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1 **Defining the hydrogeological behavior of karst springs through an integrated**  
2 **analysis: a case study in the Berici Mountains area (Vicenza, NE Italy)**

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13 **Abstract**

14 Knowledge of the hydraulic and geological properties of karst systems is a particular target for many hydrogeologists  
15 because these systems represent an important source of potable water in many countries. However, the high  
16 heterogeneity that characterizes karst systems complicates the definition of their hydrogeological properties. Complex  
17 and expensive techniques are generally used to carry out estimations of hydraulic parameters. In this study, a workflow  
18 for karst spring characterization was proposed to analyzed two springs, Nanto spring and Mossano spring, respectively,  
19 located in the Berici Mountains (NE Italy). Based on four years of continuous hourly monitoring data of discharge,  
20 water temperature and specific electrical conductivity, a hydrogeological conceptual model for the monitoring springs  
21 was proposed. Flow rate measurements, which combined recession curve, flow duration curve and autocorrelation  
22 function techniques, were used to evaluated the spring discharge variability. Changes in spring discharge can be related  
23 both to the degree of karstification/permeability and to the size of the karst aquifer. Moreover, combining monitored  
24 parameters and rainfall, analyzed by the cross-correlation function and VESPA Index approach, permitted the  
25 assessment of the spring response to recharge and the behavior of the drainage system. Although the responses to the  
26 recharge events were quite similar, the two springs showed some differences in terms of the degree of karstification.  
27 In fact, Mossano spring showed a more developed karst system than Nanto spring. Three system (two karsts and one

28 matrix/fractured) are outlined for Mossano spring, while two systems (one karst and one matrix/fractured) are outlined  
29 for Nanto spring.

30 *Keywords: Karst spring, Statistical analysis, Time series analysis, Hourly monitoring data, Berici Mountains*

## 31 **1. Introduction**

32 The analysis of karst springs is a widespread activity in hydrogeology because karst aquifers are a primary source of  
33 human water supplies in many countries (Ford and Williams 2007). The estimation of available water and the  
34 determination of water quality and vulnerability will play a growing strategic role in the future because of the  
35 increasing demand for water for drinking, irrigation, and industrial purposes (Assaad and Jordan 1994; Bakalowicz  
36 2005; Crawford and Ulmer 1994; Field 1992; Goldscheider 2012; Kresic and Stevanović 2010). The quantitative  
37 characterization of karst systems requires the definition of realistic hydraulic and geometric parameters for both the  
38 rock matrix and the conduit network (Kovács and Perrochet 2008). Classical geological and hydrogeological surveys  
39 of karst (i.e., borehole tests, tracer experiments, speleological and geophysical observations) are not only expensive  
40 and sometimes inapplicable but also provide limited information due to the great heterogeneity of karst systems  
41 (Kovács et al. 2005).

42 The monitoring of spring discharge and water physical-chemical parameters (e.g., temperature and electrical  
43 conductivity), accompanied by the analysis of the resulting hydrographs and chemographs, represent a classical  
44 hydrogeological prospection technique that is very helpful when detailed analyses, such as tracer tests and  
45 speleological investigations, are not applicable. This approach allows for the assessment of the basic hydrogeological  
46 characteristics of a karst aquifer that can be used for planning its utilization and protection. Necessary considerations  
47 regarding this method are as follows: (i) the spring hydrograph provides an integrated representation of the network of  
48 fractures and conduits transferring groundwater from the recharge to the outflow area and (ii) the quality and quantity  
49 of groundwater are of diagnostic importance for understanding the functioning of the system (Dreiss 1982, 1989; Ford  
50 and Williams 2007; Knisel 1979;).

51 Several authors have focused their attention on the analysis of recession curves. Considering a recharge event  
52 producing an increase in spring discharge, the recession curve describes the part of the hydrograph showing the  
53 progressive decrease in discharge from the peak of the discharge to the pre-storm outflow (Ford and Williams 2007).

54 Starting with the works of Boussinesq (1877) and Maillet (1905), recession curve analysis (RCA) has been used to

55 infer the geometrical or hydraulic properties of aquifers supplying springs (Bonacci 1993; Brutsaert and Nieber 1977;  
56 Covington et al. 2009; Dewandel et al. 2003; Fiorillo 2014; Kresic and Stevanović 2010; Padilla et al. 1994; Szilagyi  
57 et al. 1998; Troch et al. 1993) or to identify the flow-type induced by different degrees of aquifer karstification (Baedke  
58 and Krothe 2001; Birk and Hergarten 2010; Kovács and Perrochet 2008; Kovács et al. 2005; Malík and Vojtková  
59 2012).

60 Another approach for hydrograph analysis, derived from hydrological practices, is the use of flow duration curves  
61 (FDCs). The FDC is a cumulative frequency curve showing the percent of time during which the discharge is equal to  
62 or exceeds a specified threshold in a given period. This approach has been used to assess the range and variability of  
63 spring discharge (Hartmann et al. 2013; Kovačič 2010; Malík 2015).

64 Drainage through a karst system can be represented as an impulse function that transforms the recharge input pulse  
65 into a flow rate variation at a spring recorded by a hydrograph. The analysis of this function permits the identification  
66 of the hydrogeological features of an aquifer and its degree of karstification (Ford and Williams 2007). Time series  
67 analysis is a signal processing method employed to explore impulse functions and to improve the understanding of the  
68 hydrogeological behavior of a karst system. Mangin (1984) was the first to apply this approach in karst hydrogeology,  
69 using autocorrelation and spectral density functions to analyze the spring discharge. Subsequently, different authors  
70 have extended the application of these methodologies to other parameters (e.g., precipitation, water temperature,  
71 electrical conductivity) by the introduction of other functions, such as cross-correlation (Adji et al. 2016; Bailly-Comte  
72 et al. 2011; Fiorillo and Doglioni 2010; Kovačič 2010; Ladouche et al. 2014; Larocque et al. 1998; Mayaud et al. 2014;  
73 Zhang et al. 2013). The most widely used methodology consists of the concomitant utilization of autocorrelation  
74 functions (ACFs) and cross-correlation functions (CCFs). In particular, an ACF examines how a value depends on  
75 preceding values over a period of time (Larocque et al. 1998; Mayaud et al. 2014). The use of ACFs allows us to  
76 quantify the memory effect of a system (Mangin 1984; Panagopoulos and Lambrakis 2006). In contrast, CCFs provide  
77 an overview of the interrelationship between the input and output series (Larocque et al. 1998; Panagopoulos and  
78 Lambrakis 2006). In karst hydrogeology, a CCF is usually employed to evaluate the correlation between rainfall and  
79 spring discharge, highlighting the response of a system to the recharge impulse (Chung et al. 2018; Fabbri et al. 2013;  
80 Fiorillo and Doglioni 2010; Liu et al. 2011; Tagne and Dowling 2018; Zhang et al. 2013).

81 The Vulnerability Estimator for Spring Protection Areas or VESPA Index (Galleani et al. 2011) is a promising method  
82 used to assess the degree of vulnerability of a karst spring, but it can also be used to classify general hydrogeological

83 behavior through the analysis of spring responses to recharge impulses. The prevailing behavior is identified  
84 considering two parameters: spring discharge and electrical conductivity (Banzato et al. 2017). Moreover, an advantage  
85 of this method is the ability to combine these two parameters with water temperature to assess spring vulnerability.  
86 In this article, the RCA, FDC, ACF and CCF techniques were used to define the conceptual hydrogeological model of  
87 two springs located in the Berici Mountains (northeastern Italy). In addition, the parameters defined by the VESPA  
88 index were used to assess the type of flow and vulnerability of springs. Moreover, particular attention was paid to the  
89 meaning of the CCF analysis between spring discharge and electrical conductivity and between spring discharge and  
90 water temperature as an estimate of the minimum transit time inside the conduit network feeding the springs. These  
91 techniques enable to use of only the monitoring parameters together with rainfall events to obtain qualitative  
92 information about the hydrogeological features characterizing the analyzed springs.  
93 The objectives of this study are twofold: (i) outline a workflow for karst spring characterization and (ii) contribute to  
94 highlighting the main features of groundwater circulation in a peculiar karst system. In fact, the Berici Mountains  
95 represent a peculiar karst system because they appear as a calcareous plateau, surrounded by the Venetian Plain and  
96 isolated from the nearby Prealps.

## 97 **2. Materials and methods**

### 98 **2.1 Geological and hydrogeological settings**

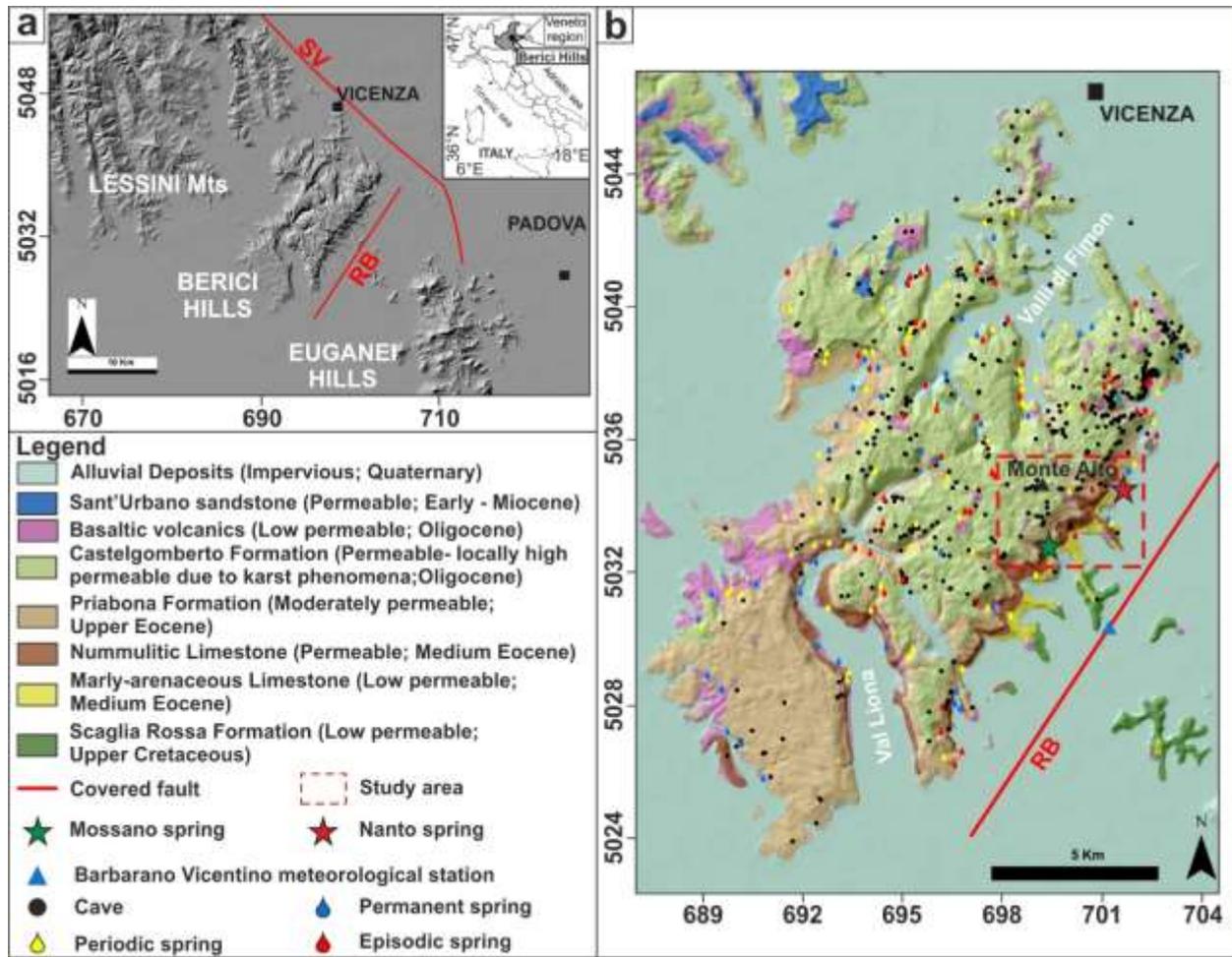
99 The Berici Mountains extend across the central part of the Veneto Region to the southwest of the city of Vicenza  
100 (Veneto, NE Italy; Fig. 1a). Together with the Lessini Mountains and the Euganei Hills, the Berici Mountains constitute  
101 a relatively undeformed foreland structural high known as the Lessini-Berici-Euganei block (LBE; Pola et al. 2014).  
102 Toward the east, the triangular-shaped LBE block is separated from the Eastern Southern Alps and their deformed  
103 foreland by the high-angle NE-dipping Schio-Vicenza fault (NW-SE trend; Fig. 1a). Within the LBE block, the Berici  
104 Mountains are separated from the Euganei Hills to the south by the high-angle Riviera Berica Fault (NNE-SSW trend).  
105 These faults are buried beneath the Quaternary alluvial deposits (Benvenuti and Norinelli 1967; Mietto 1988a; Pola et  
106 al. 2014).  
107 The Berici Mountains are an isolated plateau covering almost 200 km<sup>2</sup> (Fig. 1b) with a maximum elevation of  
108 approximately 450 m a.s.l. (Monte Alto, altitude 444 m a.s.l.). Two long and deep valleys, Val Liona and Valle di

