Hydrogeology Journal
https://doi.org/10.1007/s10040-021-02317-z

REPORT

Estimation of recharge in mountain hard-rock aquifers based on discrete spring discharge monitoring during base-flow recession

Stefano Segadelli[1] · Maria Filippini[2] · Anna Monti[2] · Fulvio Celico[3] · Alessandro Gargini[2]

Received: 10 July 2020 / Accepted: 30 January 2021

Abstract
Estimation of aquifer recharge is key to effective groundwater management and protection. In mountain hard-rock aquifers, the average annual discharge of a spring generally reflects the vertical aquifer recharge over the spring catchment. However, the determination of average annual spring discharge requires expensive and challenging field monitoring. A power-law correlation was previously reported in the literature that would allow quantification of the average annual spring discharge starting from only a few discharge measurements in the low-flow season, in a dry summer climate. The correlation is based upon the Maillet model and was previously derived by a 10-year monitoring program of discharge from springs and streams in hard-rock aquifers composed of siliciclastic and calcareous turbidites that did not have well defined hydrogeologic boundaries. In this research, the same correlation was applied to two ophiolitic (peridotitic) hard-rock aquifers in the Northern Apennines (Northern Italy) with well-defined hydrogeologic boundaries and base-outflow springs. The correlation provided a reliable estimate of the average annual spring discharge thus confirming its effectiveness regardless of bedrock lithology. In the two aquifers studied, the measurable annual outputs (i.e. sum of average annual spring discharges) could be assumed equal to the annual inputs (i.e. vertical recharge) based on the clear-cut aquifer boundaries and a quick groundwater circulation inferable from spring water parameters. Thus, in such setting, the aforementioned correlation also provided an estimate of the annual aquifer recharge allowing the assessment of coefficients of infiltration (i.e. ratio between aquifer recharge and total precipitation) ranging between 10 and 20%.

Keywords Fractured rocks · Italy · Groundwater recharge · Base-flow recession · Power-law correlation

Introduction

Hard rocks cover approximately the 20–35% of the Earth surface and many are utilized as important aquifers (Amiotte Suchet et al. 2003; Gustafson and Krásný 1994). Several of these aquifers are in mountainous areas, playing a major role in water supply along with the aquifers in flat areas of the planet (Hilberg 2016; Viviroli et al. 2007). The quantification of recharge in hard rock mountain aquifers is a key issue for the management of valuable groundwater resources as well as for the assessment of climate change impacts. Several reviews have been published that describe the main approaches for aquifer recharge estimation such as water balance methods, tracer methods, numerical methods, water-table fluctuation, river hydrograph separation, etc. (e.g. Cuthbert 2010; de Vries and Simmers 2002; Healy 2010; Huet et al. 2016; Scanlon et al. 2002). However, many of these approaches require a large amount of information from long and complex field monitoring campaigns that are hardly feasible in mountain catchments. Moreover, the hard rock environment provides additional challenges for recharge estimate due to the highly heterogeneous nature of the geologic materials (e.g. Rohde et al. 2015a; Rohde et al. 2015b; Thivya et al. 2016). For such challenging types of aquifers, more manageable approaches would be needed requiring only a few field measurements to optimize the aquifer recharge assessment.

✉ Maria Filippini
maria.filippini3@unibo.it

[1] Geological, Seismic and Soil Service, Emilia-Romagna Region Administration, Viale della Fiera 8, 4027 Bologna, Italy

[2] Department of Biological, Geological, and Environmental Sciences, Alma Mater Studiorum - University of Bologna, via Zamboni 67, 40126 Bologna, Italy

[3] Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area delle Scienze 157/A, 43124 Parma, Italy

Published online: 17 March 2021

Gargini et al. (2008) investigated the groundwater flow systems within sedimentary hard rock aquifers in the Northern Apennines (Italy), composed of calcareous and siliciclastic turbidites. It is worth noting that the term 'hard rock aquifer' is generally related to igneous and metamorphic rocks (Dewandel et al. 2006, 2011; Lachassagne 2008; Lachassagne et al. 2011; Neuman 2005); however, in some circumstances, sedimentary rocks exhibit heterogeneous and anisotropic hydraulic conductivity distributions similar to those commonly observed for hard rock units, as in the case of the calcareous and siliciclastic turbidite formations in the Northern Apennines (Gargini et al. 2014; Piccinini et al. 2013). Such units behave as very transmissive aquifers in favorable structural conditions, as evidenced by Gargini et al. (2006), Vincenzi et al. (2009), and Vincenzi et al. (2014) while investigating the hydrogeological effects induced by the drilling of a high-speed railway tunnel connecting Bologna and Florence (Italy). Gargini et al. (2008), based on a large database of flow rate measurements in springs and streams collected throughout more than 10 years, found an empirical power-law correlation between the average discharge of a spring during base-flow recession and its average annual discharge, in a dry summer climate. The correlation is controlled by the base-flow recession coefficient according to the exponential Maillet model (Maillet 1905). Assuming that the annual average discharge of a spring equals the water flow that enters the aquifer over the spring catchment, the correlation would allow estimating the annual recharge of the aquifer starting from a few measurements of spring flow rates during the base-flow recession. However, since the investigated turbiditic aquifers do not have well-defined hydrogeologic boundaries and catchments, the proposed relationship could not be exploited for the estimation of aquifer recharge.

This report aims to validate the aforementioned correlation in a new setting that also has convenient boundary conditions for the estimation of aquifer recharge. To these aims, the study identified two hard-rock aquifers with a well-defined catchment where the whole measurable discharge (i.e. the sum of spring discharges), with no loss, could be assumed equal to the recharge of the system. The two aquifers are ophiolitic olistolites (known as Mt. Prinzera and Mt. Zirone), mainly composed of fractured peridotites and fully surrounded by low-permeability units behaving as aquitards. These are located in the western sector of the Northern Apennines, in a climatic and structural setting analogous to that investigated by Gargini et al. (2008). The two selected aquifers are of environmental and social interest being located in a natural reserve area (Mt. Prinzera) and being exploited for public water supply (Mt. Zirone).

Materials and methods

Geological and hydrogeological setting

The two study areas of Mt. Prinzera and Mt. Zirone are located near the confluence between the Taro and Ceno streams, about 36 km SW of the town of Parma, in the western sector of the Northern Apennines (Emilia-Romagna Region, Italy; Fig. 1). The Northern Apennines are a typical thrust-fold chain originated from the convergence and collision between the Eurasian and African plates after the consumption of the paleo-Tethys oceanic crust of the Ligurian-Piedmont basin. Some ophiolitic bodies outcrop along the chain as isolated remnants of obducted oceanic crust. These are mostly peridotites, serpentinites, gabbros and basalts formed in the Middle to Upper Jurassic (Marroni et al. 2010) that today are embodied within allochthonous Ligurian silty-clayey complexes (Abbate 1986; Bortolotti et al. 2001).

Mt. Prinzera and Mt. Zirone are ophiolitic mountainous reliefs (olistolithes) mainly consisting of strongly serpentinized peridotites (Di Dio et al. 2005; Venturelli et al. 1997) outcropping along an orographic culmination of the external portion of the liguride units. The Mt. Prinzera ophiolitic structure covers an area of about 0.9 km^2 reaching a peak elevation of 725 m above sea level (asl); it is about 250 m thick and gently dips to the north. The Mt. Zirone ophiolite covers an area of about 2.6 km^2 with a maximum elevation of 707 m asl; it is 50 m thick and dips to the northwest. The ophiolitic rock masses have a very low matrix permeability but appear extensively fractured thus behaving as aquifers. Hydraulic tests provided a hydraulic conductivity ranging between 1.1×10^{-7} and 5.7×10^{-7} m/s for these units (Segadelli et al. 2017a). The olistolithes of Mt. Prinzera and Mt. Zirone are bordered and underlain by low-permeability deposits (Figs. 2 and 3) that are predominantly characterized by polygenic breccias made out of blocks of limestones or marly limestones inside a silty-clayey matrix with mineral cement (Segadelli et al. 2017a, b). It is reasonable to assume that these lower permeability units behave as aquitards, since the fine-grained matrix clearly dominates over the limestone blocks (Fig. 3c). Several perennial springs are located at the contact between the ophiolitic aquifers and the aquitard unit. These springs represent the whole outflow of the aquifers following the conceptual model proposed by Segadelli et al. (2017b) for Mt. Prinzera (Fig. 4).

The climate in the Mt. Prinzera and Mt. Zirone areas is midway between Mediterranean and oceanic, with humidity levels typical of boreal mountain zones close to the sea (Costantini et al. 2013; Nistor 2016). The average annual rainfall is about 1,000 mm/year and the seasonal rainfall distribution is that typical of the Northern Apennines with a main peak in autumn and a secondary peak in spring (Antolini et al. 2017). The driest season is summer-early autumn followed by a dry period of secondary importance in early winter.

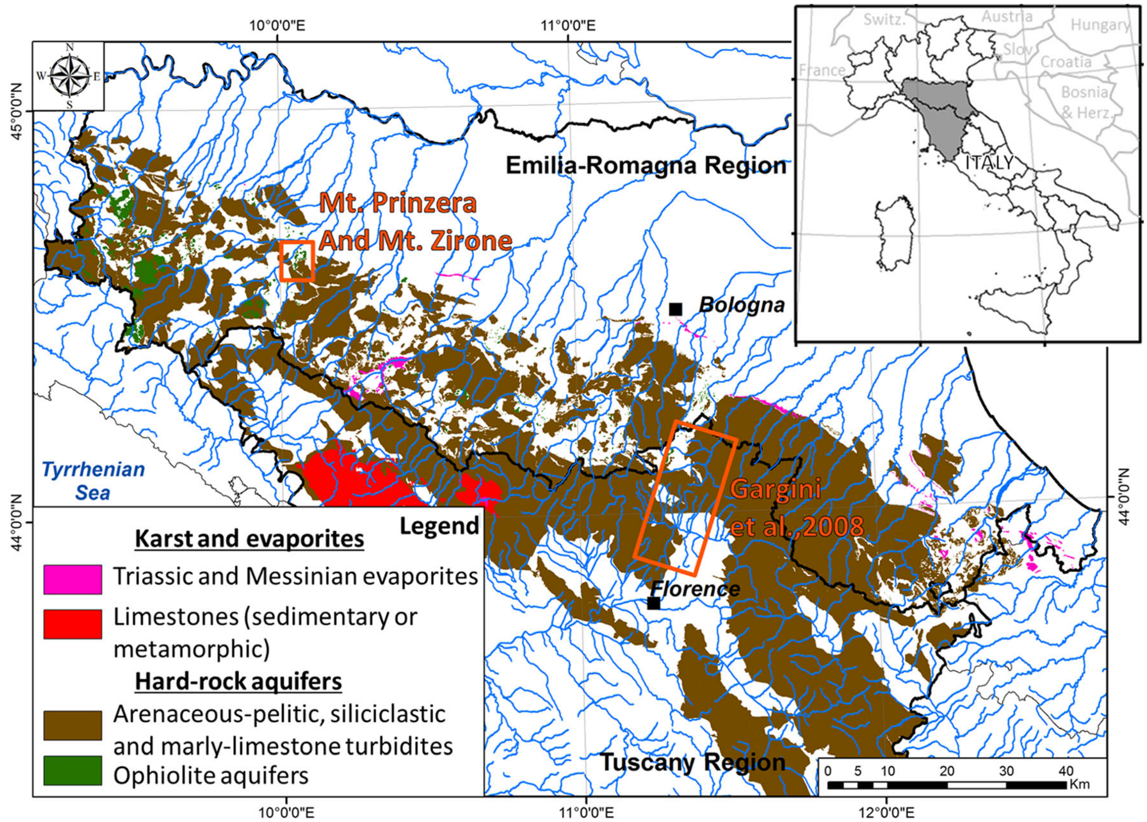

Fig. 1 Distribution of hard-rock aquifers in the Northern Apennines, Italy. The area of Mt. Prinzera and Mt. Zirone and the area previously investigated by Gargini et al. (2008) are highlighted in orange. Geological database source: Geological survey of Emilia-Romagna and Tuscany regions in GIS vector format at a scale of 1:10000

Spring survey and monitoring

A detailed field survey was carried out to identify all the perennial springs pertaining to the two investigated aquifers. The limited extent of the aquifers favoured this activity. The surveys were carried out in April 2012 and in May 2016 at Mt. Prinzera and Mt. Zirone, respectively. Seven springs were identified in the area of Mt. Prinzera and five at Mt. Zirone. All the perennial springs are located at the contact between the ophiolitic massif and the underlying aquitard units (Fig. 2). Nine out of the total 12 springs are exploited for public supply of drinking water. The remaining three are not exploited and respond to the description of rheocrene springs following Springer and Stevens (2009).

