numerical approach

Based on the conceptual model outlined by Celico et al. (2006), according to which the carbonate aquifer is compartmentalized in smaller sub-structures (Figure 1C), by means of thin aquitards, a numerical technique has been used to evaluate, at basin scale, the theoretical distribution of the potential field in ideal conditions of steady flow.

For this purpose, the effect produced by three different distributions of permeability in the subsurface has been simulated, applying the finite difference method (Thom and Apelt, 1961) as outlined by Freeze and Witherspoon (1966). The continuous flow region has been replaced by a finite set of nodal points (about 10000) arranged in a mesh-centered grid. The water table, along which the hydraulic heads have been specified, is assumed to be the upper boundary of the flow region (Figure 4) and represents the Dirichlet condition. The remaining three limits have been modeled as no flow boundaries (Figure 4), which are mathematically described by Neumann conditions.

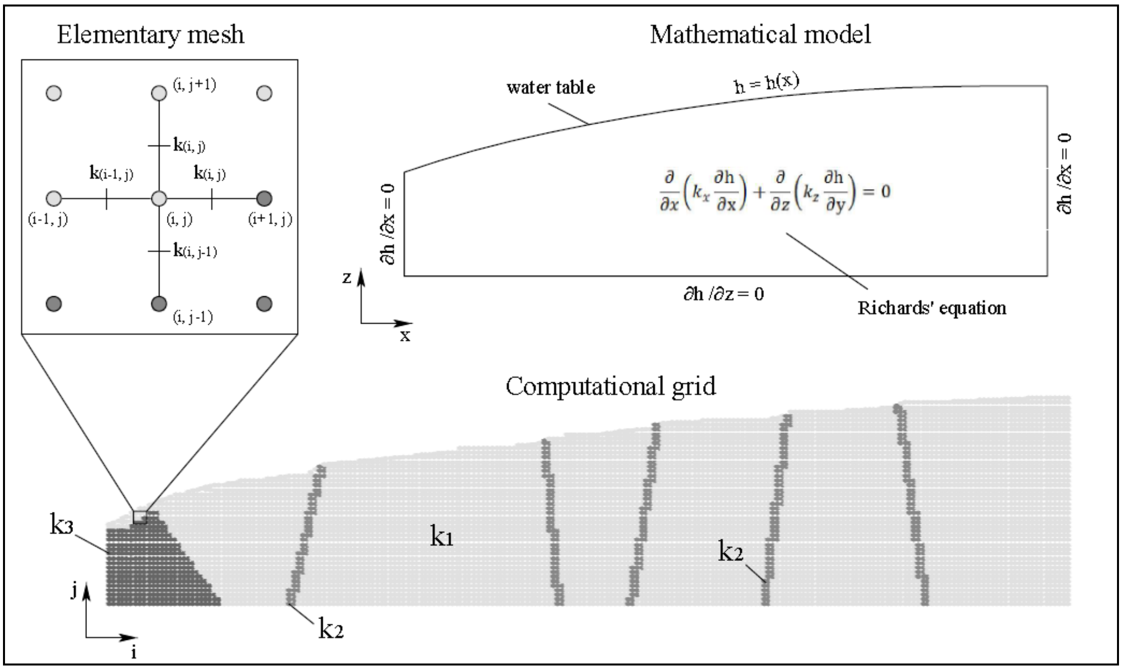

Figure 4: Mathematical model for the numerical method.

The vertical limit on the right side corresponds to the regional water table divide, which is supposed to be found where the pluvial recharge is more abundant (Figure 1A). The vertical limit on the left side is not compatible with the geologic information. Further this, a more realistic impervious boundary has been obtained by assessing exceptionally low permeability values to the cells in which the regional aquitard is expected to be found, as suggested by Freeze and Witherspoon (1966).

The partial differential equation describing the steady flow (Richards' equation, in Figure 4) can be approximated by a set of linear equations. Therefore, a finite difference approximation of the Richards' equation, has been obtained for each meshpoint, by means of the iterative procedure known as Successive Over Relaxation (SOR) (Hageman et al., 1981).

The core of the algorithm are the formulas [1] and [2]:

$$h_{i,j}^{(n+1)} = \frac{\dfrac{K_{east} h_{i-1,j}^{(n+1)}}{\Delta x^2} + \dfrac{h_{i+1,j}^{(n)}}{\Delta x^2} + \dfrac{2K_{south} h_{i,j-1}^{(n+1)}}{\Delta y_{i,j-1}\left(\Delta y_{i,j-1} + \Delta y_{i,j}\right)} + \dfrac{2h_{i,j+1}^{(n)}}{\Delta y_{i,j}\left(\Delta y_{i,j-1} + \Delta y_{i,j}\right)}}{\dfrac{K_{east}+1}{\Delta x^2} + \dfrac{2}{\Delta y_{i,j-1}\left(\Delta y_{i,j-1} + \Delta y_{i,j}\right)} + \dfrac{2K_{south}}{\Delta y_{i,j-1}\left(\Delta y_{i,j-1} + \Delta y_{i,j}\right)}} \quad [1]$$

$$h_{i,j}^{(n+1)} = (1-\omega) h_{i,j}^{(n)} + \omega h_{i,j}^{(n+1)} \quad [2]$$

where the permeability parameters are given by the formulae [3]:

$$K_{east} = \frac{K_{i-1,j}}{K_{i,j}}; \quad K_{south} = \frac{K_{i,j-1}}{K_{i,j}} \quad [3]$$