109 Fimon (Fig. 1b), extend to the core of the complex, which can then be divided into two distinct sectors, the eastern and  
110 western sectors (Mietto 1988a; Mietto and Sauro 2000).

111 The stratigraphic sequence is characterized by Upper Cretaceous to Miocene sedimentary rocks with subhorizontal or  
112 gently dipping beds and by basaltic rocks related to the Paleogene Lessini-Berici-Euganean volcanic cycle (Mietto  
113 1988a).

114 The study area is located in the eastern sector of the Berici Mountains (Fig. 1b). The oldest outcropping rocks are  
115 represented by Upper Cretaceous marly limestone of the Scaglia Rossa Formation (SR), with a thickness of some tens  
116 of meters, followed by Middle Eocene marly arenaceous limestones (ML, maximum thickness of 35 m) and  
117 Nummulitic limestones (NL, 50-90 m in thickness). These are overlapped by Upper Eocene marly limestones  
118 (Priabona Formation, PFm) that can reach a maximum thickness of approximately 200 m. The sedimentary sequence  
119 is closed by the Oligocene limestones of the Castelgomberto Formation (CFm), with a thickness ranging from 80 to  
120 200 m. The whole succession was affected by a basaltic explosive volcanism (Oligocene), with the formation of several  
121 necks, volcanoclastic rocks and tuffites of variable thickness (BV; Fig. 2 and Table 1; Bassi et al. 2000; Mietto 1988a).

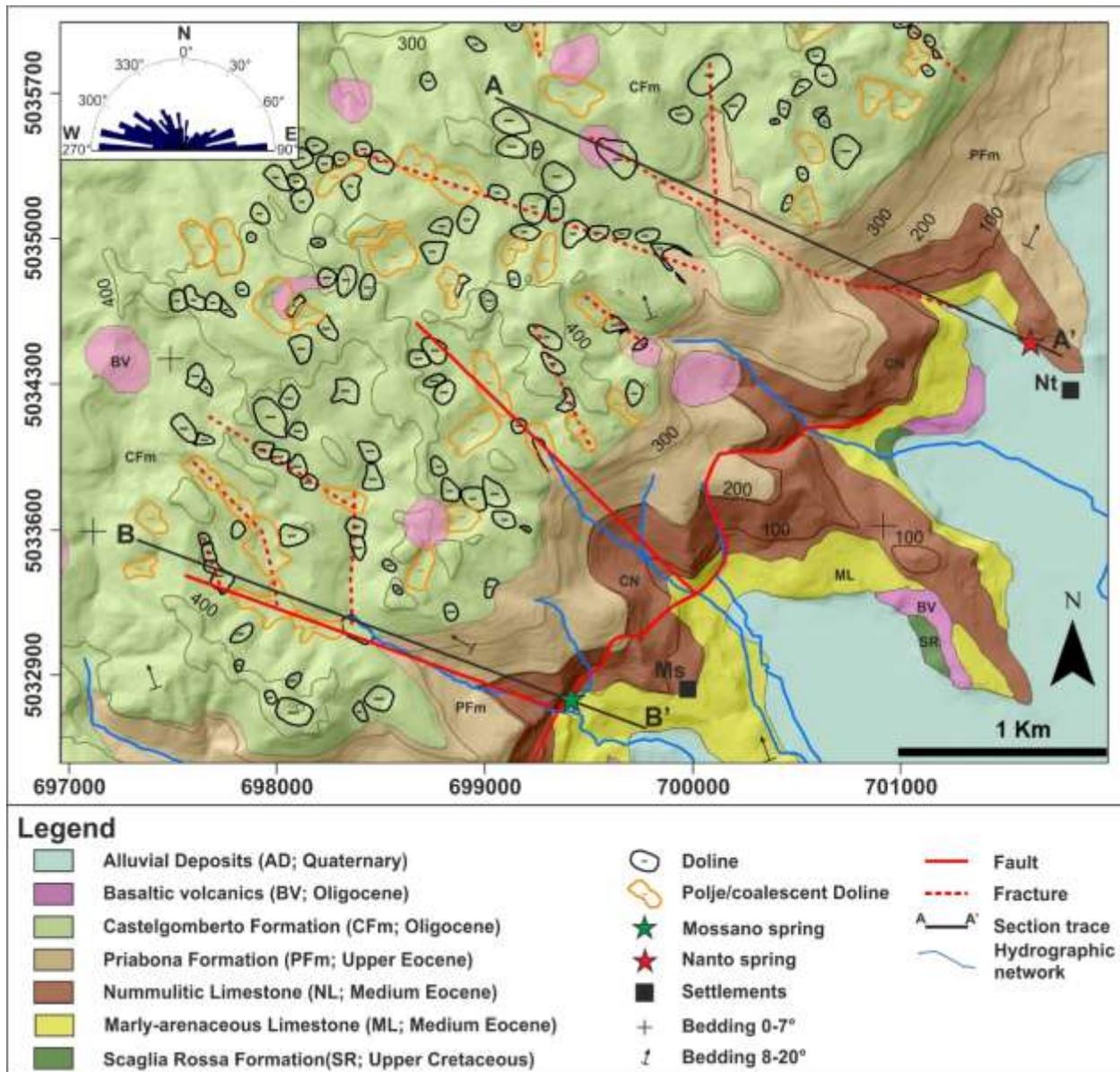
122 Karst phenomena played a significant role in the geomorphological evolution of the area, leading to the formation of  
123 both surficial and underground karst features. This phenomenon is particularly true for the high-karstified limestones  
124 of CFm, where the dolines are the most representative large-scale karst features (Castiglioni 1996; Mietto 1988b;  
125 Mietto and Sauro 2000; Sauro 2002; Sauro 2005). Considering the hypogean features, approximately 630 caves are  
126 present in the Berici Mountains, many of which located in the CFm (Fig. 1). The spatial extension of these caves range  
127 between few meters to approximately 1 km, while the maximum difference in elevation is approximately 100 m  
128 (<http://speleo.it/catastogrotte/progetto-wish/>). From a hydrogeological point of view, NL, PFm and CFm can be  
129 classified as aquifers because of their degree of karstification, while SR and ML can be considered aquitards or  
130 aquicludes due to their greater terrigenous composition. In addition, due to the low permeability of the volcanic  
131 products, BV can be considered a permeability barrier for the groundwater flow affecting the karst systems (ARPAV  
132 2007; Fabiani 1911).



133  
 134 **Fig. 1 a** Location of the Berici Mountains within the central part of the Veneto Region (NE Italy) and schematic  
 135 structural sketch (SV: Schio-Vicenza fault; RB: Riviera Berica fault). **b** Geological sketch map of the Berici Mountains  
 136 (Antonelli et al. 1990) showing the study area and the location of the monitoring springs. The springs located in the  
 137 Berici area are reported subdivided on the basis of their regime (Marcolongo 2005). The caves locations defines  
 138 utilizing the information achieved by the webgis of the Vicenza Province (<http://geoportale.provincia.vicenza.it>). In  
 139 legend, information about the permeability degree of each unit are presented (Fabiani 1911; ARPAV 2007). The  
 140 coordinates are in UTM zone 32N system using the WGS84 datum (expressed in km).

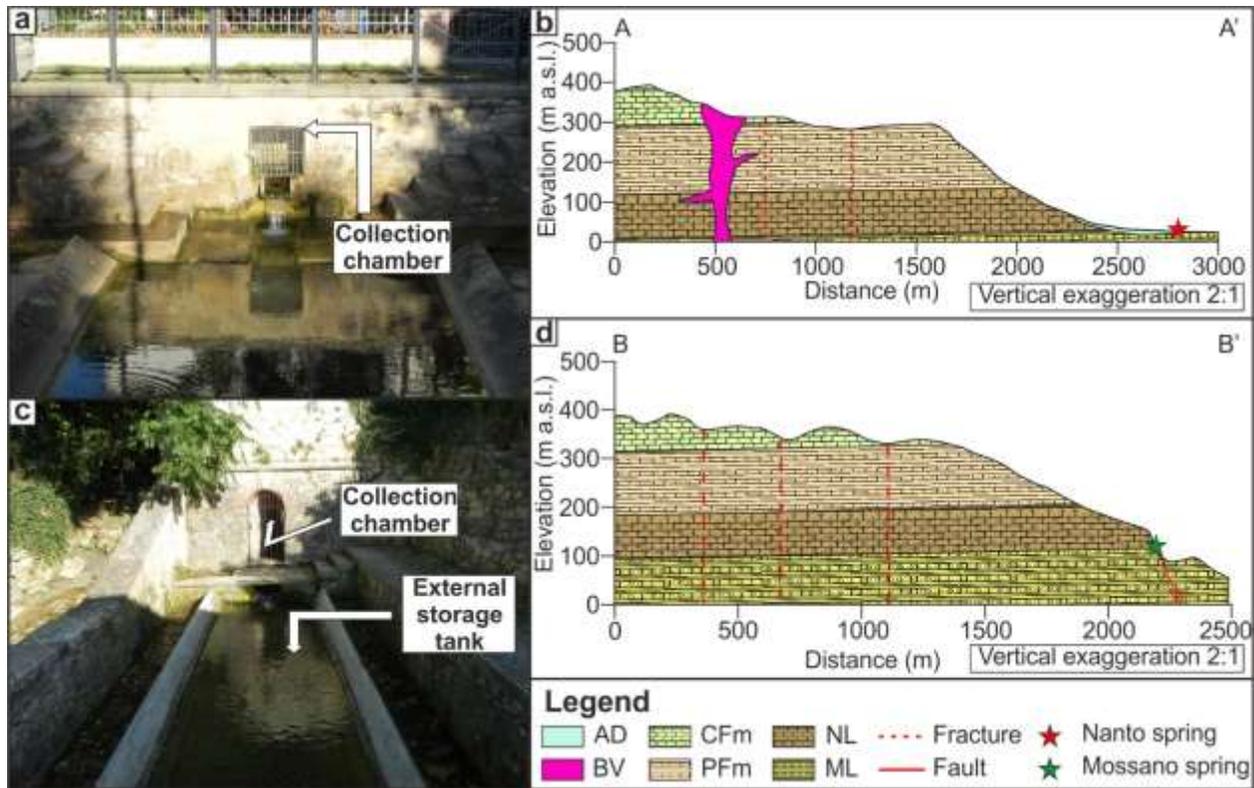
141 As typically occurs in karst environments, dolines represent a preferential path for the infiltration of meteoric water,  
 142 even though their bottom can be infilled with fine sediments. As a consequence, the Berici Mountains landscape is  
 143 characterized by the absence of any hydrographic network, and its recharge is exclusively of autogenic origin (Ford  
 144 and Williams 2007). Diffuse autogenic recharge is channelized in a well-developed underground karst system that

