HYDROGEOLOGICAL SPRING CHARACTERIZATION IN THE VAJONT AREA

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ABSTRACT
The Vajont Valley is mainly known for the catastrophic event of 9 October 1963, when a vast landslide occurred on the southern slope of the Vajont dam reservoir, causing a giant wave of water that flooded the Piave Valley below. Since then, many studies of the geological and geomechanical aspect of the landslide have been carried out, while very few studies have focused on the hydrogeological characteristics of this area. This paper proposes a hydrogeological conceptual model for the carbonate aquifers of the Vajont area, based on the continuous monitoring of two springs and environmental isotope investigations. Cross-correlation functions between time series and the VESPA index were used to delineate groundwater flow systems and the degree of karstification. This model has been confirmed by analyses of the amounts of stable isotopes, such as $^{18}$O and $^3$H, in precipitation and groundwater.

Key words: Vajont, spring, continuous monitoring, cross-correlation function, VESP A index, environmental isotopes

GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS
This paper focuses on the hydrogeological characteristics of the Vajont area. The study site is located in the municipalities of Erto-Casso (Friuli Venezia Giulia region) and Longarone (Veneto region) in the southeastern part of the Dolomite Mountains, northeastern Italy. This area is bounded by Mt. Salta (2,039 m above sea level [a.s.l.]) and Mt. Borgà (2,215 m a.s.l.) on the north, the Gallina Valley on the south, the Piave River on the west and the Zemola and Mesazzo valleys on the east (Fig. 1).

The landscape of Vajont valley was severely altered by the catastrophe of 9 October 1963, when a vast deposit of the Mt. Toc landslide completely blanketed the bottom of the valley producing an enormous wave of at least 30 million cubic metres of water which flooded the Piave Valley below.

Despite a large body of geological and geomechanical literature mainly concerning the Vajont disaster (Muller, 1964, 1968, 1987; Semenza, 1965; Corbin, 1982; Hendron & Patton, 1985; Belloni & Stefani, 1987; Nonveiller, 1987; Ghirotti, 1994; Tika & Hutchinson, 1999; Semenza & Ghirotti, 2000; Kilburn & Petley, 2003; Mantovani & Viti-Finzi, 2003; Helmsateter et alii, 2004; Genevois & Ghirotti, 2005; Veveakis et alii, 2007; Ward & Day, 2011), hydrogeological investigations are few (Busio, 1986). This is most likely due to the relatively shallow and poor groundwater circulation before the disaster, currently shown by the absence of springs in the Mt. Toc area and by the very low spring flow rates in the Vajont Valley.

The bedrock of the study area belongs to the eastern South Alpine structural unit, which represents the Neogene-Present back-thrusted (south vergent) part of the Alpine chain. The Vajont Valley coincides with the core of an Alpine syncline (Erto syncline) with an axis trending approximately E-W and gently plunging to the east (Riva et alii, 1990). The exposed deformed rocks are Liassic to Eocene carbonates and marls (Se-
The Vajont landslide occurred on the Erto syncline's south limb, which dips 30° to 50° to the north-northeast (western sector) and north (eastern sector). The landslide rupture surface is localized within the Middle-Upper Jurassic Fonzaso Formation, a sequence of thinly stratified limestones with thin (0.1-5 cm) intercalations of clays (Hendron & Patton, 1985). The sliding layered sequence was laterally constrained by a system of southward-converging subvertical faults (the Croda Bainca and Col Tramontin faults on the east and the west branch of the Col delle Erghene fault on the west), while the landslide crown was constrained by E-W-trending structures (Col delle Erghene fault; Riva et alii, 1990).

The succession of strata and their relative permeabilities are shown in Tab. 1.