and represent the permeability ratios between the nodal point (i, j) and the nodal points (i-1, j) and (i, j-1), respectively. The quantity Δx is the constant horizontal meshsize, while $\Delta y_{i,\,j}$ is the vertical meshsize between the nodal points (i, j) and (i, j+1). The structure of the formulae [1] guarantee the respect of the transfer conditions along the boundaries between media with different values of permeability. Below the upper boundary (water table profile), a non uniform vertical grid allowed to increase, locally, the number of the nodal points, enhancing the accuracy of the numerical computation. The above formulae depict the classical iterative Gauss-Seidel method with SOR refinement by the relaxation factor ω. The iteration process stops when a test on the relative error satisfies the expression [4]:

$$\frac{\left\| h_{i,j}^{(n+1)} - h_{i,j}^{(n)} \right\|}{\left\| h_{i,j}^{(n+1)} \right\|} < tol \quad [4]$$

where *tol* is the required accuracy.

In case study we used *tol* = 10^{-9}, while 1.96 represent the optimal value for the relaxation factor ω. Through, this choice the accuracy is satisfied by n = 600 iterations. A software routine in the scientific computing environment Mathematica® (Wolfram, 2003) was designed and implemented in order to determine the values of the hydraulic head in each nodal point of the computational section (Figure 4). The equipotential lines, representing the potential field, have been traced by means of linear interpolation of the calculated hydraulic heads. The flow lines have been drawn making all the intersections orthogonal with the equipotential lines, since each portion of the system (aquifer and aquitards) has been considered as an isotropic media.

Statistical approach

In order to determine the relationship between rainfall and piezometric levels, the relative time series have been analysed by cross-correlation. The cross-correlation based methodology is widely used to analyse the linear relation between input and output signals in hydrogeology. In this case study, the input signal is the rainfall and the output signal is the piezometric level.

Following the method of Fiorillo and Doglioni (2010), multiple rainfall time-series data, constructed as cumulative rainfall over varying time windows, has been used as input data. Therefore, the output signal, the piezometric level, is investigated as a consequence of the long antecedent cumulative rainfall values.

The linear cross-correlation function, $r_{xy}(k)$, is defined as (Larocque et al. 1998):

$$r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \cdot \sigma_y} \qquad [5]$$

where $C_{xy}(k)$ is the covariance between the rainfall time series x_i and the spring discharge time series y_i, computed at time lag k. σ_x and σ_y are the standard deviations of the time series.

The cross-correlation function of the two time series represents a key indicator of the degree to which the time series are linearly correlated, as a function of the time interval between individual values in the series. The values of $r_{xy}(k)$ can range between -1 (perfect negative correlation) and +1 (perfect positive correlation); a value of 0 indicates no correlation. The hydrogeological implication of these results is a broad estimation of the time required for water to flow through an investigated carbonate aquifer (Fiorillo et al., 2007; Fiorillo and Doglioni, 2010).

The link and lag between the two piezometric level data series can be also analysed by the cross-correlation; in this case, the input series has been used the P1 data series or P2 data series.

RESULTS

Theoretical steady flow system

The results of the numerical computations (Figure 5) show that due to the contrasts of permeability transversal to the groundwater flow direction, the development of more flow cells with downward and upward fluxes occurs. In particular:

- for permeability ratios k1/k2 up to 10 (Figure 5A) the refraction of the flow lines is negligible. In such a case, the physical compartmentalization of the aquifer does not entail a significant fragmentation of the major groundwater flow system.
- for permeability ratios k1/k2 higher than 100 a significant generalized increase in vertical component of flow arises (Figures 5B and C), leading to the formation of well developed sub-basins.