145 allows the circulation of infiltration waters through different-sized conduits, fractures, etc. Subsequently, water  
146 discharges from several springs located at the base of the Berici plateau and preferentially along the contact between  
147 permeable rock units (NL, PFm or CFm) and low-permeable layers (ML or SR; Fabiani 1911). This system generates  
148 a large number of springs. Approximately 166 springs are present (Marcolongo 2005). Among these springs, 43 springs  
149 show a permanent regime, while the remaining 123 springs are periodic (periods without flow during the long dry  
150 season) or episodic (periods of activity in response to only main rainfall events). Most of the permanent springs have  
151 an average discharge that is generally lower than 2 L/s, while the maximum average discharge is approximately 20 L/s  
152 (Marcolongo 2005).



153  
 154 **Fig. 2** Geologic map of the study area. Lithologies were obtained from the lithological map of the Veneto Region  
 155 (1:250,000; Antonelli et al. 1990), while the stratigraphic contacts between the different units were detailed during  
 156 field work. From the bottom: (i) Scaglia Rossa Formation (SR), Pelagic limestone containing planktonic foraminifera;  
 157 Marly-arenaceous Limestone (ML), alternating marly limestone, calcareous marls, and calcarenites interbedded with  
 158 tuffs; Nummulitic Limestone (NL) massive limestone rich in Nummulites; Priabona Formation (PFm), marly  
 159 limestones with rich fossil content; Castelgomberto Formation (CFm), massive or irregularly bedded limestones and  
 160 irregularly bedded calcarenites with miliolids and coralline red algae; Basaltic volcanics (BV), basaltic explosive  
 161 volcanism represented by necks, volcanoclastic rocks and tuffites (Bassi et al. 2000). Regarding settlements, Nt: Nanto,

162 Ms: Mossano. In the box of the top left, rose diagram of the orientations of the maximum diameter directions of dolines  
163 (DMAX; Torresan 2016). The coordinates are in UTM zone 32N system using the WGS84 datum (expressed in m).  
164 The monitored springs, called Nanto and Mossano, are two perennial springs located in the eastern part of the Berici  
165 Mountains in municipalities of the same names (Fig. 1b). The choice to monitor these two springs, among all the  
166 springs located in the Berici Mountains, is related to some pre-established requirements: (i) perennial regime; (ii)  
167 accessibility; (iii) presence of intake capture structure; and (iv) lack of water exploitation.  
168 Nanto spring (Fig. 3a) discharges at the base of the slope of the Berici Mountains at an elevation of approximately 25  
169 m a.s.l. The spring emerges at the contact between NL and the underlying ML (Fig. 2 and Fig. 3b).  
170 Mossano spring (Fig. 3c), located at an elevation of approximately 90 m a.s.l., also discharges at the contact between  
171 NL and ML (Fig. 2 and Fig. 3d). A summary of the monitored parameters for both springs is shown in Table 3.  
172 Dolines in the karst area surrounding the two springs were recognized by the analysis of satellite images (Landsat) and  
173 a Digital Elevation Model (DEM) in a GIS environment (Fig. 2). The alignment of several dolines leads to the  
174 assumption that some tectonic structures, i.e., fractures and faults, exist. The interaction between tectonics and  
175 karstification was confirmed upon considering the orientations of the maximum diameter directions of dolines  
176 (DMAX; Bondesan et al. 1992). As shown in Fig. 2, the DMAXs are preferentially WNW-oriented according to the  
177 direction of the identified structures (Torresan 2016). In addition, a structural field analysis performed near Mossano  
178 spring allowed these elements to be characterized as extensional faults related to Paleogene extensional tectonics  
179 (Zampieri 1995).



180  
 181 **Fig. 3** a Nanto spring. The CTD - Diver is located into the collection chamber; b Geological cross-sections of Nanto  
 182 spring; c Mossano spring; CTD - Diver is located into the external storage tank. Into the collection chamber a data  
 183 logger for the water temperature measurements was installed. d Geological cross-section of Mossano Spring. Cross-  
 184 section traces are shown in Fig. 2. In legend, AD: Alluvial Deposits; BV: Basaltic volcanics; CFm: Castelgomberto  
 185 Formation; PFM: Priabona Formation; NL: Nummulitic Limestones; ML: Marly-arenaceous Limestones.

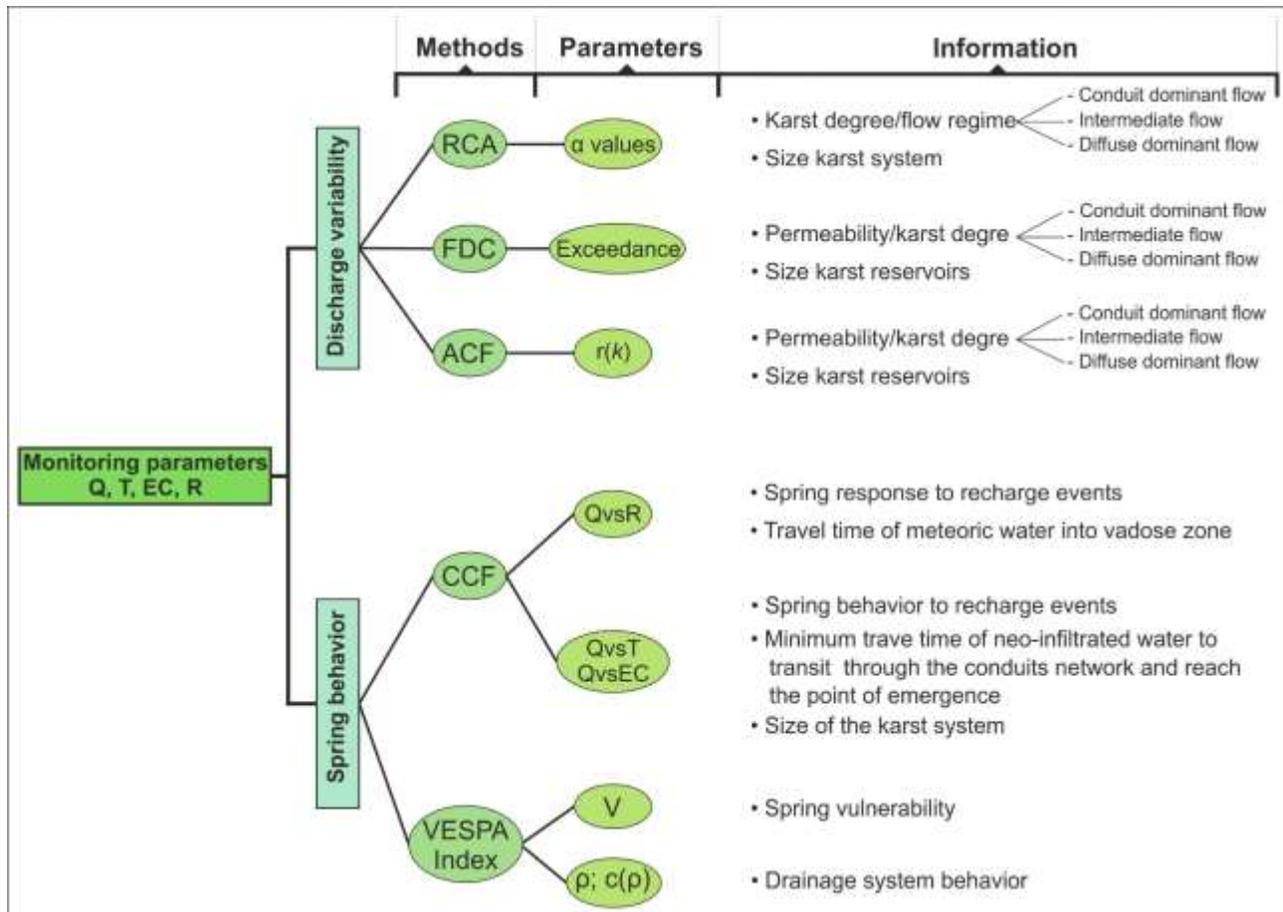
186 **2.2 Monitoring data**

187 Nanto and Mossano springs were continuously monitored for almost four years, from January 2015 to June 2018, by  
 188 two high-accuracy multiprobe sensors (CTD-Diver). The recorded parameters were (i) water level (H in cm; range 0-  
 189 1000 cm, accuracy  $\pm 0.5$  cm and resolution 0.2 cm), (ii) temperature (T in  $^{\circ}\text{C}$ ; range from  $-20$   $^{\circ}\text{C}$  to  $+80$   $^{\circ}\text{C}$ , accuracy  
 190  $\pm 0.1$   $^{\circ}\text{C}$  and resolution 0.01  $^{\circ}\text{C}$ ), and (iii) specific electrical conductivity at  $25^{\circ}\text{C}$  (EC in mS/cm; range 0-30 mS/cm,  
 191 accuracy  $\pm 1\%$  of reading and resolution  $\pm 0.1\%$  of reading). An acquisition time interval of 1 hour was chosen to  
 192 register the effect of flood events during the hydrogeological year (Galleani et al. 2011). The water level measurements  
 193 were converted to discharge (Q) values by two experimental level-discharge relations obtained through 57 flow-rate  
 194 and level measurements collected from January 2015 to June 2018 (supplementary materials).

195 The time series of both springs were subject to several interruptions due to data logger malfunctions. The main  
196 monitoring interruptions for Nanto spring occurred from September 2015 to January 2016, from October 2016 to  
197 January 2017 (only for EC), and from February 2017 to April 2017. Mossano spring experienced by only one long  
198 interruption, from September 2015 to January 2016. Moreover, both springs exhibited short interruptions during the  
199 monitoring period. It is worth mentioning that the CTD-Diver used in Mossano spring was located in an external  
200 storage tank (Fig. 3c), in which the water temperature was affected by atmospheric agents and by daily and seasonal  
201 air temperature variations. Conversely, the measurement of the water level was not directly influenced by rainfall  
202 events in the spring area. For this reason, a new data logger for Mossano spring was added on January 2018 with the  
203 aim of measuring only water temperature. This data logger was positioned in the collection chamber connected to the  
204 external storage tank (Fig. 3c), where it was impossible to conduct water level measurements.