From a hydrogeological point of view, only the Zemola Valley contains several significant springs, whereas the area around Mt. Toc is characterized by less surface water and fewer springs, most of which display low levels of discharge. This situation, we believe, is due to karstic groundwater circulation. This hypothesis is based on direct observation of sinkholes on the upper slope of the Vajont landslide; in this area, the majority of meteoric waters infiltrate without leading to a significant surface flow. The presence of karst phenomena in this

![Map of the Vajont area](image.png)
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210 mg/l), cold (6.7 < T < 10°C) and calcium magnesi-
num bicarbonate-type waters; furthermore, all the springs
have a slightly alkaline pH ranging between 8 and 8.4,
Eh ranging from 182 to 274 mV and electrical conduc-
tivity ranging from 162 to 281 μS/cm. These physico-
chemical data suggest the presence of young waters with
short travel paths. The locations of five of these springs
are shown in Fig. 2, and their corresponding Schoeller

area is well reported in the geologic literature (HEINDRON & PATTON, 1985; SEMENZA & GHIBOTTI, 2000).

In the study area, twenty springs were identified. Most of them have very low discharge (< 1 L/s) and similar physico-chemical parameters. Chemical analyses were carried out on water from eight springs (so-
dium, calcium, potassium, magnesium, total hardness,
total dissolved solids [TDS], iron, manganese, methyl
orange alkalinity, chloride, sulphate, carbonate), and
they could be classified as oligomineral (135 < TDS <

210 mg/l), cold (6.7 < T < 10°C) and calcium magnesi-
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chemical data suggest the presence of young waters with
short travel paths. The locations of five of these springs
are shown in Fig. 2, and their corresponding Schoeller
diagrams are plotted in Fig. 3.

After a reconnaissance of the geology of the study

<table>
<thead>
<tr>
<th>Unit</th>
<th>Age</th>
<th>Permeability</th>
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<tbody>
<tr>
<td>Quaternary deposits</td>
<td>Quaternary</td>
<td>Very high</td>
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<td>Alluvial deposits (Dol)</td>
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<td>Slope deposits (Overs)</td>
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<td>Glacial deposits (Dmoer)</td>
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<tr>
<td>Flysch (F)</td>
<td>Eocene</td>
<td>Very low</td>
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<tr>
<td>Erto marls (Me)</td>
<td>Paleocene</td>
<td>Very low</td>
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<tr>
<td>Scaglia Rossa (Sr)</td>
<td>Upper Cretaceous–Lower Paleocene</td>
<td>Low (B)</td>
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<td>Condensed series (Sc)</td>
<td>Malm–Upper Cretaceous</td>
<td>Very low</td>
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<td>Soccher Formation (Fsh)</td>
<td>Lower–Upper Cretaceous</td>
<td>Medium</td>
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<td>Fossas Fm. (Arp) and Ammonitico Rosso</td>
<td>Malm–Lower Cretaceous</td>
<td>Very low</td>
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<td>Vajont Limestones (Tv)</td>
<td>Dogger</td>
<td>High</td>
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<td>Ignne Formation (I)</td>
<td>Upper Lias</td>
<td>Very low</td>
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<tr>
<td>Soverzene Formation (Fex)</td>
<td>Middle and Lower Lias</td>
<td>Medium</td>
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<tr>
<td>Dolomia principale (Tp)</td>
<td>Upper Triassic</td>
<td>Medium</td>
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area, two springs with appropriate features were chosen for continuous monitoring: Ega Nass spring, on the west side of Mt. Toc (Dogna, Longarone), and Le Spesse spring, on the opposite side of the Vajont landslide (Le Spesse, Erto-Casso). In July and September 2010, two data-loggers (Diver) were installed to measure the hourly discharge, electrical conductivity (EC) and temperature (T) of the spring waters. These data were compared with rainfall from two weather stations (ARPA V and Servizio Idrografico Regione Friuli Venezia Giulia) to identify correlations between spring behavior (discharge, temperature and electrical conductivity) and rainfall events.