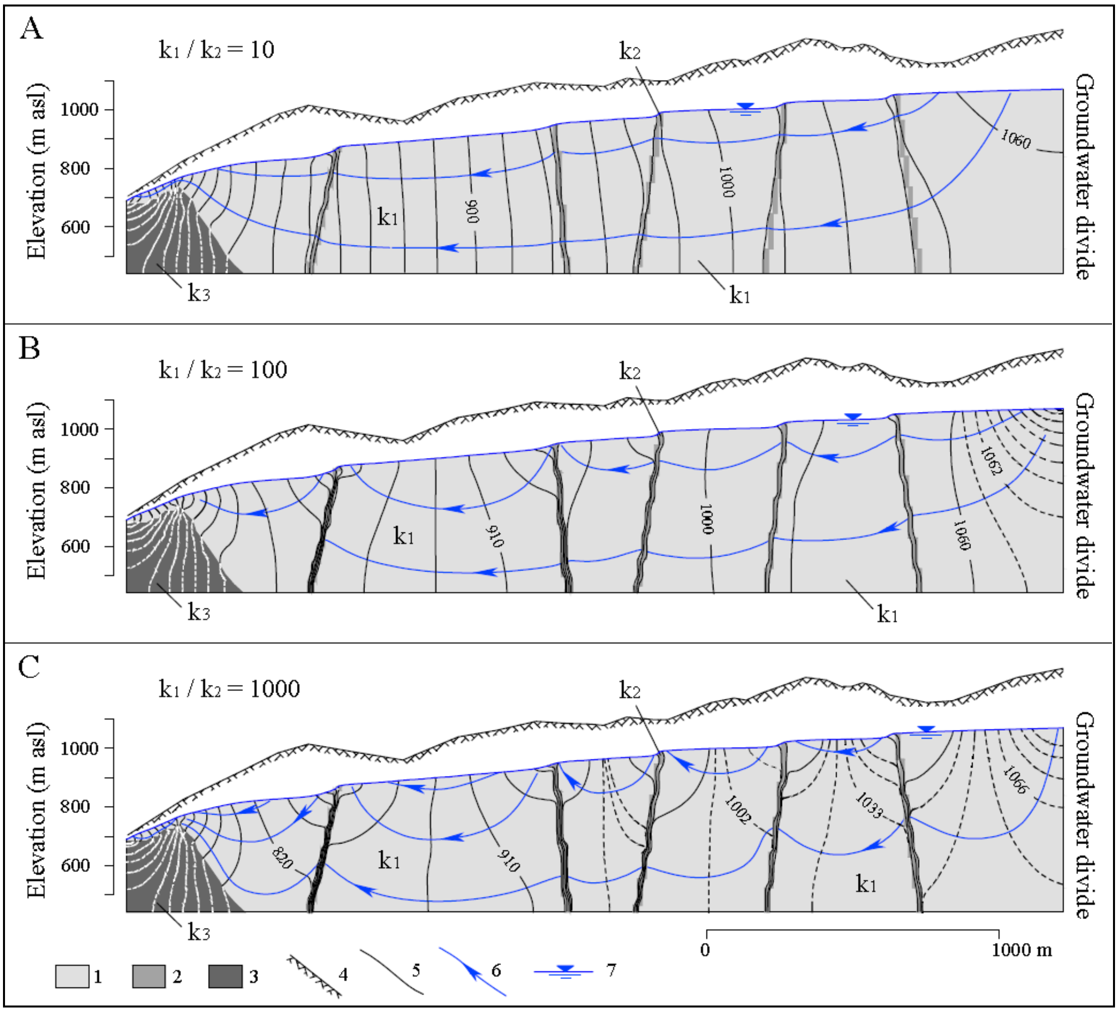

Figure 5: Regional groundwater flow pattern, for different permeability ratios.
Legend: 1) carbonate aquifer having k = 10^{-6} m/s; 2) Low-permeability fault core having 10^{-7}, 10^{-8}, 10^{-9} m/s in A, B and C, respectivrly; 3) regional aquitard having k = 10^{-15} m/s; this value allows to model the confine with the regional aquitard like a no flow boundary, following the suggestions of Freeze and Witherspoon (1966); 4) topographic profile; 5) equipotential contour line; 6) flow line; 7) water table profile.

Experimental observations

The isohyetal contour lines (Figure 1A) show that on the entire groundwater basin, a orographic control is undergone by the rainfall on the entire groundwater basin, also according to the seasonal variations of the mean values (Figure 6A). However, the rainfall is substantially homogeneously distributed just within the study site (Figure 1A), according to the monthly averages shown in Figure 6B.

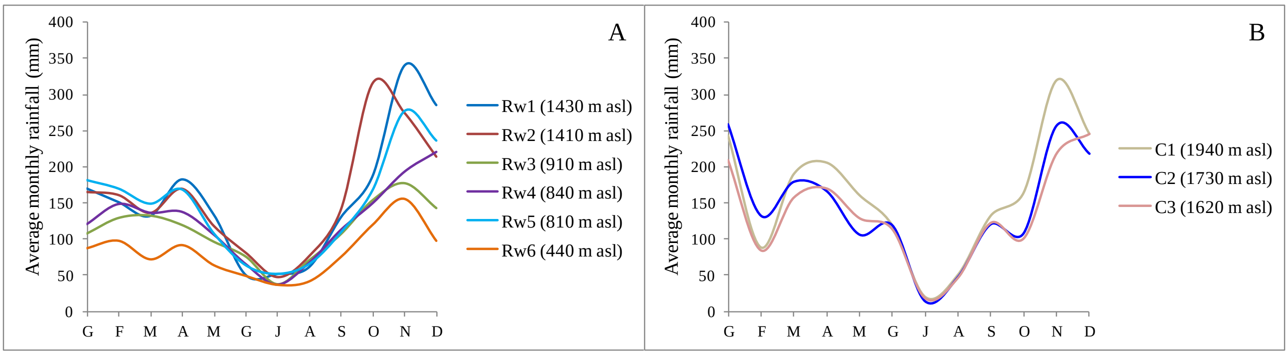

Figure 6: Average monthly rainfall based on the period 1973 - 1999 (A) and on the period 2007 - 2011 (B). The position of the stations are reported in the Figure 1A.

The responses of the piezometers P1 and P2 to the meteoric precipitations are shown in the Figure 7. For both the experimental curves, it is possible to identify four hydrologic years. For each hydrologic year, the curve is formed by three types of branches: D-type, characterized by the progressive decrease of the water level (discharge period), R-type, characterized by the progressive increase of the water level (recharge period), and I-type, characterized by the frequent fluctuations of the water level (influenced period).

In the following subsections the experimental relationships between meteoric precipitations and hydraulic head are analyzed.