205 Data collected by the Barbarano Vicentino meteorological station were used to evaluate the local precipitation and  
206 temperature and to perform the time series analysis. This station is part of a public monitoring network covering the  
207 Veneto Region, with 167 meteorological stations managed by the Regional Agency for Environmental Prevention and  
208 Protection (ARPAV). The Barbarano Vicentino meteorological station is located at an elevation of 16 m a.s.l., 2.9 km  
209 from Mossano spring and 4.2 km from Nanto spring (Fig. 1b), representing the nearest station to the monitored springs.  
210 Although the infiltration area of the two karst systems is located at an elevation of approximately 300 – 400 m a.s.l.,  
211 there are no meteorological stations representative of these altitudes close to the Berici Mountains.

### 212 **2.3 Time series analysis and vulnerability**



213  
 214 **Fig. 4** The workflow adopted in this work to achieve the final definition of a hydrogeological conceptual model. Flow  
 215 rate data are used to evaluate the spring discharge variations through Recession Curve Analysis (RCA), Flow Duration  
 216 Curve (FDC) and Auto-Correlation Function (ACF). The monitoring parameters (Q, T and EC) and the rainfall events  
 217 (R) are used to evaluate the spring behavior by Cross-Correlation Function (CCF) and VESPA Index approach. For  
 218 each approach is defined the main parameter evaluated and the types of information that can be achieved.

219 The workflow used to characterize the two monitored springs, starting from the monitored parameters, is schematized  
 220 in Fig. 4. The analysis of the variations in springs discharge and the definition of the behavior of springs were used to  
 221 delineate the conceptual hydrogeological model.

222 The discharge variations recorded in karstic springs are mainly related to the degree of recharge and karstification of  
 223 the system. For this reason, a detailed analysis of spring discharge must be performed to assess some of the main  
 224 features characterizing a given type of aquifer. In the proposed workflow, three methods were chosen to analyze the

225 flow rate variability: (i) recession curves analysis (RCA), (ii) flow duration curve (FDC) analysis, and (iii)  
226 autocorrelation function (ACF) analysis.

227 The spring response in relation to rainfall events indicates the principal characteristics of the monitored karst system.  
228 To evaluate the spring behavior, the variations in the other monitored parameters (Q, T and EC) and their relationships  
229 to recharge were considered. Two types of analyses were performed: cross-correlation functions (CCFs) and VESPA  
230 index analysis.

231 RCA allows for the study of variations in spring discharge as a consequence of recharge events. The analysis of the  
232 recession curves focused on the recession coefficient ( $\alpha$ ), which is qualitatively related to the degree of aquifer  
233 karstification (Baedke and Krothe 2001; Birk and Hergarten 2010; Dewandel et al. 2003; Fiorillo 2014; Kovács and  
234 Perrochet 2008; Kovács et al. 2005; Malík and Vojtková 2012; Tallaksen 1995) and, in part, to the size of the karst  
235 system (Bonacci 1993). The recession coefficient was used by Maillet (1905) to describe flow recession using a simple  
236 exponential equation (Bonacci 1993; Ford and Williams 2007):

$$237 \quad Q_t = Q_0 e^{-\alpha(t-t_0)} \quad (1)$$

238 where  $Q_t$  is the discharge at time  $t$ ,  $Q_0$  is the initial discharge at time  $t_0$  and  $\alpha$  is the recession coefficient.

239 Boussinesq (1903, 1904) express the recession by a quadratic form:

$$240 \quad Q_t = \frac{Q_0}{(1+\alpha t)^2} \quad (2)$$

241 Dewandel et al. (2003) pointed out that Eqn (1) provides an approximate analytical solution for the diffusion equation  
242 that describes flow in a porous medium, whereas Boussinesq's quadratic equation provides an exact analytical solution  
243 (Ford and Williams, 2007).

244 However, the mathematical properties of Eqn (1), in which the derivative is exponential and  $\alpha$  is independent of  $Q_0$ ,  
245 are more convenient than the quadratic solution in Eqn (2), explaining the widest use of the Maillet formula (Dewandel  
246 et al. 2003).

247 Although Eqn (1) is useful for describing the baseflow recession of a karst system (Kovács and Perrochet 2008; Kovács  
248 et al. 2005; Malík and Vojtková 2012), many authors have proposed describing the cumulative effects of several  
249 reservoirs in order to interpret the entire recession curve (Amit et al. 2002; Dewandel et al. 2003; Ford and Williams  
250 2007; Kovács and Perrochet 2008). As a matter of fact, the recession curve can be subdivided into multiple segments,  
251 describing different reservoirs with different hydrogeological properties (i.e., permeability, porosity, storativity), all  
252 contributing to spring discharge. For each segment, there is a corresponding  $\alpha$  value obtained by the exponential Eqn

253 (1). According to Taylor and Green (2008), a difference in  $\alpha$  exceeding one order of magnitude can be associated with  
 254 different types of flow regimes and is used to describe spring behavior during the recession period. High values of  $\alpha$   
 255 indicate fast drainage (conduit dominated flow) related to well-developed karst conduits and, thus, to a high degree of  
 256 karstification. Conversely, low values of  $\alpha$  are ascribable to diffuse flow into smaller fractures and pores (diffuse  
 257 dominated flow), indicating a lower degree of karstification (Bagheri et al. 2016; Bonacci 1993; Ford and Williams  
 258 2007; Kovács and Perrochet 2008).

259 FDC analysis is a measure of the range and variability of spring discharge. FDC analysis represents the percentage of  
 260 time during which the flow rates of a given spring exceed a specified threshold (Malík 2015). The discharges were  
 261 ordered and plotted from the highest to the lowest values, without considering their chronological sequence. The  
 262 obtained graph shows the discharge on the ordinate axis and the percentage of the monitoring time that exceeded the  
 263 specified flow-rate threshold on the abscissa axis. FDC can be used to estimate principal karst system features by  
 264 analyzing the slope of the curve. In fact, the presence of high slopes suggests well-developed karst conduits (conduit  
 265 dominant flow), whereas low slopes indicate systems with a high storage capability and a lower degree of karstification  
 266 (diffuse dominant flow; Malík 2015).

267 Moreover, the use of the autocorrelation function permits the definition of the memory of a karst system in terms of  
 268 discharge variations. The ACF can be defined as a normalized measure  $r(k)$  of the linear dependence among  
 269 successive values of the data series (discharge values in this case), and it is as described (Zhang et al. 2013):

$$270 \quad r(k) = \frac{C(k)}{C(0)} \quad (3)$$

271 in which:

$$272 \quad C(k) = \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x})(x_{t+k} - \bar{x}) \quad [k = 0, 1, 2, \dots, (n - 1)] \quad (4)$$

$$273 \quad C(0) = \frac{1}{n} \sum_{t=1}^n (x_t - \bar{x})^2 \quad (5)$$

274 where  $k$  is the time lag,  $n$  is the length of the time series,  $t$  is the time,  $x$  is a single event measurement, and  $\bar{x}$  is the  
 275 mean of the event measurements. The related autocorrelogram is useful for evaluating the memory of a system, which  
 276 is estimated through the decorrelation lag time. This lag time is defined as the time needed by the autocorrelation  
 277 function to reach a determined value, usually between 0.1 and 0.2 (Mangin 1984; Liu et al. 2011; Panagopoulos and  
 278 Lambrakis 2006; Tagne and Dowling 2018; Zhang et al. 2013). The autocorrelation values of an uncorrelated time  
 279 series rapidly decrease (Chung et al. 2018; Liu et al. 2011), which can be interpreted as a system with short memory.

280 Conversely, a high system memory results in a gentle decrease in the slope of the autocorrelation function. Therefore,  
 281 through autocorrelogram analysis, some consideration related to the degree of karstification and the size of the karst  
 282 aquifer can be made (Liu et al. 2011; Mangin 1984; Padilla and Pulido-Bosch 1995).

283 To evaluate the springs' responses over time with respect to recharge, CCFs were carried out with the monitored spring  
 284 parameters (Q, T, EC) and rainfall (R). Cross-correlation is widely used in hydrogeology to analyze linear relationships  
 285 between input and output signals (Chung et al. 2018; Fabbri et al. 2013; Fiorillo and Doglioni 2010; Liu et al. 2011;  
 286 Tagne and Dowling 2018; Zhang et al. 2013).

287 This statistical analysis was performed using R code (R Core Team 2018). Before the application of the CCFs, the data  
 288 series were filtered because the parameters Q, T and EC are usually autocorrelated. The filtering process was performed  
 289 with the use of a simple filter and defined as the differences of one lag for every parameter. This approach corresponds  
 290 to determining the difference between each value and its previous value, removing a trend and making stationary a  
 291 nonstationary time series (R Core Time 2018). CCF represents the correlations between two different data series with  
 292 respect to lag times. The cross-covariance function, where  $u$  is the input and  $y$  is the output, is given by Eqn (6) and  
 293 Eqn (7):

$$294 \quad c_{uy} = \frac{1}{n} \sum_{t=1}^{n-k} (u_t - \bar{u})(y_{t+k} - \bar{y}) \quad [k = 0, 1, 2 \dots, (n-1)] \quad (6)$$

$$295 \quad c_{uy} = \frac{1}{n} \sum_{t=1-k}^n (u_t - \bar{u})(y_{t+k} - \bar{y}) \quad [k = -1, -2 \dots, -(n-1)] \quad (7)$$

296 where  $\bar{u}$  and  $\bar{y}$  are the averages of the input and output parameters, respectively. CCF is defined as:

$$297 \quad r_{uy}(k) = \frac{c_{uy}(k)}{\sqrt{c_{uu}(0)c_{yy}(0)}} \quad (8)$$

298 Eqn (7) was used primarily to analyze the cross-correlation between R (input) and Q (output), to define the system  
 299 response and to qualitatively evaluate the travel time of the meteoric water to cross the vadose zone. When there was  
 300 a correlation to a certain lag, this was interpreted as the delay (expressed in hours) of the spring response to a recharge  
 301 event. Furthermore, cross-correlations between spring parameters, i.e., Q vs. T and Q vs. EC, were performed to assess  
 302 the spring behavior. Q vs. EC allows the evaluation of the minimum travel time of the neo-infiltrated water to transit  
 303 through the conduits system and reach the point of emergence at the springs. Consequently, information about the size  
 304 of the karst system can be obtained. Additionally, T vs. EC was calculated to evaluate whether these two parameters  
 305 were synchronous. The CCF results were plotted into two-dimensional graphs, known as cross-correlograms, in which  
 306 the correlation value (between -1 and +1) is reported on the y-axis, and the lag is shown on the x-axis. In addition, two

307 confidence bands were displayed to graphically define whether or not the two analyzed series are correlated. If two  
 308 series are correlated, the correlation value must be higher than the confidence bands. These bands, one negative and  
 309 one positive, were defined as:  $-\frac{1.96}{\sqrt{n}}$  and  $\frac{1.96}{\sqrt{n}}$ , respectively (R Core Team 2018).