**HYDROGEOLOGICAL BEHAVIOR OF LE SPESSE ANDEGA NASS SPRINGS**

**LE SPESSE SPRING**

Le Spesse spring (Figs. 2 and 4) is situated at an elevation of approximately 810 m a.s.l. close to a small hamlet in the municipality of Erto Casso (Pordenone). This spring is located west of Erto Casso, on the north side of the Vajont Valley and east of the Vajont dam, at the foot of the southern slope of Mt. Borgà. The spring emerges from the Quaternary deposits; however, after evaluating the cross section (Fig. 7), in particular the formations next to the spring, it is evident that this spring water originates in the Vajont Limestone (high permeability), which is tectonically juxtaposed against the Scaglia Rossa Formation (low permeability), and flows through and emerges from the Quaternary deposits (Fig. 6a). According to the hydrogeological classification proposed by Civita (1972), which takes into account the point of emergence, this spring can be classified as a spring of contact between units of highly contrasting permeability.

**EGA NASS SPRING**

Ega Nass spring (Fig. 5) is located on the west slope of Mt. Toc, on the east side of the Piave Valley, at an elevation of 515 m a.s.l., at Dogna (municipality of Longarone). The Vajont Limestone (high permeability) underlies the Ega Nass spring recharge area. The Vajont Limestone overlies the Igne Formation (very low permeability). The spring emerges at the exposed contact between these two units. The Vajont Limestone is characterized by a high degree of karstification. The location of this spring may also be controlled by a system of faults parallel and orthogonal to the slope (Figs. 6b and 7).

The measured discharge of the Ega Nass spring does not represent the total flow emerging because spring water emerges from several points beyond our monitoring station at the main discharge location.

**DATA MONITORING ANALYSIS**

**LE SPESSE**

An analysis of Figure 8 shows a relationship between the rainfall (P) and the spring flow rate (Q). Moreover a cross-correlation investigation has helped us to quantify the lag times over short time periods. Lagged correlation refers to the correlation between two time series at different lags, or offsets in time. The cross-correlation function (CCF) is the correlation, related to the two time series, as a function of lag. The sample cross
where \( N \) is the series length, \( \bar{u} \) and \( \bar{y} \) are the sample means and \( k \) is the lag. The sample cross-correlation is the cross-covariance of the two series divided by their standard deviations:

\[
 r_{uy}(k) = \frac{c_{uy}(k)}{\sqrt{c_{uu}(0)c_{yy}(0)}}
\]

The cross-correlation function (CCF; \( P \) vs \( Q \)) in Figure 9 shows a significantly positive correlation at lag 1, which means that the most important response in flow rate (output) occurs beginning 1 day after a rainfall event (input). Moreover, a less evident positive cross-correlation at lag 0 also indicates a certain temporal association between rainfall and the spring flow rate.

In a situation of a quick flow-rate response to rainfall events, it can be useful to compare spring water temperature (\( T_s \)) with atmospheric temperature (\( T_a \)) to ascertain whether the flow-rate increase is due to a “piston” effect or to a local rainfall infiltration.
Analysis of Figure 10a shows a positive cross-correlation between variations in $T_a$ and variations in $T_s$ at lag 0 and lag 1, indicating that the water temperature variations in the short term are strictly linked to the atmospheric temperature variations. Moreover, the temperature trend comparison in Figure 10b shows a reverse trend: in winter the $T_a$ is lower and the $T_s$ is higher, while the reverse was observed in summer. During the warm season, the temperature of spring water is colder than that in the cold season, meaning that the water discharge is in partial equilibrium with the reservoir temperature instead of with the atmospheric temperature. Evidently, the travel time through the aquifer is insufficient for water to reach a thermal equilibrium with the rock matrix: in the winter, warm water discharges represent infiltration from the previous summer, and in the summer, outflowing cold water represents infiltration from the previous winter. Only
during rainy days (short time periods) are Ts variations influenced by variations in atmospheric temperatures, due to the effects of local rainfall infiltration, as seen in the cross-correlations in Figure 10a.

A comparison between the spring flow rate (Q) and electrical conductivity (EC; Fig. 11) shows a negative cross correlation at lag 0 (e.g., when Q increases then the EC decreases and vice versa). Thus the relationship shown in Figure 11 confirms the effect of local rainfall infiltration, which temporarily decreases the EC of the spring water.