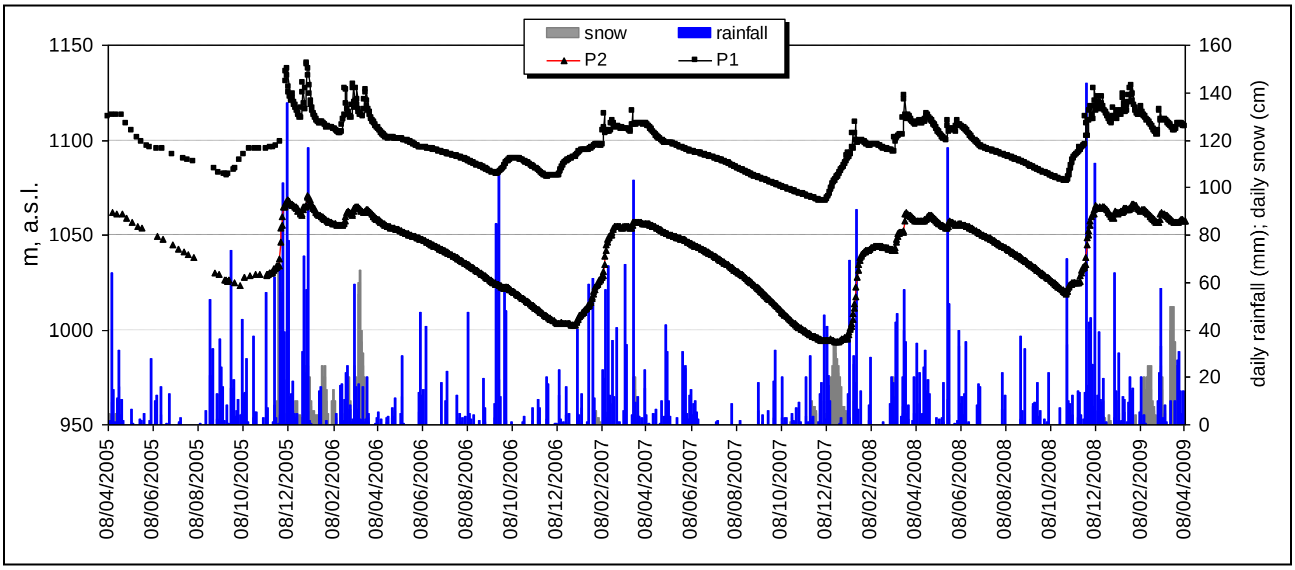

Figure 7: Piezometric level recorded in P1 and P2 wells; daily rainfall and snow accumulation recorded at Roccamandolfi (R5 in Figure 1A), from April 2005 to April 2009.

Seasonal spring 2 (1065 m a.s.l.) flowed several months a year during the observation period with a discharge ranging from 0 to 0.50 m^3/s (Figure 8).

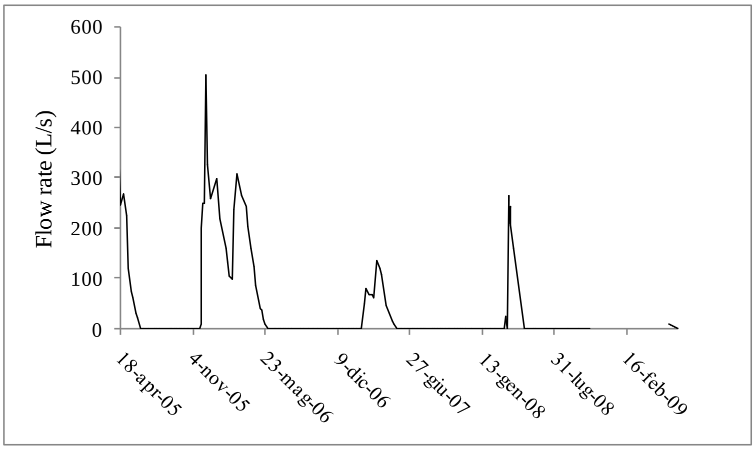

Figure 8: Hydrograph of seasonal spring 2.

<u>Relationship between piezometric levels and rainfall</u>

Figures 9a and 9b show the cross-correlation up to 360 lags ahead, between the cumulative rainfall and piezometric level P1 and P2, respectively. For both the piezometers, the cross-correlation indicates the absence of correlation for 1-day cumulative rainfall, as the highest positive value of $r_{xy}(k)$ is 0.172 obtained for k = 43 days and of $r_{xy}(k)$ is 0.227 obtained for k = 8 days, respectively.

For longer cumulative rainfall, the cross-correlation function, $r_{xy}(k)$, increases strongly and verifies that piezometric levels are controlled by cumulated rainfall over a longer period of time. For piezometer P1, the maximum value of $r_{xy}(k)$ is reached via the 120-day-moving-cumulative-rainfall time series as input, which gives $r_{xy}(k)$ = 0.847 for lag k=0 days. For piezometer P2, the maximum value of $r_{xy}(k)$ is reached via the 180-day-moving-cumulative-rainfall time series as input, which gives $r_{xy}(k)$ = 0.814 for lag k = 0 days. Furthermore, for cumulative rainfall of 90, 60 and 30 days the response of the piezometer P2 (Figure 9b) shows also a lag k>0, not observed for piezometer P1 (Figure 9a).