Discharge was monitored on a weekly basis in all the springs of Mt. Prinzera between September 2012 and September 2013, whereas the springs of the Mt. Zirone area were monitored between October 2016 and October 2017. In both cases, the monitoring lasted for at least a hydrogeologic year, i.e. from the beginning of the recharge season (corresponding to a systematic increase of water levels and/or spring flow rates) to the end of base-flow recession in the next calendar year. The field measurements of discharge (Q) were performed following an irregular timeframe due to logistic constraints (see Tables S1 and S2 in the electronic supplementary material (ESM). Discharge measurements were performed using the volumetric method due to the relatively low flow rates. In the case of springs exploited for public water supply, the time to fill a 20-L graduated bucket was measured to obtain discharge. In the case of non-exploited springs, flumes and weirs were used to convey all the water inside a smaller graduated container. Measurements were repeated at least three times at each monitoring point for the sake of accuracy. Groundwater parameters (temperature: T, electrical conductivity at 25 °C: EC, and pH) were measured on-site by means of a portable device (Eutech Instrument, Thermo Fisher Scientific Inc.) concurrently with each discharge measurement.

Estimation of averaged annual spring discharge

A power-law correlation was found by Gargini et al. (2008) between the average annual discharge of a spring from field monitoring (Q_A) and its average discharge during hydrological recession in the low flow season, i.e. summer in the investigated climate (Q_S). Such correlation was derived experimentally starting from a large dataset of 11 hydrogeologic years of discharge monitoring on more than 80 springs in hard rock aquifers in turbiditic formations of the Northern Apennines and is expressed as in Eq. (1):

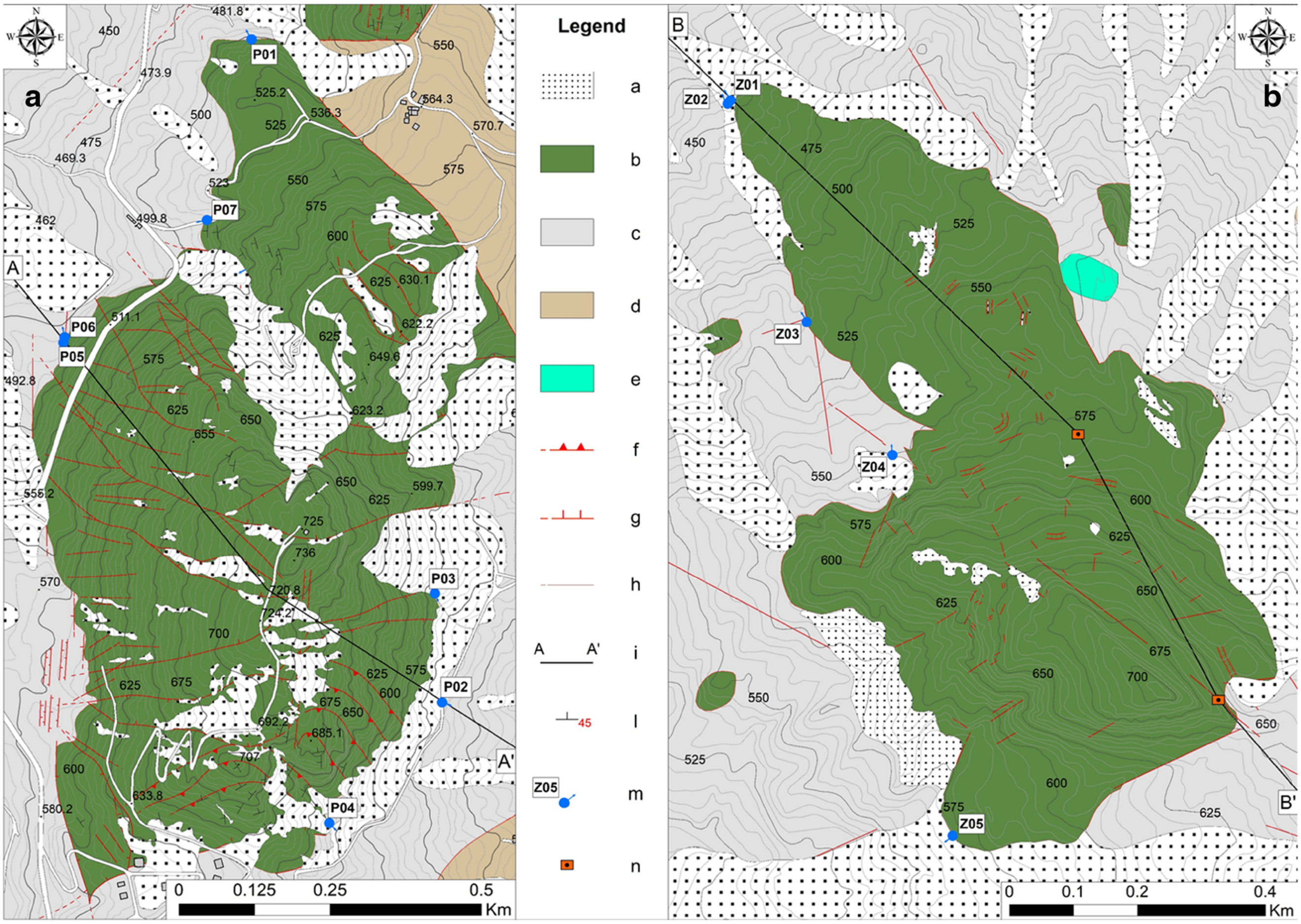

Fig. 2 Geological sketch maps of **a** Mt. Prinzera and **b** Mt. Zirone. Legend: a: Quaternary deposits; b: ophiolite hard-rock aquifers; c: polygenic breccias in clay matrix (aquitard); d: Helminthoid flysch; e: Calpionella limestones; f: thrust; g: fault (the teeth indicate the downwards moved side); h: tectonic contact; i: geological cross section; l: foliation attitude; m: perennial spring; *n:* borehole

$$Q_{\mathrm{A}} = A\, Q_{\mathrm{S}}^{B} \qquad (1)$$

The coefficient A and the exponent B were obtained from the linear fitting on a log-log plot of field data pertaining to springs with similar recession coefficients (α). The coefficient α is derived from the exponential model proposed by Maillet (1905). In particular, Gargini et al. (2008) proposed six different couples of values for A and B corresponding to different ranges of α ("classes of α", from here on; Table 1). The data within each of the six classes of α were aligned on a log-log plot of Q_{A} VS Q_{S} with a high coefficient of correlation (R^2) between 0.99 and 0.97. The rationale for choosing the Maillet model for the analysis of recession hydrographs is provided in the following section.

Equation (1) was applied to the springs of the Mt. Prinzera and Mt. Zirone to predict an average annual discharge (Q_{AE}, where the subscript E indicates an indirect estimate of Q_{A} through the equation) starting from base-flow recession monitoring (Q_{S}).

The actual averaged annual discharge Q_{A} was determined for each spring from field data. To account for the uneven distribution of Q measurements over the hydrogeologic year, Q_{A} was determined for each spring by disaggregating the flow rates measurements in four seasons (fall: from start of the hydrogeologic year to December 31st; winter: from January 1st to March 31st; spring: from April 1st to June 30th; summer: from July 1st to end of the hydrogeologic year) and by averaging the four mean seasonal values. Q_{S} was determined for each spring by averaging only the flow measurements selected for the recession analysis (criteria for the selection are in the next section).

The estimated annual flow rates Q_{AE} were compared to the average annual discharge from field monitoring Q_{A}. The goodness of the prediction was quantified separately for Mt. Prinzera and Mt. Zirone using the normalized root mean square deviation (NRMSD), expressed as in Eq. (2):

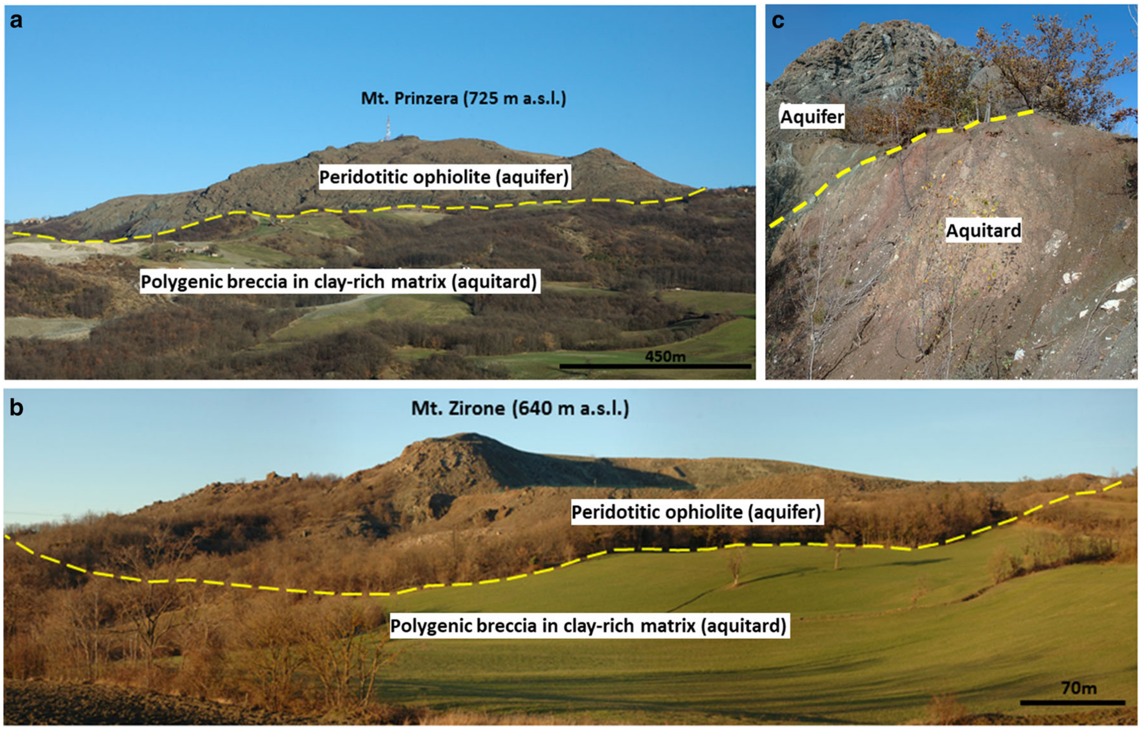

Fig. 3 **a** The landscape view of Mt. Prinzera western side and **b** Mt. Zirone southeastern side
The ophiolitic hard-rock aquifers rise from the surrounding gentle slopes made up of soft rocks (clay-rich breccias); **c** detail of the contact between the ophiolitic aquifer unit and the underlying aquitard

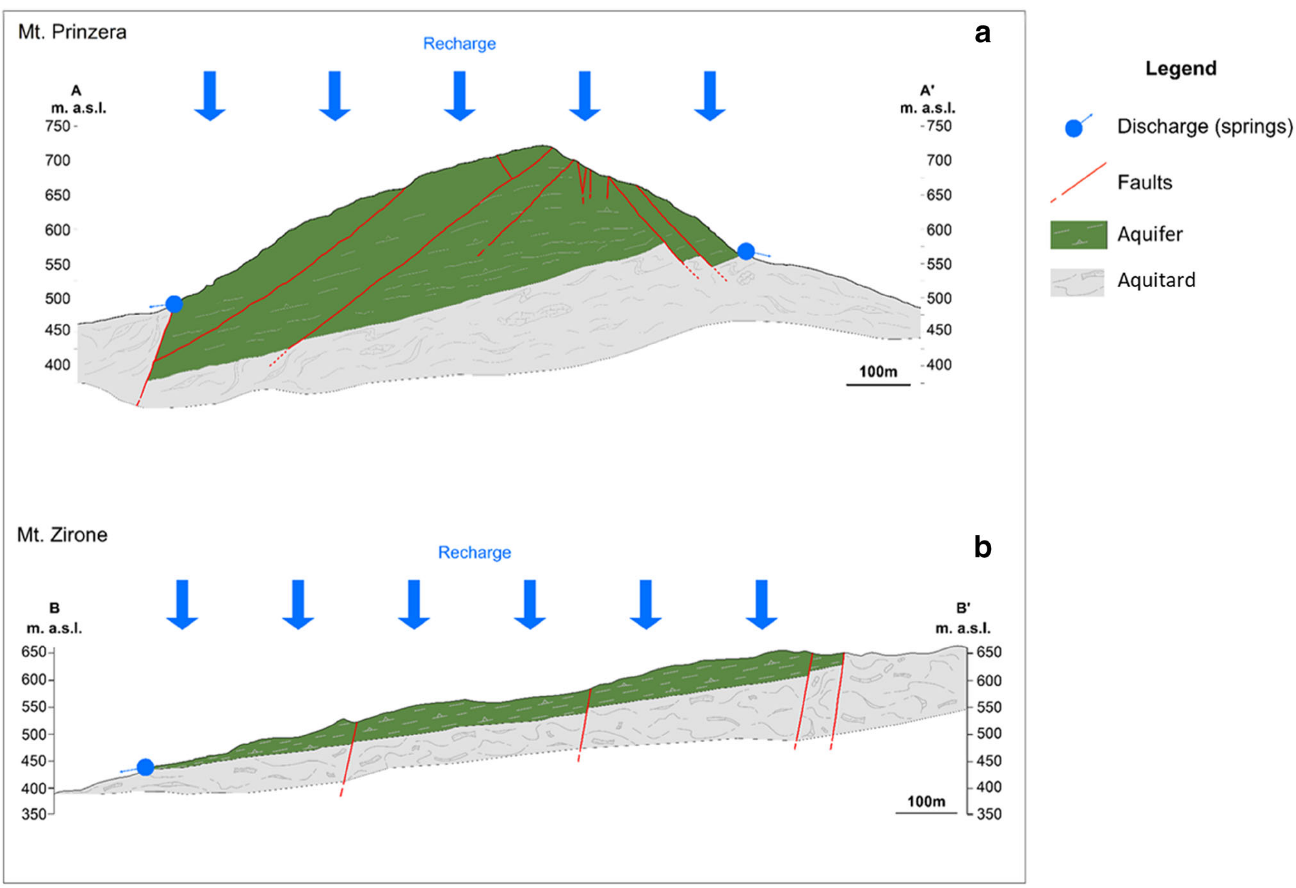

Fig. 4 Hydrogeological conceptual model of the **a** Mt. Prinzera and **b** Mt. Zirone aquifer systems. The traces of the sections are in Fig. 2