310 Through the use of more than one year of continuous hourly monitoring data, the type of spring behavior was classified  
 311 using parameters of the VESPA index (Vulnerability Estimator for Spring Protection Areas; Galleani et al. 2011) based  
 312 on the Q, EC and T values of the spring. The VESPA index  $V$  was defined by the following relationship (Banzato et  
 313 al. 2017):

$$314 \quad V = c(\rho)\beta\gamma \quad (9)$$

315 In Eqn (9),  $c(\rho)$  is the correlation factor, ranging from 1 to 0, defined as:

$$316 \quad c(\rho) = [u(-\rho) + \alpha u(\rho)]|\rho| \quad (10)$$

317 where  $\rho$  is the correlation coefficient between Q and EC, ranging between -1 and 1, calculated over more than one year  
 318 of continuous hourly data.  $u(\rho)$  is the Heavside step function:

$$319 \quad u(\rho) = \begin{cases} 1, & \rho \geq 0 \\ 0, & \rho < 0 \end{cases} \quad (11)$$

320 where  $\alpha$  is a scale coefficient ranging from 0 and 1, which is normally assumed to be 0.5, and  $\beta$  and  $\gamma$  are the  
 321 temperature and discharge factors, respectively, defined as:

$$322 \quad \beta = \left( \frac{T_{max} - T_{min}}{1^\circ C} \right)^2 \quad (12)$$

$$323 \quad \gamma = \frac{Q_{max} - Q_{min}}{Q_{med}} \quad (13)$$

324 where  $T_{max}$  and  $T_{min}$  are the maximum and minimum temperatures, respectively, and  $Q_{max}$ ,  $Q_{min}$  and  $Q_{med}$  are the  
 325 maximum, minimum and average discharge values recorded during the monitoring period, respectively. The use of  
 326 Eqn (9) allows us to define the spring vulnerability degree, as shown in Table 1. Because Eqn (9) is related to the joint  
 327 use of Q, T and EC, each factor can increase or decrease the spring vulnerability. No recharge measurements are  
 328 required for the definition of the VESPA Index, and there are no relationships between recharge and discharge. The  
 329 four degrees of vulnerability shown in Table 1 are the result of experimental applications of the VESPA Index and  
 330 local regulations (Piedmont Region, NW Italy), defining the vulnerability of a karst spring area (Galleani et al. 2011).

331

332 **Table 1** VESPA index interval for the identification of the spring vulnerability degree (from Galleani et al. 2011).

VULNERABILITY	VESPA INDEX
Very high	$V \geq 10$
High	$1 \leq V < 10$
Medium	$0.1 \leq V < 10$
Low	$0 \leq V \leq 0.1$

333 By means of  $\rho$  and  $c(\rho)$ , Galleani et al. (2011) proposed three different types of prevailing spring phenomena (Table  
334 2):

335 (i) The type A “replacement” phenomenon represents a well-developed discharge system. The replacement  
336 effect produces an increase in Q, a variation in T according to the seasonal rainfall temperatures and a decrease  
337 in EC. This replacement effect is typical for highly karstified limestone aquifers.

338 (ii) The type B “piston” phenomenon represents a moderate drainage system in which the hydrodynamic response  
339 can show impulse behavior. This phenomenon is typical for slightly karstified limestone aquifers with  
340 significant water storage. The piston effect produces increases in Q, T and EC.

341 (iii) The type C “homogenization” phenomenon is characterized by a poor-developed drainage system, where the  
342 water response to rainfall is almost absent. The Q trend presents slow and modest fluctuations that are  
343 uncorrelated with T or EC.

344 Due to the differences in the development of the fracture network, the type A drainage systems are generally the most  
345 vulnerable, while type C drainage systems are the least vulnerable (Galleani et al. 2011).

346 The type of drainage system is inferable on the basis of  $c(\rho)$  and  $\rho$ , as in Table 2. In addition, because the coefficient  
347  $\rho$  is defined as the correlation between Q and EC, a graphical comparison between these two parameters was performed  
348 to validate/deny the behavior classification and to explain the EC variations that are ascribable to the groundwater  
349 residence time in the karst aquifer. For this reason, the graphical comparison between Q and EC was not included into  
350 the workflow in Fig. 4 because it represents a supplementary analysis.

351 **Table 2** Correlation coefficient and correlation factor ranges for the three basic types of springs (from Galleani et al.  
352 2011).

Spring type and prevailing phenomena	Correlation coefficient $\rho$	Correlation factor $c(\rho)$
Type A – Replacement	$-1.0 \leq \rho \leq -0.2$	$0.2 \leq c(\rho) \leq 1.0$
Type B - Piston	$0.2 \leq \rho \leq 1.0$	$0.1 \leq c(\rho) \leq 0.5$
Type C - Homogenization	$-0.2 \leq \rho \leq 0.2$	$0 \leq c(\rho) \leq 0.2$

353 **3 Results and discussions**

354 The analyzed monitored period utilized to perform the statistical analyses ranged from April 2017 to June 2018. This  
355 period represents the longer interval time without significant monitoring interruptions. From the analysis of summary  
356 statistics (Table 3) and histograms (Fig. 5) of the monitoring data, it is possible to highlight a difference in the  
357 distribution of data between Nanto and Mossano springs. In terms of discharge, the main differences are as follows:  
358 (i) the Mossano Q distribution is bimodal, while the Nanto Q distribution is unimodal; (ii) the maximum value of Nanto  
359 is higher than the maximum value of Mossano; and (iii) the median and mean are higher in Mossano than in Nanto.  
360 Likewise, the EC values of Nanto are bimodal, and the median and mean values in Nanto are higher than those in  
361 Mossano. Furthermore, the Mossano T values are lower than the Nanto T values, and both springs show a unimodal  
362 histogram distribution of T.  
363 Regarding the rainfall data, Table 4 shows a summary of the parameters recorded over the four years of monitoring by  
364 the Barbarano Vicentino meteorological station.

365 **3.1 Spring discharge variations**

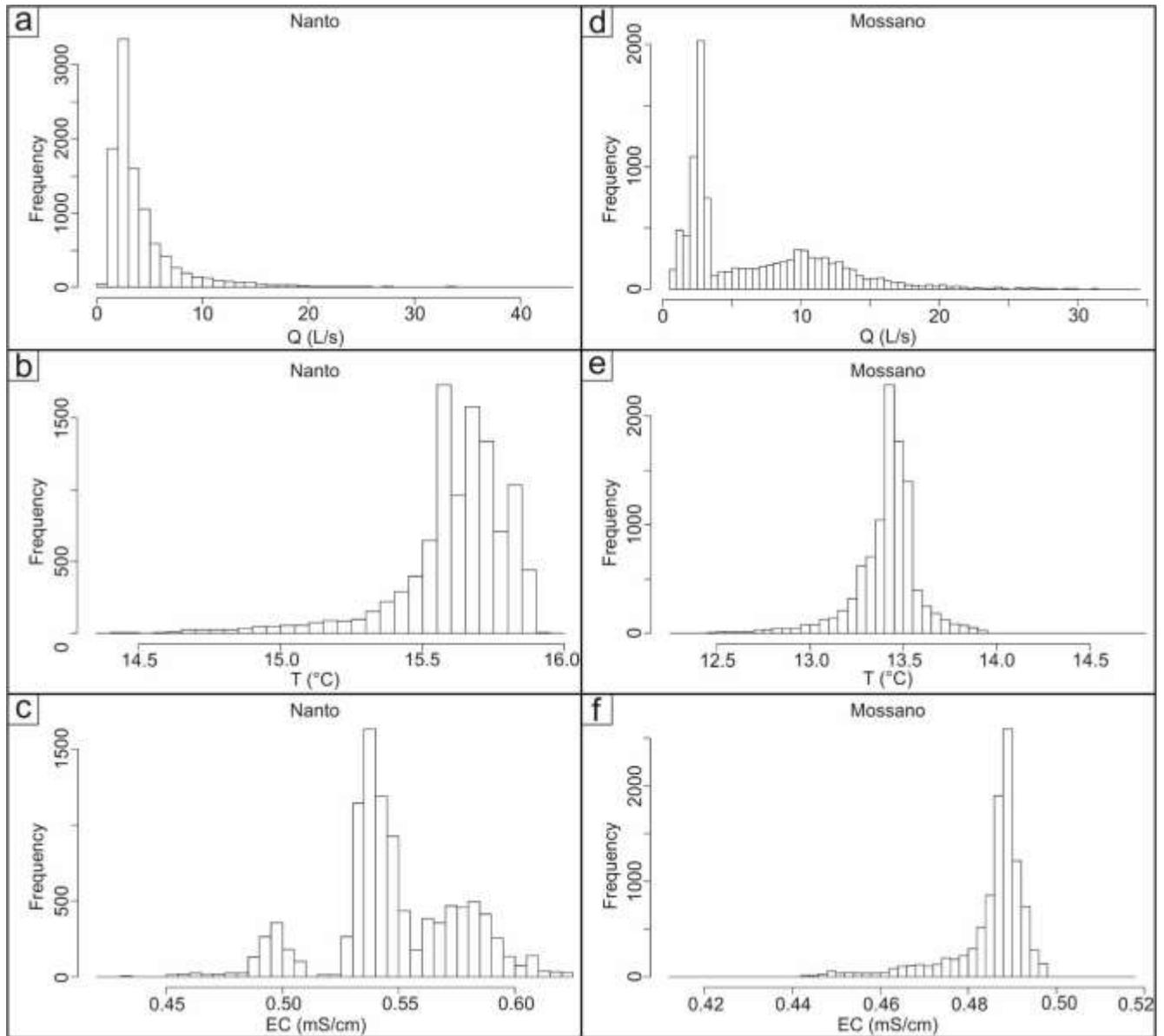
366 Maillet's equation was used to calculate the recession coefficient  $\alpha$  for different segments of the analyzed discharge  
367 curves, which were individuated in the monitoring period (January 2015 – June 2018). For this type of analysis,  
368 compared to statistical method, the entire monitored period can be used because RCA is less influenced by data  
369 continuity. Two representative recession curves among those analyzed (supplementary materials), with the related  $\alpha$   
370 values, are shown in Fig. 6. The  $\alpha$  values calculated for the Nanto and Mossano springs highlight the different  
371 karstification degrees of the lithologies forming the aquifer reservoir. The first system, described by  $\alpha$  coefficients  
372 within  $10^{-1}$  order of magnitude, is constituted by well-developed conduits, allowing for the rapid discharge of rainfall  
373 infiltration (conduit dominant flow; Taylor and Green 2008). This system is probably more developed in the limestones  
374 of the CFm and NL formations than in the marly limestone of PFm. The second system is characterized by recession  
375 coefficients within  $10^{-3}$  orders of magnitude, suggesting a slower circulation in fractured rocks (diffuse dominant flow;  
376 Taylor and Green, 2008) involving both NL

377 **Table 3** Summary statistics of the monitored parameters in the period from April 2017 to June 2018.