This hypothesis is also confirmed by a negative cross-correlation at lag 1 between rainfall (P) and EC (Fig. 12). In fact the EC decrease in the spring water at lag 1 corresponds to a maximum positive cross-correlation between flow rate and rainfall, i.e., the dilution of spring water is due to the local rainfall infiltration.

The variations in CCF found in the analyses suggest that local short-term rainfall increase spring flow rates. Other analytical results also show some characteristics of a deeper spring water components, coming from the corresponding aquifer reservoir. Figure 11a shows a visible a positive cross-correlation between Q and EC at lag 1, i.e., an increase in Q produces an increase in EC. This trend can be explained as more-conductive coming from the reservoir; this signal is not as pronounced as that from lag 0 (superficial infiltration) but is nevertheless statistically significant. In addition, a positive cross-correlation was seen between Q and Ts at lag 0 (Fig. 13a); i.e., an increase in Q is positively correlated with an increase in Ts. Figure 13b shows an at lag 0 and 1 (Fig. 15a). However, Figure 15b shows a similar temperature trend in winter, while in summer the reverse is seen. This reversal is most likely because, during the dry season, the low flow rate allows a partial equilibrium with the rock matrix.

EGA NASS

Analysis of the data from EgaNass spring tends to be less informative (than that from Le Spesse spring) because of problems related to functioning of the data-logger during the monitoring period.

Analysis of Figure 14a seems to indicate a relationship between P and Q, but CCF analysis yields no significant cross-correlations (Fig. 14b).

Analyses of atmospheric and spring water temperatures confirm a local influence of shallow infiltrating waters associated with a positive cross-correlation.
at lag 1 means that an increase of $Q$ causes a decrease of $Ts$ and vice versa, the increase in $Q$ is essentially due to rainfall infiltration after one day, after which the decrease in $Q$ is associated with water from the reservoir and an increase in $Ts$.

**VESPA INDEX**

Because we collected monitoring data spanning more than one year, the VESPA (Vulnerability Estimator for Spring Protection Areas) index was calculated to quantify the vulnerability of Le Spesse spring. This index is an estimate of vulnerability based on an analysis of spring hydrographs. The VESPA index (Galleani et alii, 2011) takes into account the discharge ($Q$), water spring temperature ($T$) and electrical conductivity ($EC$), based on 1 year of monitoring data from spring discharge.

It is well known that different hydrographs represent different aquifers (Amit et alii, 2002; Malvicini et alii, 2005). Every aquifer drainage system has an impulse function transforming an input, for example rainfall, into output parameters such as discharge, temperature and EC variations. Such an analysis may provide information regarding groundwater network connectivity (Plagnes & Bakalowicz, 2001; Vigna, 2007; Kresic & Stevanovic, 2009).

The equation for calculating the VESPA index is as follows:

$$V = c(\rho) \beta y$$

where $c(\rho)$ is the correlation factor, represented by $c(\rho) = [u(-\rho) + 0.5u(\rho)] |\rho|$, $\rho$ is the correlation coefficient between $Q$ and $EC$ related to a time interval of one year and $u(\rho)$ is the Heavside step function:

$$u(\rho) = \begin{cases} 1, & \rho \geq 0 \\ 0, & \rho < 0 \end{cases}$$

The factor $\beta$, the temperature variability factor, is defined as follows:

$$\beta = \left(\frac{T_{\text{max}} - T_{\text{min}}}{1^\circ C}\right)^2$$

where $T_{\text{max}}$ and $T_{\text{min}}$ are the maximum and minimum temperature, respectively, during the monitored year.

The factor $\gamma$, the discharge variability factor, is
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defined as follows:

\[ \gamma = \frac{Q_{\text{max}} - Q_{\text{min}}}{Q_m} \]

where \( Q_{\text{max}} \), \( Q_{\text{min}} \) and \( Q_m \) are the maximum, minimum and average discharges, respectively, during the monitored year.

Based on the correlation coefficient, Galleani et alii (2011) proposed three broad behavioral categories (Tab. 2) representing various levels of network effectiveness and, consequently, various styles of response to an infiltration input.