Table 1 Classes of recession coefficient α proposed by Gargini et al. (2008) and the A and B values associated to each class

Class	α [day^{-1}]	A	B
1	$>3\times10^{-2}$	13.0	0.99
2	3×10^{-2} to 2×10^{-2}	5.2	0.91
3	2×10^{-2} to 1×10^{-2}	2.6	0.80
4	1×10^{-2} to 6×10^{-3}	1.9	0.92
5	6×10^{-3} to 3×10^{-3}	1.3	0.93
6	$<3\times10^{-3}$	1.2	0.78

$$\mathrm{NRMSD} = \sqrt{1/n}\left[\sum_{i}^{n} = 1\ (Q_{\mathrm{AE}\ i} - Q_{\mathrm{A\ i}})^2\right] / (Q_{\mathrm{A\ max}} - Q_{\mathrm{A\ min}}) \quad (2)$$

where $Q_{\mathrm{A\ max}}$ and $Q_{\mathrm{A\ min}}$ are the maximum and minimum averaged annual flow rates from field measurements, respectively, and n is the number of monitored springs.

Analysis of spring base-flow recession using the Maillet model

The depletion hydrograph of springs and streams is the stage of the hydrograph along which the discharge decreases over time. The literature has been mostly focused on the base-flow recession, i.e. the late stage of the depletion hydrograph when streams are fed exclusively by groundwater discharge with no disturbances from recharge processes. In this stage, the recession behavior is expected to provide information on some intrinsic aquifer features (e.g. Azeez et al. 2015; Tague and Grant 2004).

One of the first studies about base-flow recession hydrographs is that of Boussinesq (1904), who proposed a nonlinear quadratic behavior of aquifer discharge during recession. That model is an exact solution of the diffusion equation (Boussinesq 1877) that describes groundwater flow through a porous medium. The solution is based on the Dupuit-Forcheimer assumptions which represent the first mathematical formulation of the ideal "Dupuit aquifer" (Dupuit 1863; Troch et al. 2013).

An approximation of the exact solution provided by Boussinesq is the linearized model proposed by Maillet (1905). Following Maillet, the relationship between the groundwater discharge of a spring or into a stream and time follow the exponential decay of Eq. (3) in the absence of outer influences such as precipitation, surface storage, groundwater abstraction or evapotranspiration:

$$Q = Q_0\, e^{-\alpha t} \quad (3)$$

where Q and Q_0 are the flow rates (L^3/T) at time t and at the beginning of the base-flow recession stage, respectively, and α is a time constant (T^{-1}) representing storage lag-time. α is related to the time required to halve the base-flow discharge ($t_{0.5}$) and can be expressed as in Eq. (4):

$$\alpha = -[(\ln 0.5)/t_{0.5}] \quad (4)$$

From a mathematical viewpoint, Eq. (3) is probably the most convenient description of base-flow recession among existing models (Dewandel et al. 2003). However, rigorous hydrological analyses applied mostly to streams have demonstrated that the linearized Maillet model is inadequate to describe the whole range of groundwater discharge behaviors during base-flow recession. Semi-logarithmic recession hydrographs of actual rivers are generally concave, suggesting that α is not constant but instead decreases with decreasing groundwater discharge into the stream (Brutsaert and Nieber 1977; Moore 1997; Shaw and Riha 2012; Wittenberg 1994). When analyzing the literature about recession analysis, one has to take into account that the recession hydrograph of a stream can be more complex than that of a spring because stream flow is more subject to interactions with other components of the hydrological cycle such as interflow, precipitation, evapotranspiration acting within the root zone, and river bank filtration, or it may be influenced by the initial moisture conditions of the watersheds (Kirchner 2009; Shaw and Riha 2012). Differently, the base-flow recession hydrograph of a spring is expected to be a mere expression of the averaged hydrogeological features of the discharging aquifer. Because of that, the recession trends of nonkarstic springs are more likely to fit simpler models such as the linearized Maillet solution, compared to streams. For instance, Dewandel et al. (2003) showed that the recession hydrographs of springs fed by ophiolite hard rock aquifers were well reproduced either by the Maillet or the Boussinesq models, depending on aquifer features.

Notwithstanding the limitations associated with the Maillet model, it was decided to use this equation to analyze base-flow recession, for two reasons: (1) the correlation between annual and base-flow discharge proposed by Gargini et al. (2008), which is the object of validation in this study, was built on that model; (2) the model allows a simple and straightforward analysis of recession hydrographs, which is consistent with the deliberately simple approach that is proposed here for recharge estimation. It is worth noting that the recession analysis is performed with the sole scope of arranging the spring hydrographs into different classes (i.e., ranges of α values) representing different "types" of recession behaviors (see previous section). To this scope, a certain degree of approximation caused by linearization may be tolerable. Moreover, the subdivision in recession classes was validated using a second type of analysis: the so-called "recession plot" (Brutsaert and Nieber 1977) which represents another derivation of the quadratic Boussinesq model. In such analysis, the first time derivative of the discharge (dQ/dt) is plotted as a function of mean discharge (Q_m) within the dt interval, on a log-log plot. The relationship is expected to be linear with a variable range of slopes. The analysis has been successfully applied in hydrological studies of stream recession (e.g. Kirchner 2009; Shaw and Riha 2012). The slopes of the recession plots were compared with the α of Maillet to verify if the same arrangement in recession classes proposed by Gargini et al. (2008) was still discernible. More details on the development of recession plots are in the ESM.

For the application of the Maillet model, a time period corresponding to base-flow recession was selected within the two hydrogeologic years covered by the monitoring. In both cases, the recession season was initiated on July 1st and lasted up until the end of the hydrogeologic year, in analogy with the recession period previously considered by Gargini et al. (2008). The choice to fix a "standard" beginning of the recession season to July 1st (regardless to the specific shape of each hydrograph) was made to test the feasibility of proposing a standard monitoring period for the estimation of recharge in climate zones similar to that of the Northern Apennines. As a first step, the recession hydrographs were handled to minimize disturbances from significant recharge events. In particular, only the progressively decreasing values of discharge were considered, making sure to keep at least three measurements for each spring. Attention was also paid to obtain a good fit of the Q data along an exponential trend line with $R^2 > 0.90$. The Maillet coefficient α was extracted from the equation of the same exponential trend line.

Results and discussion

Prediction of averaged annual flow rates

A hydrogeologic year was identified between 25 October 2012 and 28 August 2013 at Mt. Prinzera and between 17 October 2016 and 7 September 2017 at Mt. Zirone. Q_A values in the range of 0.04 to 2.69 L/s and of 0.11 to 1.42 L/s were determined from field measurements at Mt. Prinzera and Mt. Zirone, respectively, whereas Q_S values ranged between 0.01 and 0.85 L/s at Mt. Prinzera and between 0.04 and 1.30 L/s at Mt. Zirone (Table 2). The complete data-set of Q measurements is in the ESM together with the complete spring hydrographs and rainfall data from preexisting meteorological stations. Recession analysis with the Maillet model was performed on each spring hydrograph (Fig. 5) to determine α and the corresponding A and B parameters that drive the correlation between Q_A and Q_S.

Table 2 Results from summer recession analysis at the springs of Mt. Prinzera and Mt. Zirone with measured and predicted annual flow rates (Q_A and Q_{AE}, respectively). Values in *italic* are totals

Aquifer	Spring	α [day^{-1}]	Class	Q_S (L/s)	Q_A (L/s)	Q_{AE} (L/s)
Mt. Prinzera	P01	1.00×10^{-2}	3	0.848	2.689	2.279
	P02	9.00×10^{-3}	4	0.078	0.224	0.182
	P03	1.66×10^{-2}	3	0.033	0.250	0.170
	P04	2.66×10^{-2}	2	0.024	0.172	0.177
	P05	2.70×10^{-2}	2	0.077	0.375	0.505
	P06	2.50×10^{-3}	6	0.029	0.038	0.076
	P07	3.70×10^{-3}	5	0.012	0.045	0.021
	Total:			*1.101*	*3.793*	*3.409*
Mt. Zirone	Z01	1.75×10^{-2}	3	0.084	0.141	0.358
	Z02	2.65×10^{-2}	2	0.036	0.113	0.251
	Z03	4.33×10^{-2}	1	0.114	0.482	0.151
	Z04	2.90×10^{-3}	6	1.304	1.421	1.476
	Z05	7.60×10^{-3}	4	0.075	0.150	0.175
	Total:			*1.612*	*2.306*	*2.411*

All the seven springs fed by the Mt. Prinzera aquifer, except for P01, had at least one out of seven measurements of Q excluded from the recession analysis. In particular, the Q measurement of 14 July showed a deviation from the recession trend (increasing Q compared to the previous measurement) in the hydrographs of P02–P07, most likely induced by the rainfall events between 11 and 14 July (35 mm in total; see ESM). For springs P02 and P07, one and two other Q values were excluded from the analysis, respectively, for the same reason as already mentioned. In spring P05, a decreasing trend of four consecutive Q measurements was identified starting from 21 July; the former three values were excluded because they did not follow a decreasing trend. In general, the recession hydrographs of Mt. Prinzera suggest that all the springs, with the exception of P01, are responsive to rainfall events occurring during the low-flow season, likely because these are connected to shallower groundwater flow systems with a lower bulk discharge compared to spring P01.