Nanto spring	Minimum	first Quartile	Median	Mean	third Quartile	Maximum
Q (L/s)	0.41	2.10	2.93	4.35	4.74	44.86
EC (mS/cm)	0.42	0.53	0.54	0.55	0.57	0.62

<b>T (°C)</b>	14.39	15.56	15.65	15.61	15.74	15.96
<b>Mossano spring</b>	<b>Minimum</b>	<b>first Quartile</b>	<b>Median</b>	<b>Mean</b>	<b>third Quartile</b>	<b>Maximum</b>
<b>Q (L/s)</b>	0.72	2.60	4.35	6.85	10.46	34.08
<b>EC (mS/cm)</b>	0.41	0.48	0.49	0.48	0.49	0.52
<b>T (°C)</b>	12.27	13.35	13.43	13.41	13.50	14.80

378



379

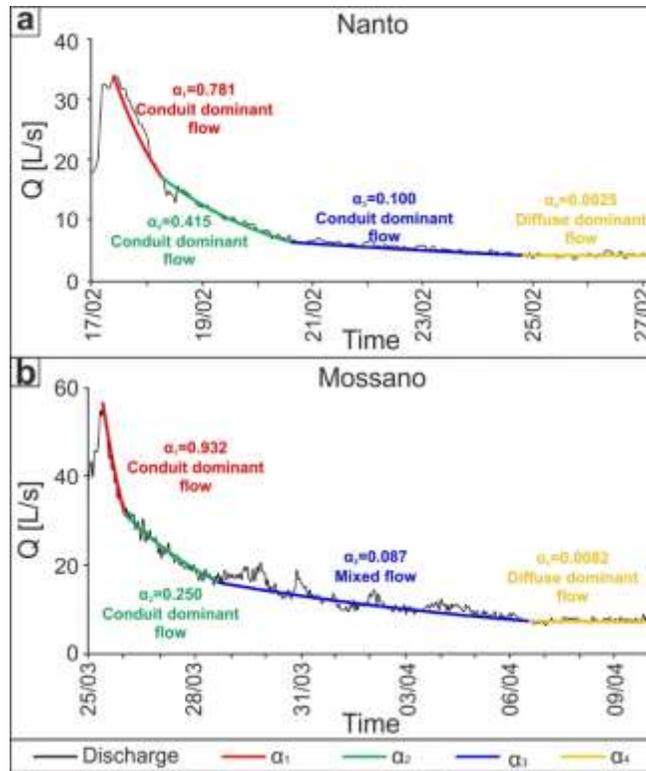
380 **Fig. 5** Histograms of the monitoring data in the period ranging from April 2017 to June 2018. **a** Discharge of Nanto  
381 spring. **b** Temperature of Nanto spring. **c** Specific electrical conductivity histogram of Nanto spring. **d** Discharge of  
382 Mossano spring. **e** Temperature of Mossano spring. **f** Specific electrical conductivity of Mossano spring.

383 **Table 4** Summary of the main parameters recorded by the Barbarano Vicentino meteorological station. For the rainfall,  
 384 both the total amount and the maximum event for each year are shown. For the air temperature, the yearly maximum,  
 385 minimum and medium values are displayed.

YEAR	RAINFALL [mm]		TEMPERATURE [°C]		
	TOTAL	MAXIMUM EVENT	MAXIMUM	MINIMUM	MEDIUM
2015	711.2	42.6	38.1	-4.3	14.3
2016	1070.4	27.2	35.0	-6.8	14.1
2017	691.4	24.2	38.1	-10.1	14.0
2018 <sup>a</sup>	462.6	20.0	33.8	-7.1	12.7

386 <sup>a</sup> Data describing the interval time ranged from January 2018 to June 2018

387 and PFm. The main difference between Nanto and Mossano is the existence of a recession value of  $10^{-2}$  for Mossano  
 388 spring, suggesting an intermediate or mixed flow system (i.e., a system bearing both karstic and fissured  
 389 characteristics). This hydrogeological behavior represents a transition between the conduit system and the matrix-  
 390 fracture system and could be related to a karstification degree of PFm that is possibly greater in the Mossano recharge  
 391 area than in the Nanto recharge area, as testify by field observations (Torresan 2016). The calculated  $\alpha$  values (Fig. 6)  
 392 are greater than the recession coefficients that are commonly available in the literature. For example, the recession  
 393 coefficients found by Amit et al. (2002) range from 0.1 to 0.0006, while Bagheri et al. (2016) showed  $\alpha$  values ranging  
 394 between 0.02 and 0.0002; furthermore, in Giacometti et al. (2017), the recession coefficients ranged between 0.01 and  
 395 0.001. The differences in these  $\alpha$  coefficients are probably due to both the geological and hydrogeological features of  
 396 the recharge areas and to the small extension of the karst systems. As a matter of fact, as stated by several authors  
 397 (Baedke and Krothe 2001; Bonacci 1993; Birk and Hergarten 2010; Fiorillo 2014; Kovács and Perrochet 2008; Kovács  
 398 et al. 2005), the recession coefficient is inversely proportional to the area of the active aquifer and/or to the recharge  
 399 area feeding the spring.

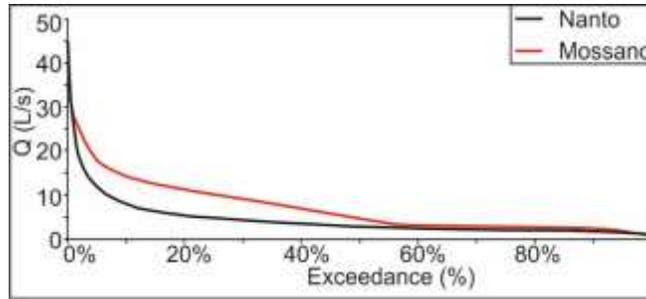


400

401 **Fig. 6** Recession curve analysis: **a** Nanto spring recession curve evaluated in the time interval between 17/02/2016 and  
 402 27/02/2016; **b** Mossano spring recession curve evaluated in the time interval between 25/03/2015 and 10/04/2015.  
 403 Type of regime define in according with Taylor and Green (2008)

404 The type of drainage system suggested by the RCA is also confirmed by the FDCs (Fig. 7). The steep slope of the  
 405 upper end of the FDCs indicates the existence of karst conduits, resulting in a highly variable spring discharge.  
 406 Conversely, the semiflat slope at the lower end of the curves indicates high water storage due to the low-permeability  
 407 system (fracture-matrix system). In addition, differences in the behavior between the two springs are highlighted.  
 408 Nanto spring shows essentially two components, while Mossano spring shows three components. This difference can  
 409 be related to the existence of an intermediate system (mixed flow, shown in Fig. 6) with a remarkable capability of  
 410 discharge (9.4-10.4 L/s, exceedance of 10-50%).

411

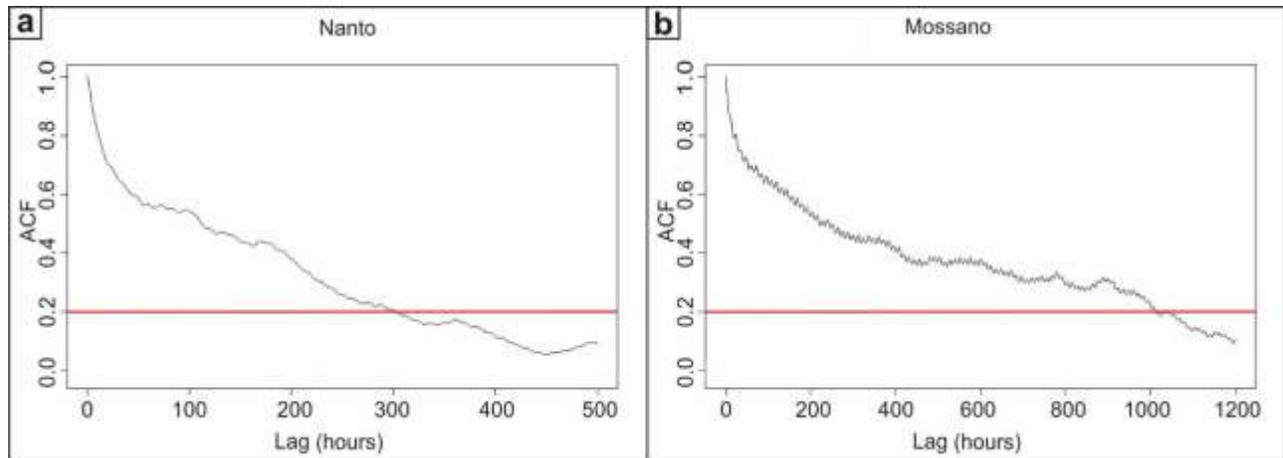


412

413 **Fig. 7** Flow duration curves for Nanto and Mossano springs.

414 ACF analysis further confirms the different behaviors of the two monitored springs. The autocorrelogram analyses  
 415 (Fig. 8) highlight an initial component characterized by a steeper slope. The ACFs quickly decrease in the first 50-70  
 416 hours, indicating the existence of well-developed karst conduits that favor a rapid discharge flow. A second component  
 417 is present only in the Mossano ACF (Fig. 8b) and shows an intermediate slope with a moderately slow reduction of  
 418 the ACF ranging from approximately 50 to 900 hours. This component can be ascribed to the existence of an  
 419 intermediate flow system that is also distinguished by RCA (Fig. 6) and FDCs (Fig. 7). Finally, the third component,  
 420 which reaches the threshold value of 0.2, developed from approximately 50 to 320 hours (almost 13 days from lag 0)  
 421 in Nanto spring and from approximately 900 to 1,000 hours (approximately 40 days from lag 0) in Mossano spring.  
 422 This third component confirms the presence of a low-permeability fracture network, which is more extensive in Nanto  
 423 than in Mossano, that influences the storage capability, delaying the groundwater flow toward the springs.  
 424 The lag times required to reach the threshold value allow for some consideration of the size of the karst systems. When  
 425 the flow rate in Nanto spring reaches the threshold value, Mossano spring has an autocorrelation of approximately 0.5.  
 426 This difference can be related to the size of the hydrogeological system, which is probably greater in Mossano than in  
 427 Nanto.

428

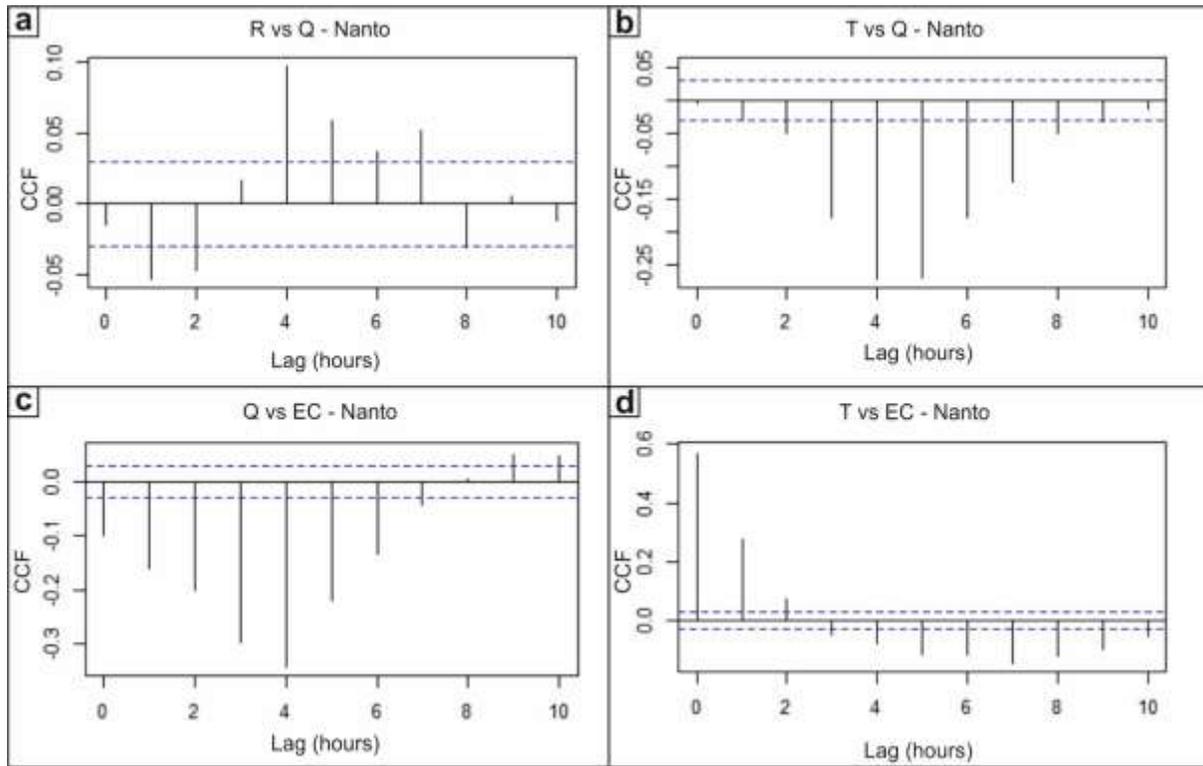


429  
 430 **Fig. 8** Autocorrelation functions in Nanto (a) and Mossano (b) springs. The considered discharge is from April 2017  
 431 to June 2018. *Horizontal red lines* represent the threshold of significance.