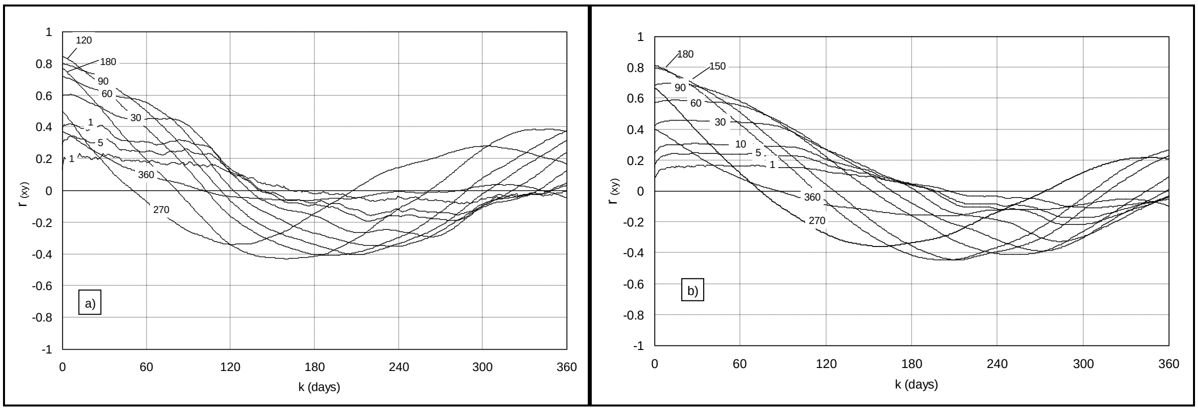

Figure 9: Cross-correlation of cumulative rainfall data (1, 5, 10, 30, 60, 90, 120, 150, 180, 270 and 360 days of cumulative rainfall) vs. piezometric level. a) piezometric level P1; b) piezometric level P2.

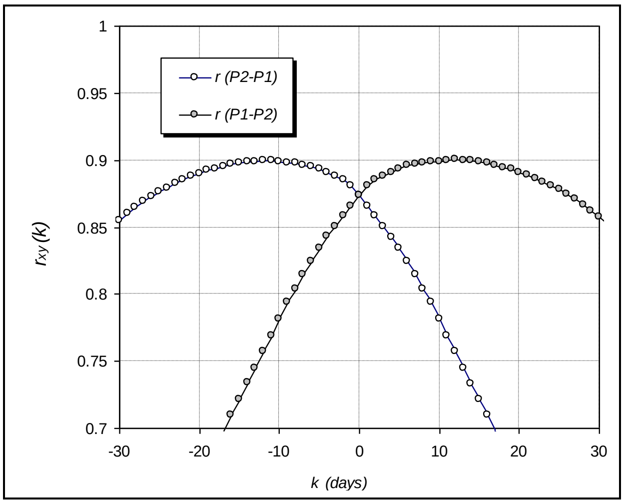

Figure 10: Cross-correlation of piezometric level P1 vs piezometric level P2, $r_{(P1-P2)}$, and vice versa, $r_{(P2-P1)}$.

<u>Relationship between the piezometric levels</u>

As it can be seen from the results of Figure 1, the highest value of r_{xy} is obtained for a lag k = 12 days ($r_{xy}(k)$ = 0,900). This result indicates that the piezometric level of P1 series presents the best overlay on the series of piezometric level P2 when shifted 12 days forward.

The linear fit between P1 and P2 data series, for k = 0, is given by the following equation:

$$y = 0.5712x + 502.89 \qquad [6]$$

where y and x are the piezometric levels (m a.s.l.).
The best linear fit occurs for k = 12 (Figure 10) and is given by the following equation:

$$y = 0.5903x + 483.06 \qquad [7]$$

Based on the equations [6] and [7], Figure 11 shows the autocorrelations of residuals of the linear models, i.e. the errors of the linear fitting. In Figure 11 the autocorrelation function of equation 7 decreases more rapidly than equation [6], but the results indicate that residuals are correlated and cannot be considered normally distributed.

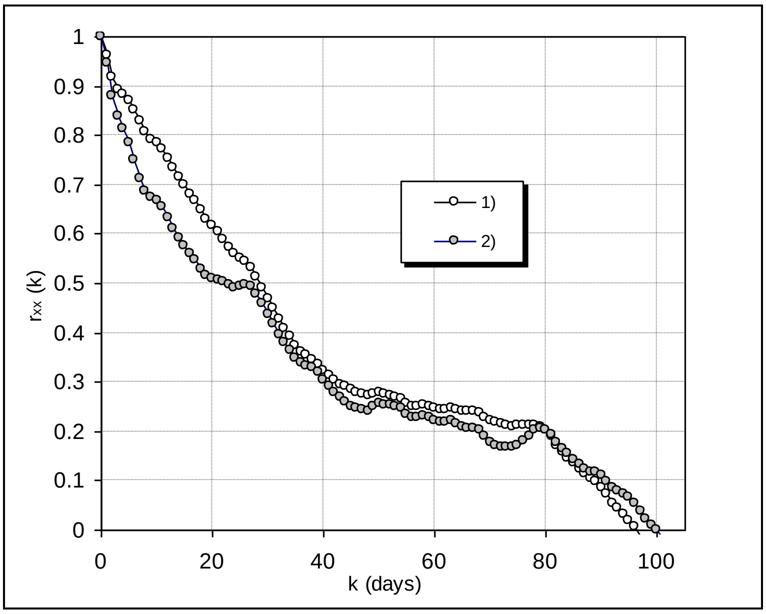

Figure 11: Autocorrelation of residuals of linear fitting of piezometric level P1 data series vs piezometric level P2 data series. 1) k = 0; 2) k = 12 days.

According to results of Figure 11, the two distinct piezometric level data series only at the beginning do not respond synchronous to the rainfall regime, as the rising of the water level in P1 is anticipated with respect to that observed in P2. Nevertheless, after 12 days, a substantial synchronism characterizing the influenced period (I-type branches) takes place between P1 and P2.

DISCUSSION

The regional groundwater basin results discretized in smaller sub-basins, each of whom characterized by little recharge and discharge zones. According to Tòth, 1963, a recharge zone is defined by flow lines diverging from the water table, while a discharge zone is defined by flow lines converging with the water table. Both of them are related only with distribution of permeability and the water table configuration.