Six measurements of Q were performed at the five springs of Mt. Zirone during the low-flow season. In springs Z01, Z02 and Z04, the Q measurements of 15 and 25 July were excluded from the recession analysis since these are higher than the preceding Q value on the hydrograph. These anomalies are likely related to the rainfall events between 11 and 14 July (38 mm in total), and that of 24 June (10 mm). In the case of spring Z05, the Q values deviating from the decreasing trend and excluded from the analysis are that of 25 July and 8 August. The deviation of 8 August may be related to a local rainfall not detected by the available pluviometers. Spring Z03 shows a decreasing trend of three consecutive Q measurements starting from 25 July; the former three values on the

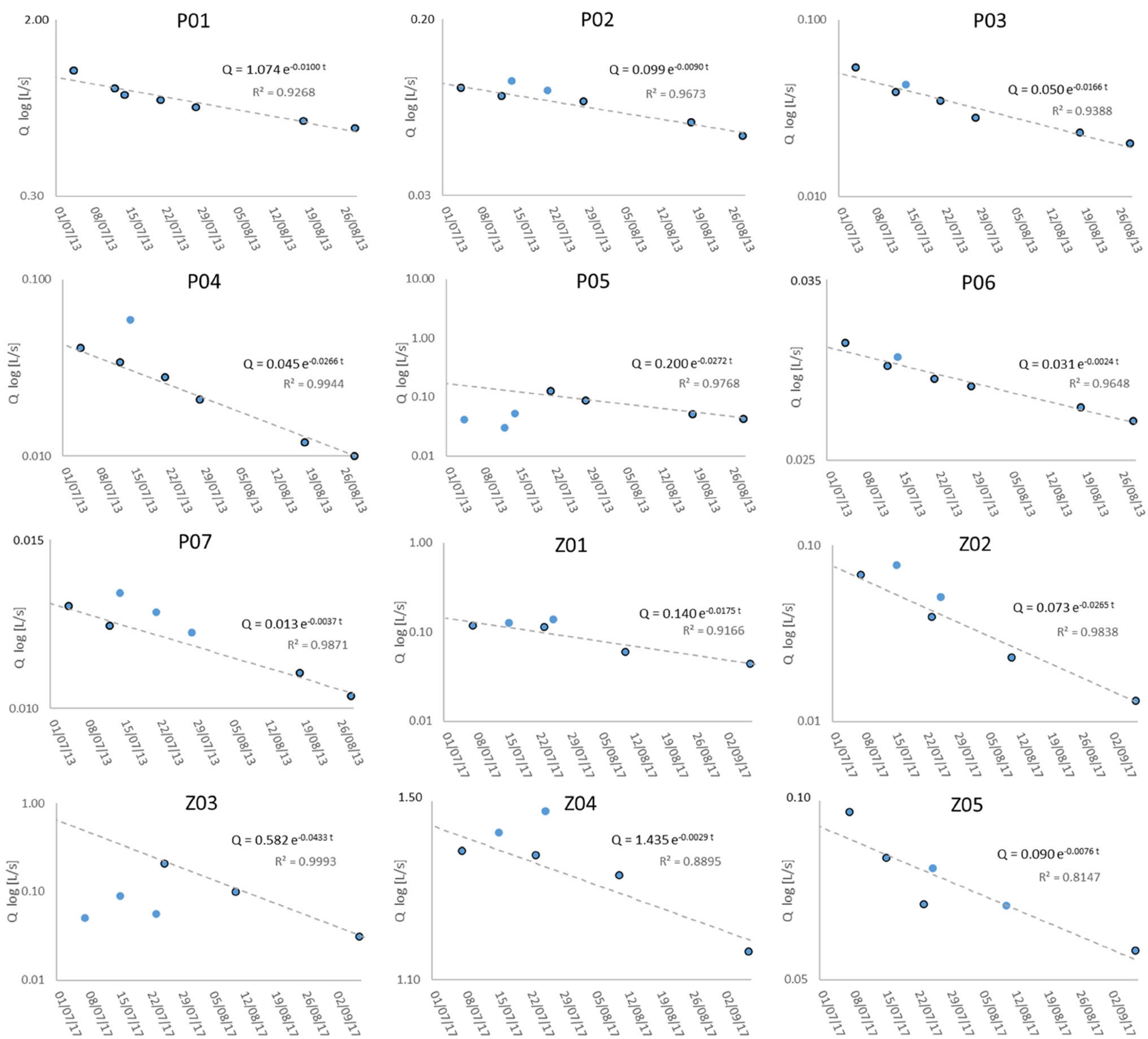

Fig. 5 Analysis of the base flow recession hydrographs of the springs of Mt. Prinzera and Mt. Zirone using the Maillet model. The blue dots bordered in black are that selected for the analysis

hydrograph were not considered since they do not follow a decreasing trend. In general, the recession hydrographs of the springs of Mt. Zirone appear less smooth compared to Mt. Prinzera. This is also reflected by the lower degree of correlation of the Q measurements on the semi-log plots, with Z04 and Z05 showing a R^2 of 0.89 and 0.81, respectively, marginally below the fixed threshold of 0.90. This may be due to a higher reactivity to rainfall events in the Mt. Zirone aquifer compared to Mt. Prinzera, possibly driven by some intrinsic features of the aquifer, e.g. smaller aquifer basin and/or higher permeability, shallower and/or faster recharge pathways. Alternatively, the less frequent and more abundant rainfall events of the summer 2017 (Mt. Zirone monitoring) may have caused more significant deviations of Q from the decreasing recession trend, compared to summer 2013 (Mt. Prinzera monitoring). In particular, 13 days of rainfall were registered out of 69 with an average of 14 mm/day during the summer of the hydrogeologic year 2016–2017, whereas during the summer of year 2012–2013, rainfall events occurred on 17 out of 58 days with an average of 6 mm/day. Nevertheless, such interannual variability was considered as an opportunity to verify the effectiveness of the proposed method in different meteorological conditions.

The Maillet coefficient α ranges between 2.7×10^{-2} and 3.0×10^{-3} days^{-1} in the springs of Mt. Prinzera and between 4.3×10^{-2} and 3.0×10^{-3} days^{-1} in the springs of Mt. Zirone. In Table 2, each spring is ranked according to the classes of α identified by Gargini et al. (2008). The coefficient α of each spring was compared with the slope of the recession plot (S) of the same spring, showing a good linear correlation between the two on a log-log plot with R^2 of 0.87 (Fig. 6). The comparison suggests that the classes of α proposed by Gargini et al. (2008) are still discernible when considering the slope of a recession plot. Because of this observation, the Maillet model is considered to be a proper tool for identifying classes of recession behavior in the type of springs that are investigated within this research.

The values of Q_{AE} range between 0.02 and 2.28 L/s at Mt. Prinzera and between 0.15 and 1.48 L/s at Mt. Zirone. A comparison between Q_A and Q_{AE} is shown in Fig. 7. In the case of Mt. Prinzera, the NRMSD between Q_A and Q_{AE} is 6.3%, suggesting an overall good prediction. P06 and P07 are the springs where Q_A and Q_{AE} show the greatest differences compared to absolute values of averaged annual discharge. It is worth noting that these are the springs with the lowest averaged annual flow rates in the Mt. Prinzera area, in the order of 1×10^{-2} L/s, and the Q measurements in the field were likely affected by a higher relative error compared to the other springs. At Mt. Zirone, Q_A and Q_{AE} show larger differences between each other compared to the springs of Mt. Prinzera, with an NRMSD of 14.5%. The noisier summer hydrographs typically observed in the Mt. Zirone springs along with the smaller number of available Q measurements compared to Mt. Prinzera may have lead to higher uncertainties in the Q_{AE} prediction. In the case of Mt. Zirone, a continuous monitoring of flow rates (or a higher frequency of discontinuous measurements) may have helped increase the accuracy of Q_S estimates and the consequent prediction of Q_{AE}.

The sum of Q_A in the springs of Mt. Prinzera is equal to 3.79 L/s, whereas the sum of Q_{AE} is 3.41 L/s, with a small difference between the two of 0.38 L/s. In the case of Mt. Zirone, the sum of Q_A and Q_{AE} is respectively 2.31 and 2.41 L/s, with a difference of 0.11 L/s.

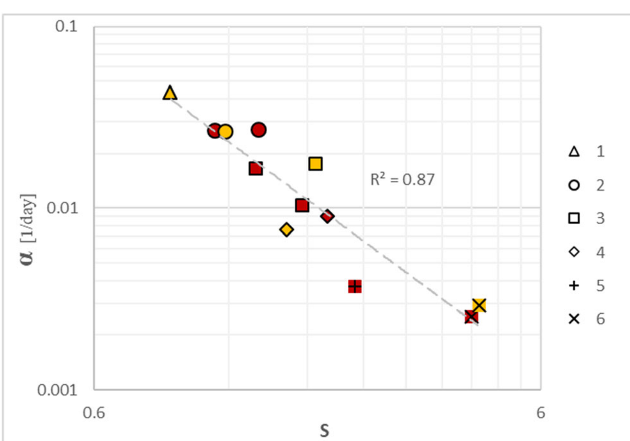

Fig. 6 Comparison between the coefficient α of Maillet and the slope S of the recession plot. The "recession classes" are identified with different symbol shapes. The springs of Mt. Prinzera and Mt. Zirone are depicted with red and yellow symbols, respectively

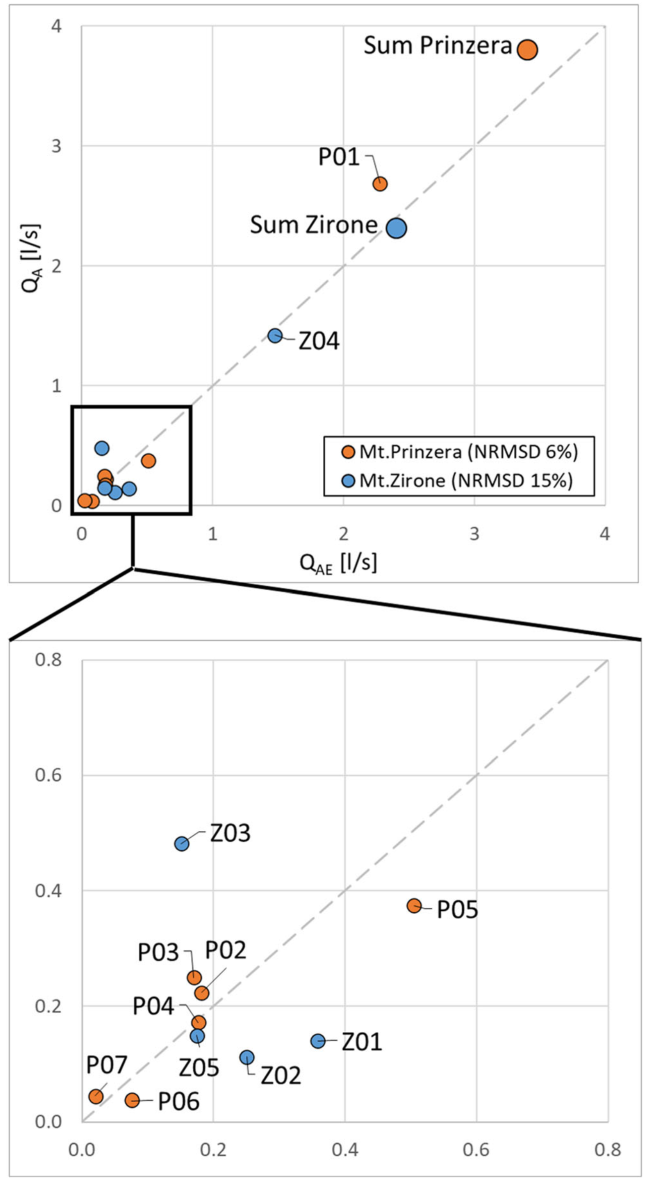

Fig. 7 Comparison between measured and predicted averaged annual flow rates (Q_A and Q_{AE}, respectively) at the springs of Mt. Prinzera and Mt. Zirone

Estimation of aquifer recharge

Since the monitored springs of Mt. Prinzera and Mt. Zirone are the discharge outlets of a well-delimited aquifer system, the sum of averaged annual discharges of the two groups of springs over their catchment area corresponds to the recharge ("R" from now on) of the aquifer, assuming a steady-state condition over the hydrogeologic year. Such a condition is plausible in the presence of short and relatively quick groundwater flow paths from the recharge area to the discharge points. Short and quick flow paths were inferred in the two aquifers based on the temperature and electrical conductivity of spring water (see data of T and EC in the ESM). In detail, the average annual water temperature ranges between 10.3 and 12.5 °C at the springs of Mt. Prinzera and between 10.4 and 12.5 °C at the springs of Mt. Zirone, showing values very similar or slightly lower than the average annual air temperature measured at the selected meteorological stations (12.0 °C in hydrogeologic year 2012–2013 and 12.5 °C in 2016–2017, respectively for Mt. Prinzera and Mt. Zirone). Shallow groundwater temperature is expected to be 1 to 2 °C higher than the average annual air temperature (Anderson 2005; Benz et al. 2017). If the temperature of groundwater discharging from springs is similar to air, it likely means that the temperature signal of the recharging water is preserved down to the discharge points, which can be explained assuming short and shallow flow paths through the aquifer. The average annual EC of spring water ranges between 281 and 474 µS/cm at Mt. Prinzera and between 218 and 522 µS/cm at Mt. Zirone. Such values are in the low range of EC previously observed in literature for groundwater in ophiolitic aquifers (typically up to 2,000 µS/cm; e.g. Abdalla et al. 2016; Dewandel et al. 2005; Güler et al. 2017), suggesting a short groundwater–rock interaction time. In particular, EC values <850 µS/cm are representative of quick shallow groundwater circulation following Dewandel et al. (2005).

For the estimation of R, a total catchment area of 771,478 m^2 was considered for Mt. Prinzera and of 534,000 m^2 for Mt. Zirone (i.e. the extent of the ophiolitic outcrops), whereas the monitored hydrogeologic years lasted for 307 and 325 days, respectively. R values of 130 and 117 mm throughout the hydrogeologic year was estimated for the Mt. Prinzera from Q_A and Q_{AE}, respectively, whereas at Mt. Zirone R values of 121 and 127 mm were derived from Q_A and Q_{AE}, respectively. In both settings, estimation of R from Q_A or Q_{AE} shows small differences (13 mm at Mt. Prinzera, corresponding to the 10.6% of averaged R, and 6 mm for Mt. Zirone, equal to 4.5% of averaged R).