432 **3.2 Spring behavior**

433 To evaluate the spring responses, cross-correlation (CCF) analyses were performed considering the period from  
 434 January 2018 to June 2018 (Fig. 9 and Fig. 10). This interval time represents the monitoring period in which the  
 435 parameters Q, T and EC are representative for both springs and without missing data. The cross-correlation between  
 436 R (input) and Q (output) allows us to identify the spring response in terms of discharge variations as a consequence of  
 437 recharge events. Fig. 9a clearly shows positive correlations at lags of 4 and 5 hours for Nanto spring, meaning a  
 438 response delay of discharge occurs 4-5 hours after a rainfall event. Additionally, for Mossano spring, the significant  
 439 positive correlations at lags of 5 and 6 hours (Fig. 10a) define a response occurring with a delay of 5-6 hours after a  
 440 rainfall event. However, both springs also showed negative correlations (lags of 1 and 2 hours for Nanto spring and  
 441 lags of 3 hours for Mossano spring). A possible interpretation of this result is that 1-3 hours after rainfall events  
 442 (increased R), the discharge is constant/decreasing due to its natural trend before the recharge flow perturbation. This  
 443 behavior is interpreted as the necessary travel time for neo-infiltrated water to cross the vadose percolation zone and  
 444 reach the saturated zone of the karst aquifer, increasing its hydraulic head and, as consequence, the spring discharge.  
 445 The CCFs of Q vs. T and Q vs. EC are also useful for analyzing the springs' behavior. Both springs showed only  
 446 negative significant correlations (Fig. 9b-9c and Fig. 10b-10c), indicating a contrasting response between discharge  
 447 and both temperature and specific electrical conductivity, traducing in a replacement behavior (Type A drainage  
 448 system). In particular, CCFs between Q and T indicate a maximum negative cross-correlation at a 1-hour lag in

449 Mossano and a 4-hour lag in Nanto (Fig. 9b and Fig. 10b). Similarly, the CCFs between Q and EC show a maximum  
 450 negative correlation at a 2-hour lag in Mossano and a 4-hour lag in Nanto (Fig. 9c and Fig. 10c). Of interest are the  
 451 differences in the response delay between the input (Q) and output (T, EC). The Nanto negative correlations for T and  
 452 EC have 2-6 hour delays in comparison with the discharge (Fig. 9b-9c), while they have 1-3 hour delays in Mossano  
 453 (Fig. 10b-10c). Furthermore, the CCFs between



454  
 455 **Fig. 9** Cross-correlation between the monitored parameter in Nanto spring in the period between January 2018 and  
 456 June 2018. **a** Cross-correlation between R vs Q. **b** Cross-correlation between Q vs T. **c** Cross-correlation between Q  
 457 vs EC. **d** Cross-correlation between T vs EC. The *dashed blue lines* represent the confidence bands.

458 T and EC showed a very high positive correlation at lags of 0 hours and 1 hour (Fig. 9d and Fig. 10d), showing that  
 459 these two parameters behave in the same way. The shortest delay in both springs can be considered an estimate of the  
 460 minimum time needed by the infiltrated waters to transit through the conduit network and reach the point of emergence  
 461 (e.g., the first arrival time of a tracer test; Ford and Williams 2007). Considering that EC is less subject to external  
 462 agents compared to T, it is possible to demonstrate the different hydrogeological behaviors of the investigated system.  
 463 In Nanto, the first negative correlation between Q and EC at lag 0 can be related to the fact that once the freshwater

464 has infiltrated the karst aquifer, it reaches the spring in less than 1 hour. All the negative correlations between lags 0  
465 and 7 can be interpreted as the time needed for all of the neo-infiltrated water to reach the spring, with a maximum  
466 peak of concentration at 4-hour lag. In Mossano spring, the first negative correlation is at a 1-hour lag, indicating that  
467 after infiltration into the karst reservoir, the freshwater reaches the emergence point after 1 hour. The total time required  
468 to deplete the neo-infiltrated water is 3 hours, with a maximum peak at 2-hour lag. Two main differences can be  
469 observed between Nanto and Mossano springs: (i) the instantaneous response in Nanto can be related to both the  
470 existence of a well-developed karst system and the size of the hydrogeological system (smaller in Nanto than in  
471 Mossano), and (ii) the longer time needed to deplete the freshwater in Nanto is probably due to a high contribution of  
472 a fracture/matrix system rather than a conduit system. Conversely, the shorter time in Mossano may be related to the  
473 concomitant influence of three systems (instead of two), namely, the conduit system, the intermediate system and the  
474 fracture/matrix system, with the intermediate system developed inside the marly limestones of the PFM.

475  
476 The VESPA index was calculated considering more than one year of continuous hourly monitoring data (April 2017-  
477 June 2018), without a large number of missing data, as suggested by Banzato et al. (2017). The results are summarized  
478 in Table 5. Nanto is classified as a highly vulnerable spring ( $V=1.78$ ; Table 1), which exhibits with homogenization  
479 behavior ( $\rho=0.14$ ;  $c(\rho)=0.07$ ; Type C in Table 2). Conversely, Mossano is classified as a replacement spring (Type A  
480 in Table 2) by the coefficient  $\rho$  and as a replacement/piston (Type A/B) spring by the factor  $c(\rho)$ , while the VESPA  
481 index ( $V=13.04$ ) points to a very high degree of vulnerability (Table 1). The VESPA Index suggests different  
482 behavioral categories for Nanto spring and Mossano spring. Because the spring behavior is defined as the correlation  
483 between Q and EC, it is worth observing the related hydro- and chemo-graphs (Fig. 11). Both springs exhibit a  
484 comparable discharge trend (Fig. 11a), which is supported by the positive correlation of 0.66. However, Mossano  
485 spring shows a greater variability in the flow rate than of Nanto spring. These discharge variations can explain the  
486 higher degree of vulnerability of Mossano spring (Table 5). Regarding the EC, both springs shown decrease in EC,  
487 corresponding to the main Q peaks (Fig. 11b), indicating a replacement behavior, as suggested by the CCFs analyses.  
488 This observation highlights the existence of well-developed karst conduits that rapidly discharge infiltrated waters and  
489 that are poor in ion content, as a consequence of recharge events. In addition to this behavior, Nanto spring show a  
490 general increasing trend, which is more prominent after the time 4000 hours (Fig. 11b), that is related to an increase in  
491 the ion content of the groundwater due to a low-permeability system (fractures/matrix system). In particular, the

492 increase in EC are more accentuated after the EC negative peaks for Nanto spring. In terms of spring behavior, the  
493 conduit system shows a replacement behavior, while a homogenization behavior can be attributed to the  
494 fractures/matrix system. The VESPA Index does not allow the separation of these two contribution. However, the  
495 results obtained by the analysis of the  $\rho$  and  $c(\rho)$  factors for Nanto spring emphasized that the homogenization drainage  
496 system prevails over the replacement system, confirming that the fractures/matrix system is more extensive than karst  
497 system.

498 In contrast, excluding the EC negative peaks corresponding to the recharge events, Mossano spring show a generally  
499 constant EC trend (Fig. 11b). In addition, after the decrease in EC corresponding to the Q peaks, the EC recovery is  
500 gradual. The difference between Nanto and Mossano springs can be explained by the presence of an intermediate  
501 system in Mossano, between the conduits system and the fractures/matrix system, producing a progressive transition  
502 from high- to baseflow. The progressively recovery of EC values in Mossano spring defines three permeability systems  
503 that are responsible for the general replacement behavior individuated by the VESPA Index analysis.

### 504 **3.3 Hydrogeological conceptual model**

505 According to the proposed workflow (Fig. 4), combining the performed analyses and results, a hydrogeological  
506 conceptual model for both springs can be delineated. The analysis of the variations in spring discharge, accomplished  
507 using the RCA, ACF and FDC techniques, allow us to obtain qualitative information about the permeability of the  
508 karst system, related to the degree of karstification, and to the size of the karst system. The study of the spring behavior,  
509 accomplished using the CCFs and VESPA Index analyses combined with monitored parameters (Q, T, EC) and the  
510 recharge (R), allow us to obtain information about: (i) the spring response, which can be related to the neo-infiltrated  
511 water travel time across both the vadose zone and the saturated zone, (ii) the size of the karst systems and (iii) the degree  
512 of vulnerability of the karst springs.

513 Conceptually, it is possible to consider the two analyzed karst system as a multireservoir system to explain their  
514 hydrogeological structure. In the case of Nanto spring, two reservoirs with different karstification degrees can be  
515 individuated. In fact, RCA, FDC and ACF analyses delineated the existence of both well-developed karst conduits and  
516 a fractures/matrix system of lower permeability. In addition, the fractures/matrix system is more developed in size than  
517 the conduit system, as indicated by the FDC and ACF results. After a rainfall event, the neo-infiltrated water requires  
518 4-5 hours to move across the unsaturated zone and reach the karst aquifer, as shown by the CCF between Q vs. R.  
519 Subsequently, the fresh water reaches the point of emergence of the spring through the well-developed karst conduits