A Type A spring is one associated with a highly effective drainage system, with well-developed karst conduits, quick, strong discharge, and discharge that is rapidly depleted. This type of system has also been called a hypersensitive karst (Hobbs & Smart, 1986). The value of the annual discharge variability index (Meinzer, 1923) is quite high, with values upwards of 100%.

A Type B spring is associated with a moderately effective drainage system. In these types of aquifers, a certain storage volume is present, and the infiltration produces a typical “piston effect” for mobilizing the resident groundwaters. Groundwater is in thermal equilibrium with its reservoir, and its EC is primarily than that of freshly infiltrated waters. The piston effect produces an increase in \( Q \), EC and T.

A Type C spring is associated with a relatively ineffective drainage system, and the piston effect is barely visible or absent. The discharge displays low fluctuations, with delays of up to several months associated with significant changes in rainfall. The electrical conductivity and temperature show similar trends, with low variations. A large saturated zone is present, and water infiltrations reach equilibrium with the aquifer and resident groundwater; external output due to the infiltrative process is strongly reduced.

In this case, only our data from Le Spesse spring were collected over a sufficiently long monitoring period. The monitoring period spanned from 1 October 2010 to 30 September 2011, during which time the discharge, temperature and EC data were monitored hourly.

The results show a correlation coefficient (\( \rho \)) of -0.1. Thus, Le Spesse spring falls into type C (homogenization; Tab. 2).

This result is in agreement with previous analyses, indicating that the initial increase of discharge was due to local infiltrating waters, and only after a period of time did the groundwater arrive from the deep reservoir.

A \( \beta \) factor of 2, a \( \gamma \) factor of 2.8 and a \( c(\rho) \) factor of 0.1 produce a VESPA index of 0.83, which places Le Spesse spring in the category of medium vulnerability (0.1 < \( V \) < 1 ; Tab. 3).

### ISOTOPIC ANALYSIS

In this study, an analysis of stable isotopes in waters, such as oxygen-18 (\( \delta^{18}O \)) and deuterium (\( \delta D \)), was also performed. Le Spesse and Ega Nass springs were sampled monthly from April to August 2011. Three rain samplers were installed, the first in Cava Buscada (municipality of Ero-Casso, at an altitude of approximately 1,750 m a.s.l.), the second in Le Spesse (in the same municipality, at an altitude of 810 m a.s.l.) and the third in Longarone (at approximately 450 m a.s.l.; Fig. 1). Beginning in April 2011, eleven samples of rainfall waters and sixteen samples of...
spring water were collected. The samples were then analyzed at the Geosciences Department of Trieste University to measure their stable isotopic contents.

The derived (empirical) relationship between local δ¹⁸O and δD is as follows:

\[ \delta D = 7.9 \delta ^{18}O + 12.24 \]

The highly correlative plot of the experimental data (coefficient of correlation of 0.98) and a high similarity between own experimental line and those from the literature (Gat & Carmi, 1970; Craig, 1961; Longinelli & Selmo, 2003; Fig. 17) indicate that evaporation in the Vajont area does not affect the amount of D and ¹⁸O in local rainfall and mixing with connate or very old waters may be excluded.

From Figure 17, it may be seen that the values of spring samples are less scattered/dispersed. An attenuation phenomenon of seasonal variations in spring waters is well known. As groundwater enters confined conditions, it is isolated from further seasonal and rainfall contribution and its isotopic compositions are attenuated to values representing a weighted mean of meteoric water inputs. The spring values show variation with respect to time, but while the variation in rainfall samples show a direct correlation with respect to air temperature, the spring samples show a shift in time. This phenomenon is observable both in the δ¹⁸O and δD contents (Fig. 18).

An explanation for this trend is that during summer the spring discharge mainly consists of water that infiltrated during the previous winter, as suggested by the comparison between discharge and water temperature. In fact, during the dry season the bulk discharge is from groundwater storage (fissure/porous matrix network; Clark & Fritz, 1997), whereas in the wet season the groundwater is mixed with waters of local infiltration.