The values of R are consistent with that estimated from an annual water budget in the two aquifers (R_{wb}; see ESM), when assuming a much higher infiltration potential at Mt. Zirone compared to Mt. Prinzera. Such higher infiltration is justified by a more pronounced stress-release condition (testified by rock slope deformations and fractures with larger aperture and higher persistence) and a higher percent of bedrock outcrop at Mt. Zirone compared to Mt. Prinzera, as discussed in section S6 of the ESM.

A coefficient of infiltration (C) was estimated for the two aquifers of Mt. Prinzera and Mt. Zirone corresponding to the ratio between R throughout the monitored hydrogeologic years (derived by Q_A or Q_{AE}) and the precipitation over the aquifer catchment during the same time span (P, equal to 1,011 and 632 mm, from Mt. Prinzera and Mt. Zirone, respectively; see ESM). The estimated C values are 0.13 or 0.12 at Mt. Prinzera, and 0.19 or 0.20 at Mt. Zirone, starting from Q_A or Q_{AE}, respectively. The higher C values detected for Mt. Zirone compared to Mt. Prinzera are consistent with the observed higher reactivity to rainfall events for Mt. Zirone, suggesting a higher hydraulic conductivity or the occurrence of faster or preferential recharge pathways compared to Mt. Prinzera. The hypothesis is also consistent with the formerly inferred higher infiltration potential compared to Mt. Prinzera. The values of C estimated for Mt. Prinzera and Mt. Zirone are similar to that experimentally derived for Northern Apennine turbiditic aquifers by various authors, ranging between 0.13 and 0.17 (Gargini et al. 2014; Piccinini et al. 2013; Vincenzi et al. 2014). Such similarity in terms of hydrodynamic properties also enhances the idea that the turbiditic units in the Northern Apennines behave as hard rock aquifers as much as peridotitic ophiolites.

Major shortcomings of the proposed method for aquifer recharge estimation

Spring discharge distribution along the hydrogeologic year

The proposed correlation between Q_A and Q_S was observed and validated on spring hydrographs typical of fractured aquifers without significant heterogeneities at the catchment scale, in a Mediterranean climate. In such settings, the spring hydrographs are most typically characterized by an overall high discharge period with several peaks during fall, winter, and early spring, followed by a generalized decrease of discharge down to base-flow recession in late-spring and summer. The methodology described in detail in section 'Analysis of spring base-flow recession using the Maillet model' is tailored over this type of discharge pattern. A different spring discharge distribution, e.g. with several maxima and base-flow recessions per hydrogeologic year, may be expected in different climates and/or in aquifers with highly heterogeneous properties at the scale of the catchment (e.g. karst aquifers). Further investigations are needed to assess whether the proposed method could be employed on spring discharge hydrographs different than that described in the preceding.

Shape of the base-flow recession hydrograph

The proposed correlation between Q_A and Q_S is driven by the Maillet model that describes an exponential decay of discharge during the base flow recession. Any deviation from the exponential decay pattern, e.g. discharge peaks caused by significant recharge events during the low flow season, may hamper the identification of a Maillet coefficient α representative of the spring behavior thus decreasing the reliability of the annual discharge estimate. For example, the relatively poor fit between Q_A and Q_{AE} observed at Mt. Zirone is likely attributable to the noisy recession hydrographs that challenged the identification of α, as widely discussed in section 'Prediction of averaged annual flow rates'. In the occurrence of springs highly reactive to single recharge events, the issue of noisy hydrographs may be partly mitigated by increasing the frequency of discharge measurements so that any transitory deviation from the recession trend could be identified and conveniently managed.

Assumption of steady-state flow at the scale of the hydrogeologic year

The proposed approach for aquifer recharge estimation grounds on the assumption of a steady-state condition between aquifer recharge and spring discharge over the hydrogeologic year. Such a condition can be considered broadly valid in relatively small catchments where the main groundwater flow paths are rather quick, which is often the case of mountain hard-rock aquifers composed of fractured permeable materials of limited extent and thickness laying over an impermeable bedrock. In the case of larger aquifers where longer residence times must be considered, the correlation between Q_A and Q_S cannot be exploited for the estimation of aquifer recharge.

Conclusions

The empirical correlation proposed by Gargini et al. (2008) between the average annual discharge of a spring and its average discharge during base-flow recession was applied to two ophiolitic aquifer systems with well-defined hydrogeologic boundaries and well-identified discharge outlets (springs) at the aquifer-aquitard boundaries. The method provided a reliable estimate of average annual discharges starting from few field measurements in the low flow season, thus confirming the validity of the correlation for hard rock aquifers in a dry summer climate, regardless to bedrock lithology. The adequacy of the Maillet coefficient α to discriminate among recession behaviors of springs was tested through a comparison between α and the slope of the so-called "recession plots". The comparison proved that the different discharge behaviors inferred using α are still discernible when analyzing the spring recession hydrographs with a model different than that of Maillet.

Since the two investigated aquifers are "close" systems with quick groundwater circulation inferable from temperature and electrical conductivity of the spring water, the average annual discharge of springs was assumed equal to the annual aquifer recharge over the spring catchment and used to estimate coefficients of infiltration for the aquifers which turned out to be consistent with that of other fractured aquifers in the same area.

The proposed correlation would significantly reduce the time and logistic efforts for aquifer recharge estimate in mountain areas, thus supporting the application of groundwater budgets and the assessment of climate change effects on the groundwater resource.

Notwithstanding the overall good predictions obtained at the Mt. Prinzera and Mt. Zirone aquifers, the proposed method is still affected by a few shortcomings that should be carefully considered for a broader applicability, i.e. distribution of spring discharge over the hydrogeologic year, need for an "undisturbed" base-flow recession hydrograph, and the annual steady-state assumption. Further tests are needed to verify the reliability of the proposed correlation in different hard rock settings, either in similar climate zones or in regions with different seasonal variations along the hydrogeologic year (e.g. in Alpine-like settings where the low flow season is in winter).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10040-021-02317-z.

Acknowledgements We acknowledge the two anonymous reviewers and the editor for providing insightful suggestions that improved the quality of the manuscript.

Funding Open access funding provided by Alma Mater Studiorum - Università di Bologna within the CRUI-CARE Agreement.

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Estimation of recharge in mountain hard-rock aquifers based on discrete spring discharge monitoring during base-flow recession

Stefano Segadelli[a], Maria Filippini[b] *, Anna Monti[b], Fulvio Celico[c], Alessandro Gargini[b]

[a] Geological, Seismic and Soil Service, Emilia-Romagna Region Administration, Bologna, Italy

[b] Department of Biological, Geological, and Environmental Sciences - BiGeA, Alma Mater Studiorum University of Bologna, via Zamboni, 67, 40126; Bologna, Italy, maria.filippini3@unibo.it

[c] Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Italy

* Corresponding author

HYDROGEOLOGY JOURNAL – ELECTRONIC SUPPLEMENTARY MATERIAL

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S1. Discharge, temperature and electric conductivity measurements at the springs of Mt. Prinzera and Mt. Zirone

		P01			P02			P03			P04			P05			P06			P07			
		Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	days after previous measure
Fall	25/10/2012	0.666	12.6	372	0.302	13.1	395	0.165	12.0	372	0.038	13.2	540	0.153	13.1	311	0.037	12.4	310	0.069	14.2	322	\
	27/10/2012	0.915	12.5	408	0.650	13.2	427	0.163	12.0	377	0.140	13.0	636	0.190	13.0	364	0.043	12.3	307	0.110	13.8	373	2
	30/10/2012	1.652	12.0	446	0.517	13.2	354	0.530	11.8	350	0.138	12.0	624	0.846	13.2	373	0.041	12.1	316	0.093	12.9	366	3
	02/11/2012	2.272	11.9	454	0.524	13.4	347	0.688	11.8	347	0.191	12.5	592	0.660	13.4	351	0.040	12.3	312	0.111	12.6	365	3
	06/11/2012	2.350	11.7	457	0.479	13.3	355	0.540	11.7	344	0.184	12.8	540	0.734	13.4	355	0.039	12.3	314	0.103	12.9	360	4
	09/11/2012	1.953	11.5	449	0.353	13.2	370	0.363	11.7	345	0.172	12.4	511	0.390	13.2	331	0.038	12.1	313	0.097	12.5	344	3
	16/11/2012	2.126	11.4	444	0.575	13.1	384	0.464	11.6	353	0.241	12.2	541	0.511	13.0	343	0.042	12.2	315	0.120	12.1	368	7
	24/11/2012	2.108	11.2	400	0.217	13.0	374	0.233	11.7	333	0.146	12.0	459	0.242	12.7	288	0.060	12.4	318	0.089	11.9	309	8
	30/11/2012	5.240	11.1	419	0.379	12.9	357	0.420	11.5	346	0.200	11.0	482	0.872	12.6	308	0.042	12.2	304	0.142	11.3	378	6
	03/12/2012	4.490	10.9	418	0.532	12.8	375	0.520	11.5	337	0.320	10.5	515	1.100	12.4	350	0.051	12.1	310	0.150	10.6	383	3
	11/12/2012	3.660	10.5	407	0.433	12.7	366	0.340	11.6	346	0.210	9.5	486	0.754	12.1	311	0.041	12.1	306	0.131	10.0	373	8
	23/12/2012	2.892	10.4	378	0.117	12.6	384	0.180	11.6	357	0.100	10.7	466	0.213	11.8	296	0.036	12.0	304	0.076	9.5	315	12
	29/12/2012	2.187	10.3	368	0.099	12.4	380	0.141	11.6	354	0.089	10.3	459	0.130	11.5	286	0.035	12.0	304	0.068	9.5	312	6
Fall average		2.501	11.4	417	0.398	13.0	374	0.365	11.7	351	0.167	11.7	527	0.523	12.7	328	0.042	12.2	310	0.105	11.8	351	
Winter	05/01/2013	2.296	10.3	368	0.091	12.3	370	0.131	11.7	346	0.081	11.0	444	0.260	11.7	297	0.037	12.1	301	0.090	9.4	344	7
	12/01/2013	2.218	10.3	355	0.087	12.1	366	0.128	11.7	340	0.057	9.6	436	0.103	11.4	280	0.035	11.9	305	0.084	9.5	318	7
	18/01/2013	2.018	10.0	353	0.148	12.1	346	0.240	11.7	350	0.113	8.9	446	0.530	11.2	330	0.039	11.9	308	0.096	9.0	322	6
	25/01/2013	2.934	10.1	389	0.219	12.2	359	0.403	11.7	360	0.169	9.6	457	0.801	11.0	350	0.042	11.9	312	0.115	8.7	332	7
	31/01/2013	2.703	10.0	394	0.212	12.4	331	0.316	11.6	337	0.272	10.5	472	0.700	10.2	313	0.040	11.7	289	0.050	8.5	317	6
	09/02/2013	4.193	9.8	377	0.156	12.2	320	0.364	11.6	319	0.237	10.2	423	0.332	9.1	284	0.038	11.6	285	0.018	7.9	295	9
	16/02/2013	3.306	9.6	364	0.134	12.1	313	0.292	11.6	310	0.210	10.0	412	0.229	9.0	270	0.037	11.5	280	0.017	6.7	292	7
	22/02/2013	2.083	9.5	344	0.113	11.9	322	0.189	11.5	316	0.174	9.1	407	0.356	8.9	303	0.038	11.3	297	0.030	5.6	310	6
	28/02/2013	1.945	9.6	365	0.190	12.1	335	0.220	11.5	342	0.209	10.2	423	0.488	9.0	317	0.039	11.6	295	0.018	5.6	307	6
	08/03/2013	5.156	9.9	389	0.254	12.3	324	0.512	11.6	334	0.365	10.6	431	0.713	8.7	343	0.044	11.7	292	0.020	6.1	314	8
	15/03/2013	4.746	9.8	374	0.236	12.3	319	0.353	11.5	340	0.248	10.8	425	0.553	7.9	305	0.042	11.4	293	0.015	6.7	305	7
	19/03/2013	5.597	9.8	388	0.397	12.1	350	0.731	11.5	353	0.624	11.0	434	0.923	8.0	321	0.048	11.5	300	0.020	6.9	317	4
	22/03/2013	4.395	9.8	377	0.321	12.1	291	0.646	11.5	324	0.548	11.2	425	0.776	8.1	297	0.043	11.7	295	0.011	7.8	313	3
	29/03/2013	5.899	9.7	368	0.274	12.1	310	0.382	11.4	315	0.359	10.9	413	0.760	7.6	273	0.042	11.5	292	0.010	7.4	303	7
Win. Average		3.535	9.9	372	0.202	12.2	333	0.351	11.6	335	0.262	10.3	432	0.537	9.4	306	0.040	11.7	296	0.042	7.6	314	
Spring	03/04/2013	6.400	10.2	384	0.423	12.1	284	0.670	11.4	319	0.520	11.5	416	1.010	7.8	287	0.043	11.4	302	0.012	8.5	313	5
	06/04/2013	6.532	10.0	384	0.514	12.0	301	0.751	11.4	323	0.680	11.0	419	1.110	7.2	295	0.044	11.4	306	0.014	7.9	320	3
	10/04/2013	5.569	10.2	386	0.347	12.0	290	0.390	11.4	318	0.530	12.0	413	0.900	7.3	263	0.042	11.3	302	0.011	9.5	306	4
	13/04/2013	6.092	10.4	384	0.279	12.1	305	0.330	11.5	324	0.420	12.1	423	0.556	7.4	258	0.040	11.3	300	0.013	9.8	308	3
	16/04/2013	7.023	10.6	382	0.211	12.1	321	0.272	11.5	331	0.320	12.1	434	0.213	7.6	251	0.038	11.3	307	0.014	12.0	311	3
	19/04/2013	5.112	10.7	377	0.185	12.2	329	0.232	11.5	335	0.267	12.5	436	0.134	7.8	252	0.037	11.2	310	0.052	12.8	312	3
	23/04/2013	4.184	10.8	375	0.194	12.2	326	0.216	11.5	336	0.178	12.1	444	0.464	7.6	254	0.041	11.0	308	0.051	12.1	310	4
	26/04/2013	3.673	10.9	374	0.189	12.2	329	0.221	11.5	333	0.172	13.2	447	0.420	8.6	256	0.042	11.0	307	0.045	13.3	309	3
	30/04/2013	3.302	11.1	373	0.184	12.2	332	0.227	11.5	336	0.166	12.6	450	0.375	8.3	258	0.043	11.1	306	0.040	12.7	307	4
	04/05/2013	3.061	11.1	370	0.168	12.2	338	0.199	11.6	341	0.154	13.6	457	0.270	8.9	255	0.041	11.1	307	0.027	13.7	305	4
	09/05/2013	3.358	11.3	375	0.154	12.2	344	0.171	11.6	346	0.143	12.9	465	0.175	8.4	253	0.039	11.0	308	0.015	14.9	302	5
	15/05/2013	3.179	11.4	367	0.140	12.3	349	0.153	11.6	349	0.137	12.4	458	0.170	8.4	260	0.038	11.0	301	0.014	15.1	299	6
	19/05/2013	3.425	11.4	366	0.182	12.2	331	0.204	11.6	343	0.132	12.3	463	0.478	8.6	260	0.044	11.2	302	0.015	14.2	301	4
	23/05/2013	2.940	11.3	366	0.170	12.1	334	0.193	11.5	344	0.123	12.3	477	0.287	8.6	250	0.042	11.2	303	0.014	13.9	297	4
	28/05/2013	2.466	11.3	366	0.159	12.1	338	0.182	11.5	345	0.114	12.4	487	0.274	8.7	241	0.039	11.2	305	0.014	13.7	294	5
	04/06/2013	2.207	11.4	363	0.150	12.3	345	0.130	11.7	361	0.099	13.0	491	0.122	8.9	238	0.037	11.3	303	0.014	14.1	291	7
	12/06/2013	1.939	11.5	360	0.138	12.4	353	0.096	11.8	367	0.079	12.8	497	0.074	9.0	234	0.036	11.3	301	0.014	14.5	289	8
	20/06/2013	1.663	11.6	357	0.124	12.7	359	0.079	12.0	370	0.061	13.5	502	0.060	9.9	230	0.033	11.5	298	0.013	15.7	287	8
	29/06/2013	1.419	11.3	355	0.108	12.6	364	0.061	12.1	374	0.084	13.3	506	0.054	10.2	224	0.032	11.7	299	0.013	15.2	284	9
Spr. Average		3.871	11.0	372	0.212	12.2	330	0.251	11.6	342	0.230	12.5	457	0.376	8.4	254	0.040	11.2	304	0.021	12.8	302	
Summer	04/07/2013	1.156	11.4	341	0.096	12.7	373	0.054	12.3	380	0.041	13.8	508	0.042	10.8	221	0.031	11.9	297	0.013	16.0	282	5
	12/07/2013	0.958	11.6	348	0.088	12.9	386	0.039	12.4	393	0.034	15.2	513	0.030	11.2	218	0.030	12.0	295	0.012	16.6	280	8
	14/07/2013	0.892	11.7	345	0.103	13.0	388	0.043	12.5	402	0.059	16.7	518	0.053	12.2	222	0.030	12.0	297	0.013	17.6	285	2
	21/07/2013	0.845	11.9	343	0.093	13.1	386	0.035	12.6	397	0.028	15.7	514	0.125	12.8	219	0.029	12.2	295	0.013	17.7	283	7
	28/07/2013	0.784	12.0	341	0.083	13.4	383	0.028	12.9	392	0.021	15.9	509	0.088	13.0	218	0.029	12.0	294	0.012	17.5	280	7
	18/08/2013	0.676	12.2	340	0.066	13.5	380	0.023	12.8	386	0.012	16.5	498	0.052	13.2	215	0.028	11.7	291	0.011	18.2	278	21
	28/08/2013	0.625	12.5	338	0.057	13.8	378	0.020	13.0	383	0.010	17.9	493	0.043	13.4	214	0.027	11.4	290	0.010	19.0	276	10
Sum. Average		0.848	11.9	342	0.084	13.2	382	0.035	12.6	390	0.029	16.0	508	0.062	12.4	218	0.029	11.9	294	0.012	17.5	281	
Year Average		3.060	10.9	379	0.240	12.5	348	0.279	11.7	348	0.198	12.1	474	0.417	10.2	282	0.039	11.7	302	0.047	11.8	315	