Therefore, with respect to the case study, the intermediate discharge zones are not necessarily related with springs or with zones in which concentrated evapotranspiration takes place, since they could be found at significant depth from the ground surface. Rather, in absence of such mechanisms which allow the mechanical removal of the groundwater, the discharge zones could represent groundwater fluxes emerging from the flow region and feeding the downgradient sub-structures.

An exhaustive understanding of the role played by the permeability distribution can be evaluated by combining these theoretical considerations with the analysis of the field observations.

For this purpose, the experimental data (Figure 7) discussed above can be conveniently summarized as follows:

1. in the piezometer P1, the hydraulic head is held until about 80 m above the water level recorded in the piezometer P2, at the end of the discharge period;
2. during the discharge periods (D-type), between P1 and P2 the decreases of the hydraulic heads are different in amount and velocity; in P2 the lowering of the water level is greater and faster than in P1;
3. the rising of the water level in the piezometer P2 takes place after a longer antecedent rainfall (Figures 9 and 11), suggesting an apparently slower response to the rainfall of the sub-structure where this piezometer has been drilled;
4. during the recharge periods, the increases of the hydraulic heads in P1 and P2 are different in amount and velocity. Despite the mentioned delay in response to the rainfall, faster and grater raising of the water level is observed in P2 (Figure 7). This anomalous behaviour suggests that the only rainfall can not explain in exhaustive way the experimental observation; rather, in addition to the rainfall, more hydrogeological processes could interact, determining the dynamic functioning of the system;
5. synchronous frequent fluctuations in hydraulic heads can be observed between P1 and P2, during the influenced period (I-type), as shown in Figure 10. The beginning of this period is also marked by the activation of the seasonal spring 2, which is characterized by a jagged hydrograph;

6. in P1, the mentioned fluctuations of the water level are more amplified than in P2 (Figure 7).

Conceptual functioning model

The field evidence has been analyzed to outline a conceptual functioning model for the groundwater flow system. In order to simplify this discussion, it is useful to consider first of all a bi-dimensional problem with just two sub-structures: Ω1, in which is P1 perforated, and Ω2, in which is P2 perforated. Moreover, let us consider just one aquitard, which we will call B1, interposed between the sub-structures Ω1 and Ω2 and a second aquitard, which we will call B2, located down-gradient of the sub-structure Ω2 (Figure 12).

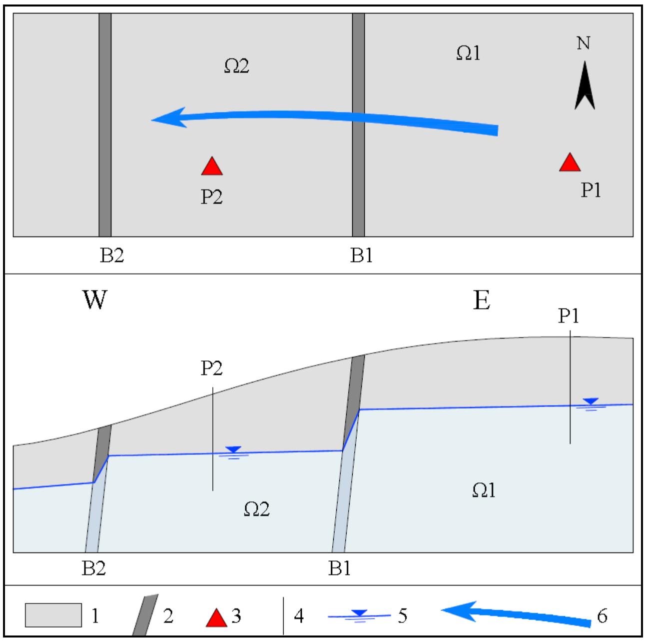

Figure 12: Schematic representation of the hydrogeologic system aimed to provide a conceptual explanation of the experimental data. Legend: 1) highly permeable carbonate aquifer 2) low-permeability fault core; 3) position of the observation well; 4) observation well; 5) water table profile; 6) regional groundwater flow direction.

The following discussion regards the explanation of the six points listed above.

1) compared with the hydraulic gradient found in the carbonate aquifer, the anomalous difference in hydraulic head between P1 and P2 (until 80 m) can be explained by the role played by the fault zones which act as permeability barriers (aquitard B1, in the specific case). In fact, significant differences in hydraulic heads between two sub-structures, Ω1 and Ω2, can be held if, through the aquitard B1, located in the middle, concentrated hydraulic head losses take place (Casagrande, 1937; Freeze, 1971; Cedergren, 1989).