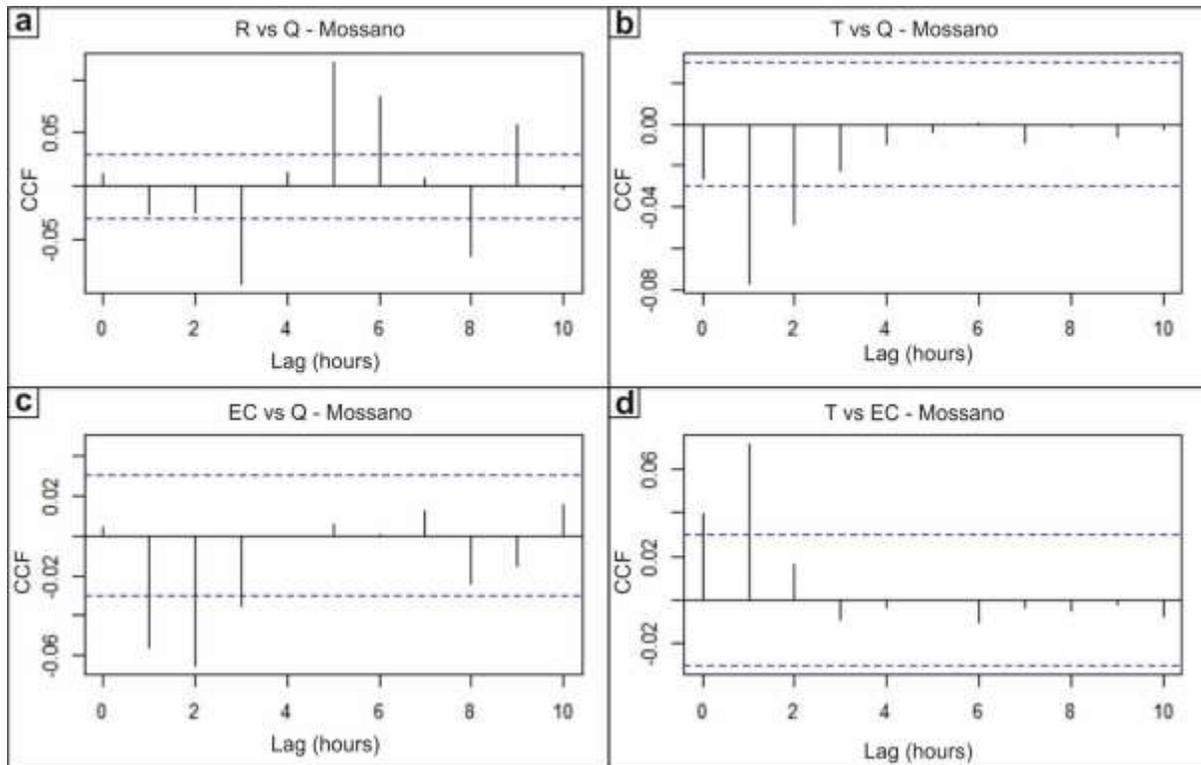
520 in less than an hour (Q vs. EC). However, the contribution of karst conduits to the depletion of neo-infiltrated water is  
521 less than that of the fractures/matrix system, shown by the CCF between Q vs. EC. The abrupt increases in the EC  
522 after the EC negative peaks (Fig. 11b), in conjunction with the recharge events, are attributable to the net transition  
523 between a conduit-dominant flow to a diffuse-dominant flow.

524 The results obtained through the use of RCA, FDC and ACF analyses allowed for the identification of the existence of  
525 three reservoirs affecting Mossano spring. In particular, a karst conduit system and a fracture/matrix system, separated  
526 by an intermediate system, were individuated. The intermediate system is relevant in the existence of the Mossano  
527 spring. In fact, the intermediate system is active for a longer time compared to the other two systems, as indicated by  
528 the ACF and FDC analyses. The intermediate system, constituted by both karstic and fissured features, is more  
529 developed in size compared to the other two systems. During a recharge event, the infiltrated fresh water reaches the  
530 karst aquifer after 5-6 hours, as indicated by the CCF between Q vs. R. Due to the high permeability of the karst  
531 conduits, the travel time of the neo-infiltrated water across the karst reservoir is shorter (about 1 hour) and the water  
532 is depleted after approximately 3 hours (the CCF between Q vs EC). The existence of the intermediate system allows  
533 for the gradual recovery of the baseflow stage, as suggested by the progressive increase of in EC after the negative  
534 peaks related to infiltration processes (Fig. 11b).

535 Comparing Nanto spring and Mossano spring, some differences appears. In terms of karstification degree, the Mossano  
536 system is more karstified than the Nanto system. In fact, in the Nanto system, the fracture/matrix system prevails over  
537 the conduit system while, in Mossano, an intermediate system exists. This conclusion is further emphasized by the  
538 results of the RCA, FDC and ACF analyses. The intermediate system affecting Mossano spring is probably due to the  
539 PFm that may be more permeable in the Mossano karst area.

540 Regarding the size of the karst domain, ACF analysis shows that the Mossano karst system is greater than the Nanto  
541 system. Additionally, the CCF between Q vs. EC confirm the different size by comparing the time of the first arrival  
542 of freshwater at the springs. However, the transit time needed for the water to infiltrate the epikarst is comparable (4-  
543 6 hours). This last aspect is amenable to the same features of the recharge area, constituted by an alteration of the CFm  
544 with the formation of soil, mainly used for agricultural purposes.

545 Finally, other differences are highlighted by the VESPA Index that identify Nanto as a high vulnerable spring with a  
546 Type C drainage system while Mossano as a very high vulnerable spring characterized by a Type A drainage system.



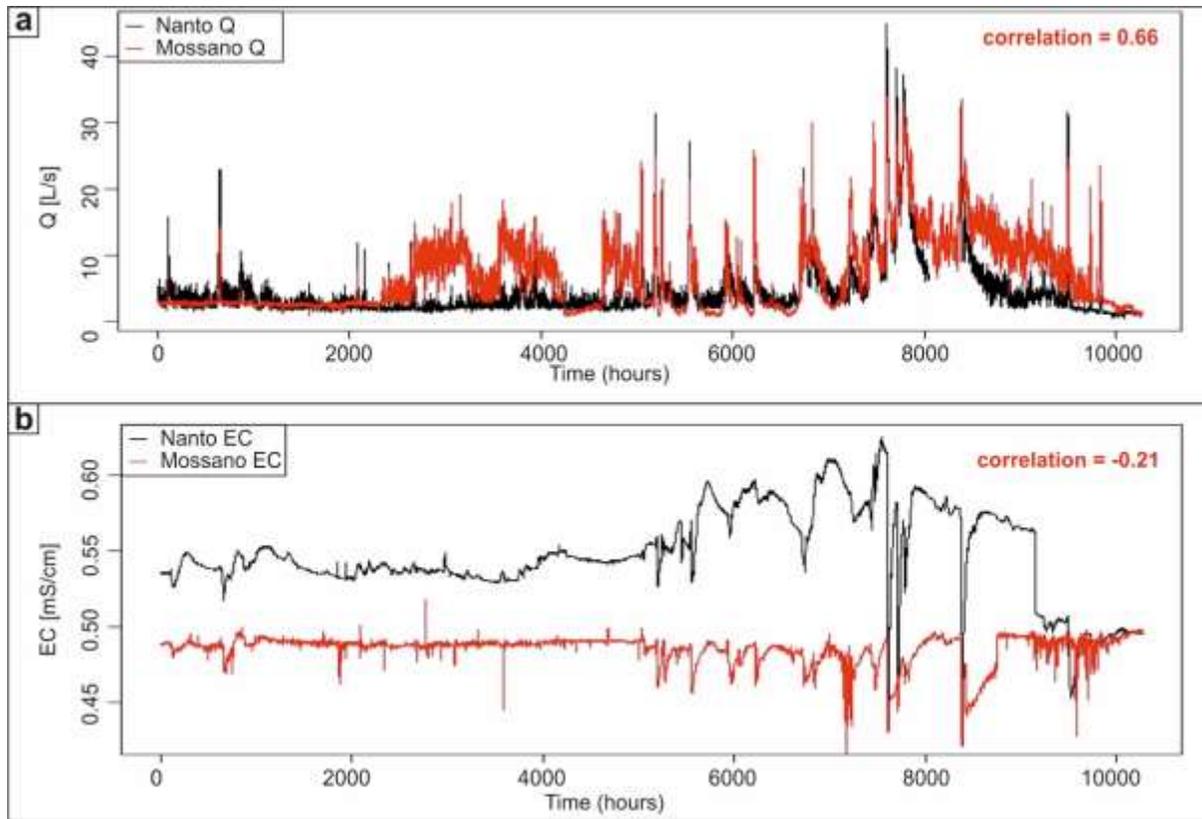
547  
 548 **Fig. 10** Cross-correlation between the monitored parameters in Mossano spring in the period between January 2018  
 549 and June 2018. **a** Cross-correlation between P vs Q. **b** Cross-correlation between Q vs T. **c** Cross-correlation between  
 550 Q vs EC. **d** Cross-correlation between T vs EC. The *dashed blue lines* represent the confidence bands.

551 **Table 5** VESPA index parameters for the two analyzed springs evaluated in the period between April 2017 and June  
 552 2018. The parameters are defined in Eqn. 9-13.

Spring	$\rho$	$c(\rho)$	$\beta$	$\gamma$	$V$
Nanto	0.14	0.07	2.47	10.45	1.78
Mossano	-0.42	0.42	6.42	4.87	13.04

553

554



555  
 556 **Fig. 11** Comparison between the two analyzed spring parameters in the period between April 2017 and June 2018: **a**  
 557 comparison between Nanto discharge and Mossano discharge. **b** Comparison between Nanto-specific electrical  
 558 conductivity and Mossano-specific electrical conductivity.

559 **4 Conclusions**

560 In this study, a workflow for the hydrogeological characterization of karst springs was proposed. This workflow was  
 561 applied to the study of two spring, located in the Berici Mountains (Vicenza, NE Italy), with the aim of increasing the  
 562 knowledge of groundwater circulation in a peculiar karst system.

563 A multiapproach for the analyses of spring discharge variations, using recession curve analyses, flow duration curves  
 564 and auto-correlation functions techniques, was employed to evaluated the karst degree and the size of the system.  
 565 Moreover, by combining the monitoring parameters (Q, T, EC) with recharge events (R) through the joint use of cross-  
 566 correlation functions and the VESPA Index approach, it was possible to obtain qualitative information of: (i) the spring  
 567 response to recharge events, (ii) the travel time of meteoric water into both the vadose zone and the conduits network

568 (iii) the size/permeability of the karst system, (iv) the spring vulnerability and (v) the drainage system behavior. The  
569 information obtained by all the performed analyses allows us to define a hydrogeological conceptual model for each  
570 spring that can be used to explain the main features that characterize each karst system. In fact, the previously  
571 mentioned quantitative/qualitative information comprises peculiar points in the preliminarily studies of a karst spring,  
572 finalized to its potentiality assessment in the water supply.

573 The two monitoring springs show the same behavior as a consequence of the recharge events, as supported by both the  
574 CCFs and graphical comparison between Q and EC (Fig. 11). However, the analyses of spring discharge variations  
575 and the VESPA Index allow us to delineate some differences between Nanto and Mossano springs. In fact, Mossano  
576 spring is composed of three systems with different degrees of permeability, whereas the Nanto spring reservoir is  
577 characterized by two systems. Another difference is that karst behavior prevails in Mossano spring (the conduit and  
578 intermediate systems), while fracture/matrix behavior prevails in Nanto spring. This result is further supported by the  
579 VESPA Index, which delineates Nanto spring as a Type C drainage system and Mossano as a Type A drainage system.  
580 The results obtained can be extend to the others perennial springs affecting the south-eastern part of the Berici  
581 Mountains in which the geological and hydrogeological conditions are the same characterizing the Nanto and Mossano  
582 karst systems. However, a monitoring is indispensable in order to correctly establish the hydrogeological features  
583 affecting these perennial springs.

584 Although in this work, 4 years of continuous monitoring parameters were collected, only the continuous data from one  
585 year were indispensable to perform all of the analyses included in the proposed workflow.

586 The combined use of such methodologies allows us both to support the detail of the hydrogeological conceptual model  
587 and to limit the loss of information or erroneous interpretation that can result from using only one technique. For  
588 example, the results achieved by the  $\rho$  coefficient do not allow the identification of the existence of the karst conduits  
589 for Nanto spring, delineating a Type-C behavior ascribable to a matrix-fracture system. However, although the RCA,  
590 FDC and ACF individuated the existence of both karst conduits and the matrix-fracture system, the VESPA Index  
591 approach allows us to confirm/define that the matrix-fracture system prevails over the conduit system.

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595 **References**

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