Table S1 – Discharge (Q), temperature (T) and electrical conductivity (EC) measurements at the springs of Mt. Prinzera along the hydrogeologic year 2012-2013 (the Q measures selected for summer recession analysis are highlighted in red).

		Z01			Z02			Z03			Z04			Z05			
		Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	days after previous measure
Fall	17/10/2016	0.135	12.1	333	0.111	12.4	644	0.800	8.9	420	0.907	11.7	228	0.047	14.7	434	\
	27/10/2016	0.140	12.1	328	0.286	12.3	648	0.408	9.5	445	1.010	11.7	226	0.121	14.8	532	10
	31/10/2016	0.129	12.1	324	0.169	12.2	617	0.310	8.8	470	0.991	11.7	227	0.072	14.1	478	4
	08/11/2016	0.364	12.3	331	0.326	12.2	568	0.422	8.1	468	1.835	11.6	233	0.241	13.8	544	8
	15/11/2016	0.175	12.3	321	0.092	11.9	573	0.333	8.0	500	1.508	11.5	225	0.221	13.1	475	7
	22/11/2016	0.200	12.2	325	0.097	11.6	566	0.343	8.1	530	1.662	11.5	225	0.228	12.8	470	7
	29/11/2016	0.178	12.1	322	0.070	11.4	587	0.371	7.4	537	1.612	11.4	224	0.210	12.5	464	7
	09/12/2016	0.164	12.1	323	0.050	11.2	572	0.392	6.9	539	1.750	11.4	222	0.189	12.3	478	10
	14/12/2016	0.148	12.0	325	0.038	11.0	532	0.628	7.2	525	1.760	11.4	220	0.176	12.1	474	5
	22/12/2016	0.157	12.0	314	0.097	10.6	528	0.526	6.0	543	1.737	11.4	214	0.195	11.9	509	8
	30/12/2016	0.149	11.9	326	0.063	10.4	529	0.353	4.7	540	1.615	11.2	221	0.152	11.4	470	8
Fall average		0.176	12.1	325	0.127	11.6	579	0.444	7.6	502	1.490	11.5	224	0.168	13.0	484	
Winter	10/01/2017	0.130	11.5	321	0.042	9.8	508	0.427	4.3	528	1.458	11.1	219	0.130	10.8	466	11
	17/01/2017	0.121	11.4	319	0.031	9.4	498	0.410	4.5	500	1.372	11.1	216	0.120	10.5	464	7
	31/01/2017	0.111	11.4	304	0.020	9.2	468	0.405	5.1	480	1.229	11.1	207	0.112	10.1	443	14
	07/02/2017	0.380	11.5	324	1.054	8.5	480	3.720	5.1	435	2.030	11.1	223	0.531	8.7	522	7
	14/02/2017	0.190	11.5	321	0.380	8.9	470	0.913	6.1	478	1.608	11.0	213	0.236	10.1	453	7
	21/02/2017	0.153	11.4	310	0.113	8.7	466	0.843	6.8	489	1.501	11.0	215	0.223	10.2	442	7
	28/02/2017	0.133	11.3	303	0.093	8.8	466	0.750	7.3	472	1.431	11.0	215	0.236	10.4	438	7
	07/03/2017	0.163	11.2	313	0.117	8.8	506	1.080	7.3	499	1.537	10.9	218	0.257	10.3	477	7
	15/03/2017	0.168	11.2	319	0.134	8.8	502	0.793	7.5	505	1.502	10.9	221	0.209	10.7	446	8
	20/03/2017	0.147	11.2	317	0.125	9.0	508	0.653	8.1	504	1.466	11.0	218	0.203	10.8	444	5
	30/03/2017	0.142	11.1	322	0.122	9.0	524	0.832	9.4	509	1.458	10.9	220	0.193	11.5	457	10
Win. average		0.167	11.3	316	0.203	9.0	491	0.984	6.5	491	1.508	11.0	217	0.223	10.4	459	
Spring	06/04/2017	0.130	11.1	321	0.110	9.2	514	0.675	9.8	514	1.431	10.9	219	0.182	11.3	451	7
	11/04/2017	0.124	11.1	318	0.091	9.3	513	0.580	9.8	506	1.374	11.0	216	0.169	11.4	436	5
	18/04/2017	0.119	11.1	317	0.080	9.9	509	0.488	9.9	509	1.337	11.0	215	0.152	11.6	437	7
	28/04/2017	0.116	10.9	316	0.070	9.6	507	0.368	9.4	498	1.256	10.9	215	0.136	11.8	438	10
	08/05/2017	0.199	11.0	322	0.188	10.2	518	0.686	10.4	515	1.417	11.0	218	0.180	12.0	455	10
	12/05/2017	0.155	11.0	322	0.099	10.4	510	0.612	10.6	511	1.357	11.0	216	0.141	12.1	448	4
	19/05/2017	0.120	11.1	320	0.054	10.3	504	0.450	12.0	495	1.301	11.1	216	0.125	12.4	438	7
	26/05/2017	0.096	11.1	318	0.030	10.4	501	0.305	13.5	480	1.251	11.1	215	0.110	12.8	430	7
	31/05/2017	0.085	11.3	318	0.020	10.8	498	0.213	14.6	465	1.199	11.1	214	0.104	13.0	425	5
	12/06/2017	0.071	11.3	320	0.011	11.6	488	0.100	17.8	444	1.162	11.1	212	0.091	13.5	433	12
	26/06/2017	0.058	11.3	321	0.008	12.2	476	0.056	16.6	428	1.109	11.2	209	0.088	14.0	444	14
	30/06/2017	0.160	11.4	327	0.143	12.5	520	0.383	17.0	448	1.801	11.2	223	0.118	14.4	450	4
Spr. average		0.119	11.1	320	0.075	10.5	505	0.410	12.6	484	1.333	11.1	216	0.133	12.5	440	
Summer	07/07/2017	0.118	11.4	325	0.068	12.8	505	0.051	17.5	421	1.376	11.3	215	0.096	14.8	443	7
	15/07/2017	0.126	11.6	325	0.077	12.8	508	0.090	17.8	422	1.421	11.3	218	0.080	15.0	440	8
	23/07/2017	0.114	11.6	328	0.039	12.8	500	0.056	18.7	419	1.367	11.4	215	0.067	15.3	436	8
	25/07/2017	0.138	11.8	334	0.051	12.9	509	0.210	17.9	440	1.475	11.4	216	0.077	15.7	433	2
	10/08/2017	0.060	12.1	332	0.023	13.2	506	0.100	18.5	434	1.319	11.5	215	0.067	16.0	442	16
	07/09/2017	0.044	12.1	326	0.013	12.8	519	0.031	17.6	424	1.155	11.5	216	0.056	16.3	438	28
Sum. average		0.100	11.8	328	0.045	12.9	508	0.090	18.0	427	1.352	11.4	216	0.074	15.5	439	
Average		0.146	11.6	321	0.121	10.7	522	0.535	10.3	483	1.428	11.2	218	0.160	12.5	458	

Table S2 – Discharge (Q), temperature (T) and electrical conductivity (EC) measurements at the springs of Mt. Zirone along the hydrogeologic year 2016-2017 (the Q measures selected for summer recession analysis are highlighted in red).