2) The barrier effect caused by the aquitard B1, interposed between Ω1 and Ω2, could be higher than that yielded by the barrier B2, located down-gradient of Ω2. Therefore, up-gradient of the barrier B1, the discharge flow could be much more impeded, compatibly with the slower decrease in hydraulic head recorded in P1. Conversely, the groundwater discharge through the barrier B2 is more effective, compatibly with the faster decrease of the water level observed in P2.The difference in degree of compartmentalization between B1 and B2 is also inferable by the wavelet which the curve (D-type) recorded in P1 forms during the second hydrologic year (Figure 7). After a small rise of the water level, the decrease takes place slowly, rather than that observable during the influenced periods (I-type branches; Figure 7). Contemporarily, the decrease of the water level in the piezometer P2 is much less influenced (Figure 7), in agreement with a less effective compartmentalization exercised by the aquitard B2.
3) If the barrier effects produced by the aquitards B1 and B2 are not the same, it should not be surprising to discover that the recharge periods detectable in P1 and P2 begin in different times. In particular, if the discharge through the barrier B2 is higher than that through B1, the beginning of the recharge period observable in P2 can be delayed. As a matter of fact, the difference between the aquitards B1 and B2, in terms of buffering (which results from a combination of hydraulic conductivity, thickness and integrity) also influences the recharge during the high flow period. In particular, despite the pluvial recharge, it is substantially homogeneous on the considered portion of the groundwater basin (Figures 1A, and 6B), up-gradient of the more effective barrier B1, we can expect that the rainfall (or better the effective infiltration) can sooner reflect an increase of the hydraulic head. Instead, down-gradient of B1, the rate of the infiltration, for a short period, can just be able to balance the discharge through the relatively more permeable aquitard B2, as indicated by the water level observed in P2. Obviously, in the measure in which the difference in hydraulic head between Ω1 and Ω2 increases, the enhancement of the non-equilibrium conditions within the aquitard B1 is expected. As a result, between the two sub-domains, a transfer of groundwater will take place, tending to minimize the difference in hydraulic head between them. In other words, with the beginning of the recharge period, the local infiltration, for the sub-structure Ω2, is enough just to balance the groundwater flowing through the aquitard B2 (the hydraulic head in P2 remain stationary). At the same time, from the sub-structure Ω1, the phreatic surface tends to move toward Ω2, but it is slowed down by the barrier B1, after that the water table surface migrated through B1, in addition to the local infiltration (which balances the

amount of groundwater flowing through the aquitard B2), the groundwater coming from Ω1, allows for the rising of the water level in Ω2 (observed in P2).

4) Within the sub-structure Ω2, however, the raising of the water level is always quicker, probably due to a lower effective porosity of the rock. Further this, the modification of the water table configuration, could enhance the response of Ω2, compatibly with the faster raising of the water level observed in P2. In fact, at first, because of the local flow pattern with respect to orientation of the aquitard B1, only a relatively small rate of the groundwater will move into the sub-structure Ω2. Later, the successive changing of the local flow scheme could create a greater convergence of the flow lines on Ω2 from the up-gradient portion of the basin. In this case, along the aquitard B1 surrounding the sub-structure Ω2, the inflow surface will increase at the expense of the outflow surface. It follows that, given a specific value of effective porosity of the rock, within the sub-structure Ω2, the increasing of the ratio inflow/outflow will cause a quicker rise of the water table. The new flow configuration, compatibly with the hydraulic conductivity of the aquitard B1, leads to the minimization of the difference in hydraulic head between Ω1 and Ω2, as showed by the higher rise of the water level observed in P2.

5) Statistically, only after 12 days (Figure 10) a synchronism of the water level between P1 and P2 is observed (I-type branches; Figure 7). The culmination of the water levels is accompanied by frequent fluctuations observed in both P1 and P2. These jagged hydrographs suggest a significant influence of the rainfall combined with a rapid discharge of the groundwater at an outlet point. Such conditions could take place when the water table intercepts (i) a zone of the aquitard in which the buffering is absent, and/or (ii) the termination of the aquitard on the ground surface, allowing for the activation of temporary and seasonal springs. In fact, for a specific sub-structure, if the inflow (pluvial recharge plus the flow rate coming from the up-gradient portion of the groundwater basin) is higher than the outflow, the water table surface has to rise. Nevertheless, constant head conditions occur in correspondence of the outlet point, in which the water table cannot further rise. Rather, the outlet point can work as a hinge with respect to which the water table can swing. This mechanism can explain the frequent fluctuations of the water table as a rapid response to the rainfall during the influenced periods.

6) During the influenced periods, however, the behavior of the system reflects also the heterogeneity in effective porosity. In P1 the water table is too deep to intercept the epikarst. Therefore, the amplified jagged fluctuations of the groundwater level are in agreement with the lower effective porosity of the fissured media. However, since P1 is

located distant from the springs, the influenced conditions could indicate that in some zones of the aquitard B1 the buffering is absent, also indicating that the precipitation of calcite within the fault cores could be not uniform. Conversely, within the sub-structure Ω2 the water table is much closer to the ground surface and it can intercept the epikarst horizon. The higher effective porosity of the epikarst can attenuate the oscillations of the water table.

The conceptual model described above, is based on few hydrogeologic elements (only two sub-structures Ω1 and Ω2 and only two aquitards B1 and B2) just by the necessity to explain in the easiest way the observed complex dynamics. A refinement, however, is possible in order to take into account more field evidence:

- firstly, the number of fault zones between P1 and P2 is more than one. Therefore, rather than the only one B1, a higher number of permeability barrier probably exists;
- furthermore, in comparison with the hydraulic gradient in the carbonate aquifer, a wide difference in hydraulic heads (until 80 m) would suggest only for the aquitard B1 the hydraulic conductivity is exceptionally low (10^{-15} m/s). Even though it could be theoretically possible, the aquitard B1 would impede the dynamic interactions observed between the sub-structures Ω1 and Ω2 during the recharge period (Figure 7);
- conversely, relatively rapid decrease of the hydraulic heads during the discharge periods suggests scarce barrier effect exercised by the aquitards.

Probably, instead of the only aquitard B1, according to the conceptual model in Figure 1C, exists a set of barriers $\overline{B}_1$. In this case, the total head losses, observed between P1 and P2, is distributed among more aquitards, one of which with a relatively higher permeability or with a lower integrity.

A conceptual functioning model concerning the dynamic behavior in such a hydrogeological system can be inferred from the results of the numerical analysis performed by Freeze (1971). He studied the propagation of the water table through a composite dam under saturated – unsaturated conditions. The phenomenon is influenced by the distribution of the water content within the unsaturated media. However, after a rapid rise of the water level in the reservoir located up-gradient of the dam, the propagation of the phreatic line is rapid within the high permeable material but it slows down within the low permeability core. Therefore, it is possible to deduce that the smaller is the thickness of the barrier permeability the faster is the propagation the phreatic surface crossing the aquitard.