Even if few isotopic data are present, it is possible to assume that the phase shift of isotopic values in the spring water samples were due to the residence time of rainfall in the aquifer. This phenomenon is also known in the literature as seasonal isotopic inversion (Longinelli & Selmo, 2010).

Afterwards, the average value of rainfall isotopic composition was calculated to estimate a relationship between δ¹⁸O in local rainfall and elevation.

We were aware of the limited number of data and anomalous isotopic values found in the Longarone rainfall samples (elevation 450 m a.s.l.), which suggested that we eliminate these data from the estimation. Nevertheless, we estimated a theoretical meteoric local line of δ¹⁸O vs elevation (notwithstanding the evident limit of two available points). The δ¹⁸O and δD values found in the Longarone rainfall samples were more negative than those in Le Spesse rainfall samples (750 m a.s.l.). However, these anomalous values are common in the Alpine areas, and they are mainly related to the position of the mountains with respect to the direction of the prevailing wind and the prevailing trajectory of the rain-cloud front (Longinelli & Selmo, 2010).

When including only the Le Spesse and Cava Buscada δ¹⁸O average contents vs altitude, it was possible to estimate an approximate theoretical meteoric local line (Fig. 19), as follows:

\[ \delta ^{18}O = -0.0028 h - 5.0393 \]

where h is the elevation (m a.s.l.).

The line shows an average gradient of -0.28% for every 100 m of elevation gain. This gradient is very similar to the medium line over the Adriatic slope presented by Zuanni et alii (1974), as shown in Figure 19.
By calculating the average values of δ¹⁸O in spring water, it becomes possible, using the medium local line, to calculate the average elevation of water that recharges the aquifers supplying the springs in our study area. The calculated elevations of aquifer recharge water are approximately 1,700 m a.s.l. for Le Spesse spring, 1,600 m a.s.l. for Ega Nass spring, 2,200 m a.s.l. for Cava Buscada spring and 1,900 m a.s.l. for Del Cristo spring. The results show recharge rates that are in agreement with local hydrogeological and morphological conditions.

**HYDROGEOLOGICAL CONCEPTUAL MODEL**

In a general conceptual model, the karstic reservoir may be thought of as two interconnected parallel flow systems, one associated with high-conductivity karstic channels and the other with a low-hydraulic-conductivity but high-storage-capacity, fissured, porous aquifer (Benischke et alii, 1988; Seiler et alii, 1989; Maloszewski et alii, 2002). These two different parts of the aquifer hold different volumes of water. The first reservoir consists of a fissured, porous medium and contains a relatively large volume of water, whereas the second reservoir consists of karstic drain-
In our springs, the conceptual model derives from analyses of diagrams displaying discharge, temperature and EC, different cross-correlations and the VESPA index, which are partially based on isotopic analytical results. In particular, Le Spesse spring shows a slow circulation of the deep reservoir water, and the high increases in discharge are essentially due to local infiltration rather than infiltration in the true (larger) recharge area (increases in discharge are associated with decreases in EC and T; there are positive cross-correlations between Ta and Ts). The comparison between discharge and temperature shows a decrease in Ts during the summer and an increase during the winter, indicating a discharge of deep reservoir water in partial thermal equilibrium with the rock matrix, and this seasonal trend was confirmed by the isotopic analytical results (seasonal isotopic inversion). A residence time of six months for the total spring flow is a relatively low value for karst aquifers.

The conceptual model is one of a regular discharge (base flow of deep waters) along with a local circulation directly linked to infiltration through the debris, which was confirmed by the correlation coefficient of the VESPA index. The absence of a piston effect confirms the low level of karstification of this aquifer and a misleading karst response due to local infiltration.

The rainfall water enters the aquifer system at the surface of the catchment area and infiltrates down to karstic channels. From these channels, a portion of the water enters the fissure-porous aquifer. Water entering the karstic-fissured system from these channels contributes to the mean transit time of water in that system. The water in the channels finally discharges at the springs. The composition of the spring water is a weighted combination of water fluxes from both the karstic and fissured/porous sources. Thus, the karst is not well developed and its channels are of lesser hydrodynamical relevance than the fissured part of the reservoir.

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