S2. Hydrographs of the springs of Mt. Prinzera and Mt. Zirone

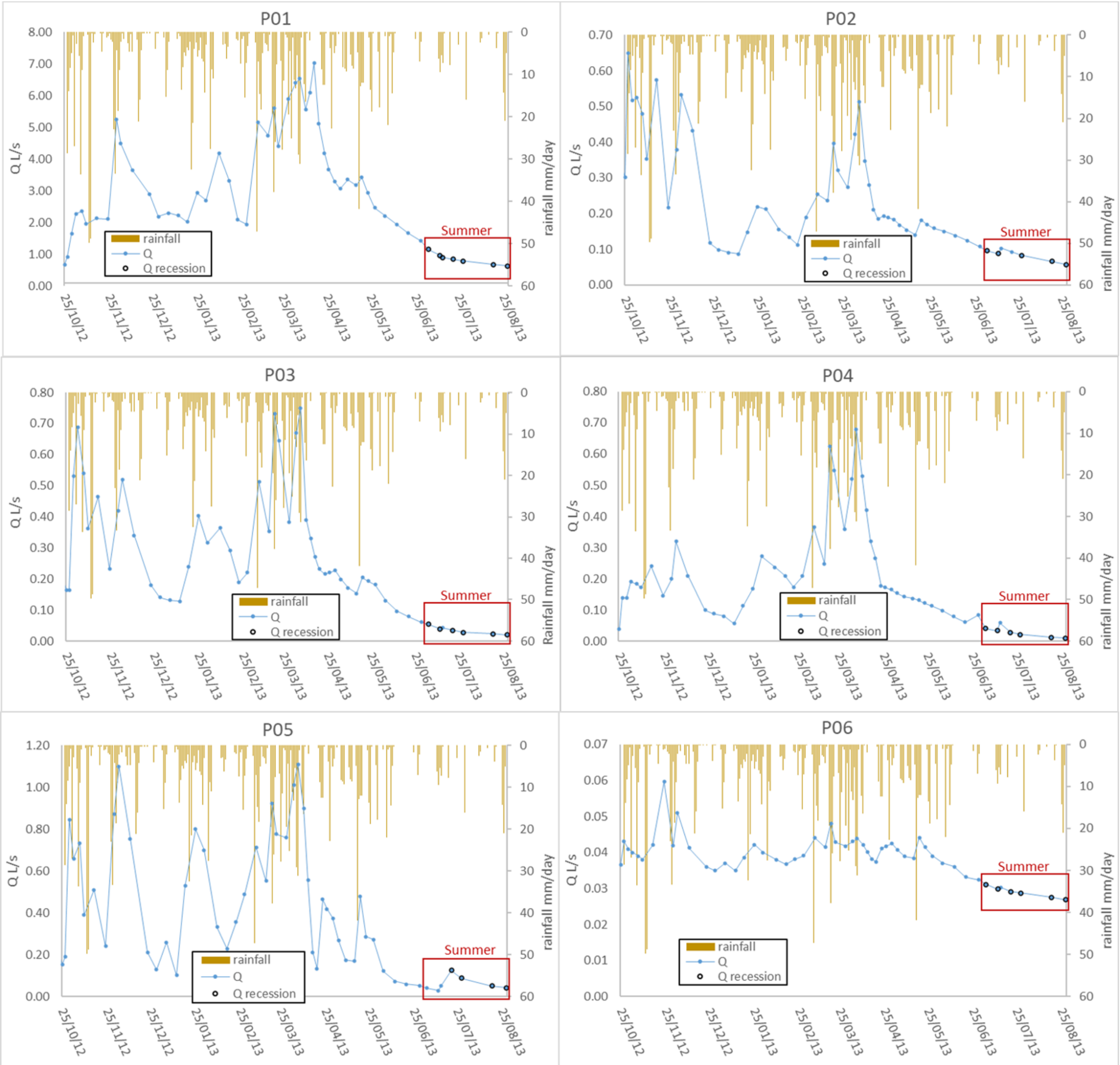

Figure S1 (I)- Hydrographs of the springs of Mt. Prinzera and Mt. Zirone. The summer part the hydrographs analyzed in Fig. 5 of the main article is highlighted in red. The maximum daily rainfall values among the ones registered at the selected monitoring stations (see Section S3 below) are reported on each hydrograph.

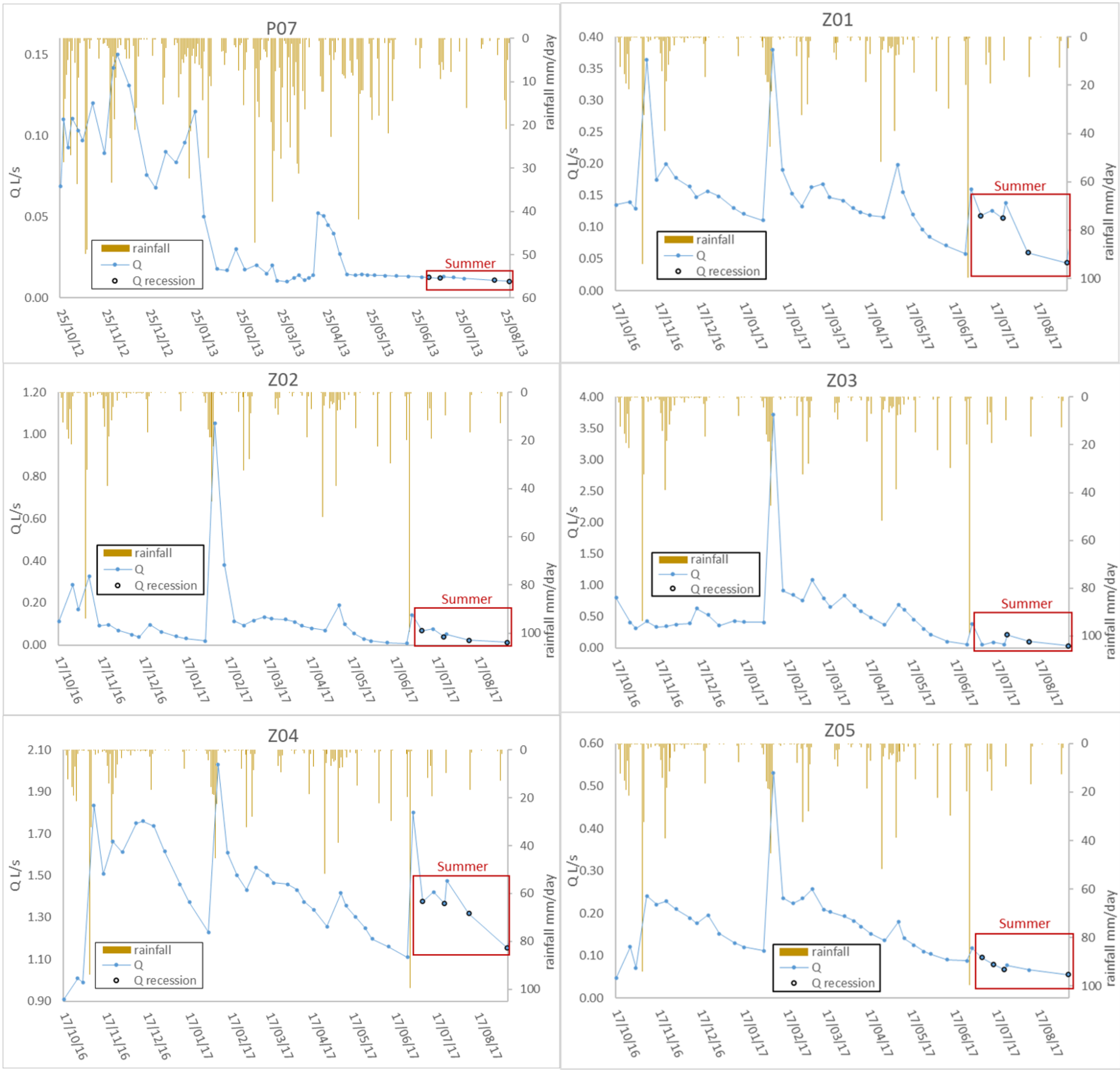

Figure S1 (II)- Hydrographs of the springs of Mt. Prinzera and Mt. Zirone. The summer part the hydrographs analyzed in Fig. 5 of the main article is highlighted in red. The maximum daily rainfall values among the ones registered at the selected monitoring stations (see Section S3 below) are reported on each hydrograph.

S3. Estimation of annual precipitation along hydrogeologic years 2012-2013 (Mt. Prinzera) and 2016-2017 (Mt. Zirone)

Daily precipitation and air temperature data were acquired from several meteorological stations (rain and temperature gauges) of the Hydro-meteorological Service of the Environmental Protection Agency for the Emilia Romagna Region (ARPAE) (Fig. S2).

In order to estimate the annual precipitation P over the catchments of Mt. Prinzera and Mt. Zirone, a linear relationship was identified in the two areas between P and the elevation of selected rain gauges (Fig. S3). Three and four rain gauges were selected for Mt. Prinzera and Mt. Zirone, respectively, among the ones active in the hydrological year of the survey (2012-2013 or 2016-2017). The selected gauges are located at different elevations between 169 and 808 m a.s.l. (Tab. S3).

The areas of Mt. Prinzera and Mt. Zirone were split into four altimetric belts with a 100 m altitude spacing. The rainfall volume corresponding to each belt was determined by multiplying the belt surface for the value of P corresponding to the averaged belt elevation. The sum of P volumes from the different belts was divided by the total area to obtain a value of annual P representative for the whole massif ("P_{TOT}"; Tab. S4).

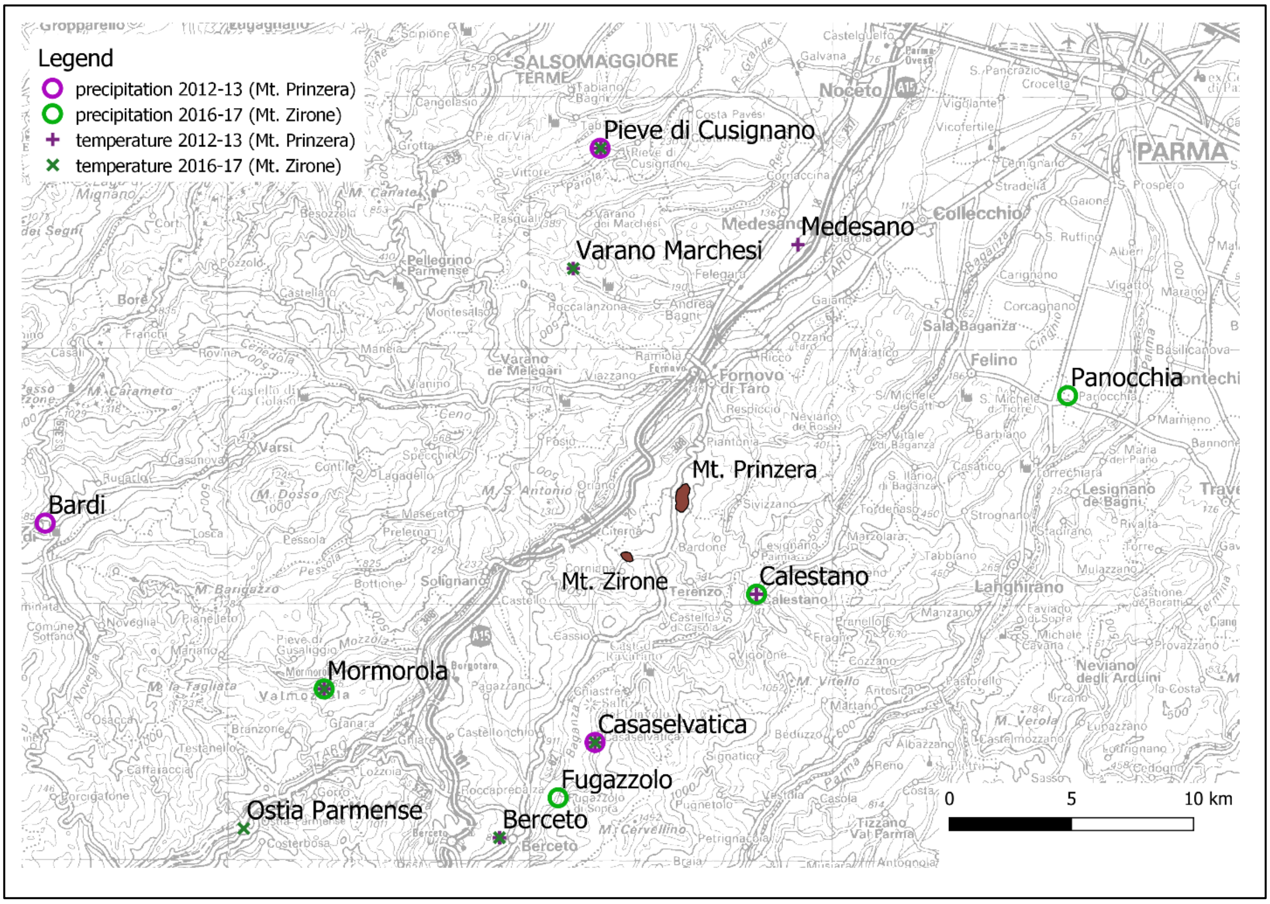

Figure S2 – Location of the meteorological stations selected among the ones active in the hydrogeologic years 2012-2013 and 2016-2017 for daily precipitation and temperature.