In Acqua dei Faggi, some experimental data published by Celico et al. (2006) seem to confirm that the thickness of the fault cores acting as an aquitard is up to a few meters (Figure 3).

Further this, by means of slighter contrasts of permeability, the duration of the transient conditions in each aquitard can be shorter. It follows that each sub-structure is made more sensitive with respect to modifications of the groundwater flow pattern (e.g. convergence of the flow line on a specific sub-domain). In such conditions, a quick response of a sub-domain could be further enhanced in the measure in which it has a small volume, scarce effective porosity and high reception with respect to the rainfall, according to Celico et al. (2006). Consequently, the compartmentalization of the aquifer system, rather due to pure aquitards, can still be due to slight contrasts of permeability if more factors work in synergy.

CONCLUSIONS

The carbonate aquifer of Acqua dei Faggi is compartmentalized in smaller sub-structures by means of low-permeability fault zones, variously oriented. Based on the conceptual distribution of permeability, three different conceptual scenarios have been outlined by finite difference method for the steady flow system at basin scale. The degree of compartmentalization may be negligible or very pronounced depending on the rate of the contrasts of permeability. However, the relationships between the local rainfall and the hydraulic heads suggest that the functioning mechanisms controlling the groundwater flow dynamics in heterogeneous systems could be more complex than previously thought. During the discharge periods, relatively rapid decreases of the hydraulic heads indicate that the aquitards do not efficiently impede the groundwater flow, producing slights contrasts of permeability with the adjacent portions of the fissured media. Furthermore, the relationship between hydraulic heads, indicating progressively a faster discharge for the downgradient portion of the groundwater basin, suggest that each aquitard could impede the groundwater flow in different rates, depending on its specific hydraulic conductivity, integrity and thickness. As a result, the groundwater flow pattern is continuously changing, causing a non-uniform reconfiguration of the potential field within the flow region, according to Bear, 1987 and Javandel and Whiderspoon, 1969. Further this, despite the substantial uniform distribution of the rainfall (Figures 1A and 6B), for the downgradient part of the basin, the recharge events are delayed, but they are also quicker and greater (Figure 7). This evidence indicates that delayed modifications of the groundwater flow pattern play an important role in controlling the local response of the system. In particular, the increasing convergence (or divergence) of the flow lines can work:

- by adding to the general recharge (or discharge) events, enhancing the local response;
- by countering to the general recharge (or discharge) events, modulating the local response.

In other words, the experimental evidence indicates that even though the modifications of the groundwater flow pattern represent the effect of the non-uniform rebalancing of the hydraulic heads, they may represent also an important concause controlling the local recharge and discharge processes, beside the meteoric precipitations. Such conditions are facilitated by slight contrasts of permeability, combined with (i) small volume of the sub-structures, (ii) low effective porosity of the sub-surface characterizing the flow region and (iii) high receptivity of the media with respect to the rainfall, according with previous studies (e.g., Celico et al., 2006).

On the whole, although in theoretically steady conditions slight contrasts of permeability do not compartmentalize the flow system (Figure 5A), in a dynamic scenario they do, also allowing for a relevant complexity of the groundwater flow.

In light of the worldwide diffusion of the heterogeneous systems, a better understanding of their behavior provides an essential tool for planning the rational usage of the groundwater resources. The present work emphasizes the need to refine this knowledge, especially by means of field activities.

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Conclusions

In the light of what has emerged from the work set out above, it is possible to deduce the following.

In the case of systems consisting principally formations with low permeability, even when, at the basin scale, they significantly impede groundwater flow, due to their heterogeneity the dynamics observed within them are heavily controlled by the functioning of the adjacent hydrostructure; in greater detail, both lateral and vertical interactions with the nearby aquifer can occur. As a matter of fact, uphill from where the feeding carbonate hydrostructure rests above the Lorda syncline, a dominant downward flow through the less permeable portion of the silico-clastic sequence is expected; downhill, along the bottom valley, where the deep carbonate aquifer is associated with a significantly lower head, a dominant upward flow through the silico-clastic sequence is expected. Because of the heterogeneity of the system (highly permeable horizons and the network of structural discontinuities like faults and fractures), however, the groundwater flow dynamics are strictly controlled by the behavior of the highly permeable carbonate systems.

In the case of highly receptive hydrogeologic systems, due to the heterogeneity of the rock masses, during recharge and discharge, non-uniform rebalancing of the hydraulic heads can occur. This leads to the activation of further modifications of the field potential, which could transmit downgradient, due to the lesser permeable portions of the media, also with a delay. However, because of the high receptivity of the entire aquifer system with respect to the rainfall, the overlapping of the effects yielded by the variations of the groundwater flow pattern are able to significantly regulate the dynamic functioning of the system, counteracting or enhancing the general raising (or lowering) of the water table.

On the whole, the results of these studies highlight the important role played on the groundwater basins by the distribution of permeability, which can make the flow dynamics more complex than usually believed. A more concrete possibility of continuing future studies optimizing the usage of multi-level monitoring systems follows. As a matter of fact, the need to refine their knowledge through experimental activities arises from the important implications of such dynamics on both the usage and the protection of groundwater resources. Further this, the usability of the conceptual models here outlined arises from the widespread diffusion of the heterogeneous rock masses.