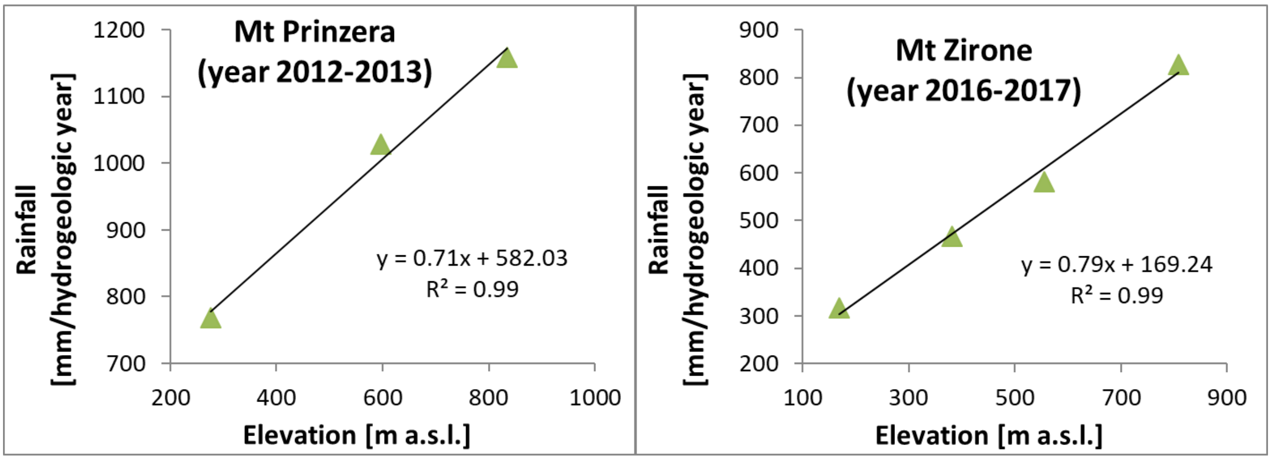

Figure S3 – Linear relationship between the elevation of the meteorological stations and the annual rainfall in the hydrogeologic year of interest.

	Meteorological station (ARPAE)	Elevation	Precipitation [mm]*
Mt. Prinzera	Pieve di Cusignano	277	768
	Bardi	597	1028
	Casaselvatica	834	1159
Mt. Zirone 2016-17	Pannocchia	169	317
	Calestano	381	468
	Mormorola	556	582
	Fugazzolo	808	828

* total precipitation over the monitored hydrologic year

Table S3 – Ground elevation at the selected meteorological stations and annual rainfall during the hydrogeologic year of interest.

	Altimetric belt	Precipitation [mm]	Belt area [m^2]	Precipitation volume [m^3]	P_{TOT} [mm]
Mt. Prinzera 2012-13	A1 (400-500)	900.45	27721.00	24961.37	
	A2 (500-600)	971.21	324291.00	314954.66	
	A3 (600-700)	1041.97	372578.00	388215.10	
	A4 (700-735)	1102.12	46888.00	51676.02	1010.8
Mt. Zirone 2016-17	A1 (400-500)	525.82	32000.00	16826.24	
	A2 (500-600)	605.06	290000.00	175467.40	
	A3 (600-700)	684.30	210000.00	143703.00	
	A4 (700-707)	729.47	2000.00	1458.93	631.94

Table S4 – Altimetric belt areas and estimation of R_{TOT} for Mt. Prinzera and Mt. Zirone. Calculations are described in Section 3.3 of the main text.

S4. Hydrograph analysis by means of "recession plots"

A well-known hydrological method to examine recession hydrographs of streams is to plot the rate of change in discharge (dQ/dt) versus the mean discharge over the dt interval (Q). This kind of plot is also known as "recession plot". The method was first proposed by Brutsaert and Nieber (1977) to avoid picking the exact time at which recession begins, and further investigated e.g. by Mendoza et al. (2003), Shaw and Riha (2012), Troch et al. (2013).

The recession plot method has been here applied to the spring hydrographs of Mt. Prinzera and Mt. Zirone as an alternative to the Maillet model for the analysis of recession.

We built a recession plot for each spring considering the whole depletion hydrograph, i.e. from the maximum peak of discharge (April and February in the cases in Mt. Prinzera and Mt. Zirone, respectively) down to the end of the hydrologic recession (end of August in both aquifers) (Fig. S4). We removed secondary discharge peaks along the falling limb of the hydrograph by taking into account only decreasing discharge values (i.e. negative values of dQ/dt). The correlation coefficient of the individual recession plots is much higher for the Mt. Prinzera springs (R^2 of 0.71 on average) compared to Mt. Zirone springs (R^2 of 0.54 on average).

The averaged value of the slopes (S) of the recession plots is 2.0 for the springs of both aquifers, consistently with the values obtained by Shaw and Riha (2012) that analyzed individual recession events in streams.

A subdivision in "recession classes" is proposed in the main text that is based on the value of the recession coefficient α of Maillet. The value of S of each spring was chosen as the parameter to be compared with the α of the same spring to assess if the subdivision in recession classes proposed in the main text was maintained when analyzing spring hydrographs with the recession plot method instead of the Maillet model. The comparison between α and S is shown and discussed in the main text.

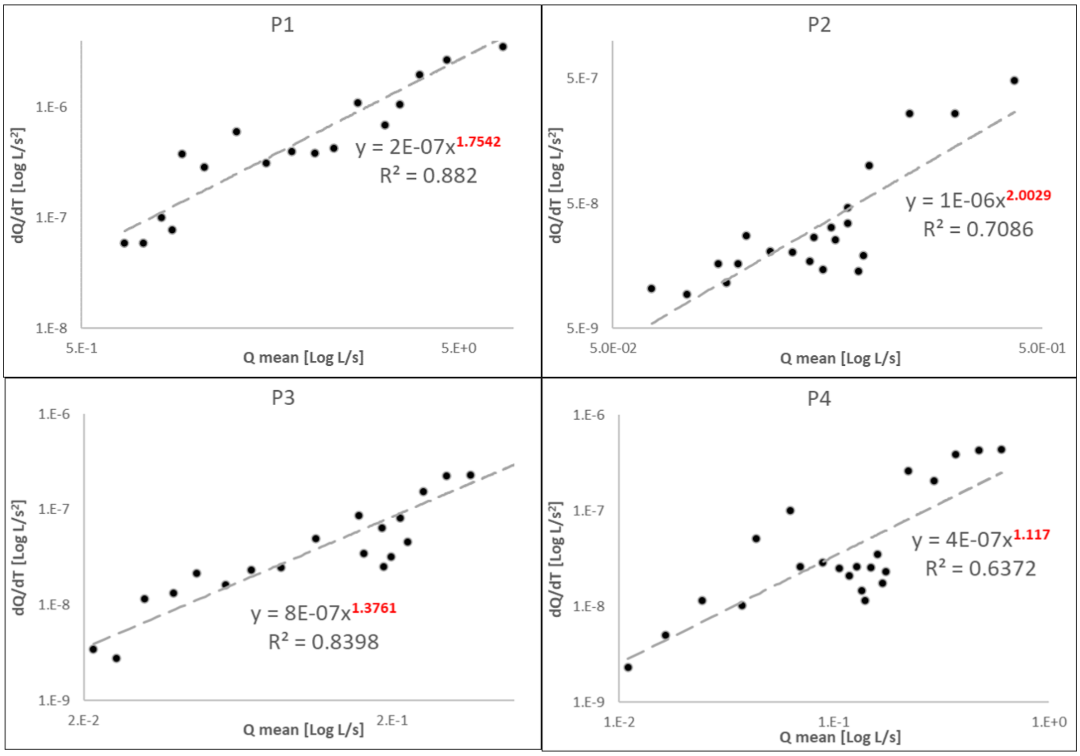

Figure S4 (I) – Recession plots from the depletion hydrographs of the springs of Mt. Prinzera and Mt. Zirone. The value of S is highlighted in red.

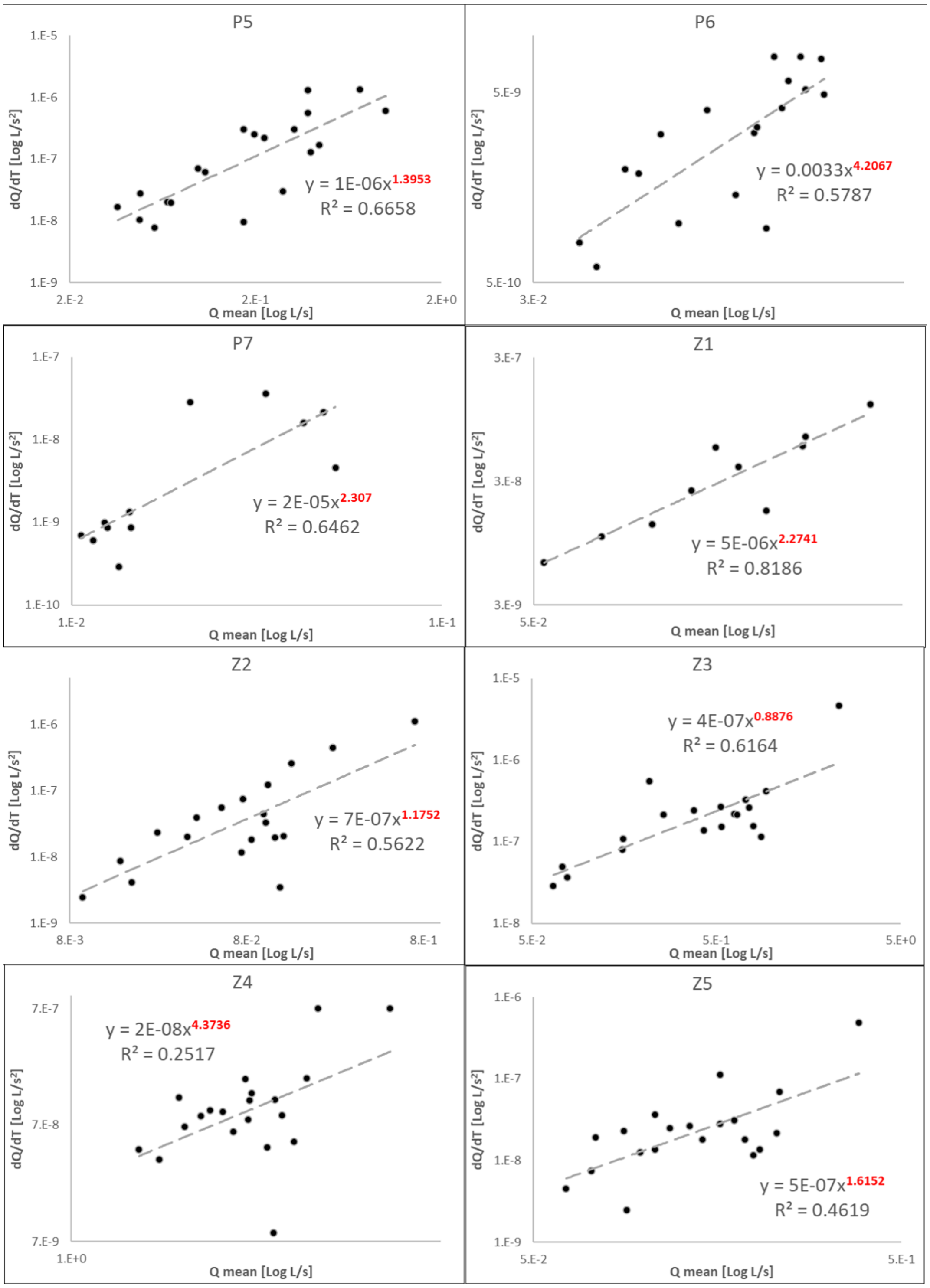

Figure S4 (II) – Recession plots from the depletion hydrographs of the springs of Mt. Prinzera and Mt. Zirone. The value of S is highlighted in red.

S5. Estimation of recharge at Mt. Prinzera and Mt. Zirone from annual water budgeting

The aquifer recharge R_{wb} of Mt. Prinzera and Mt. Zirone was estimated through a water budget equation (S1) for the two monitored years (2012-2013 and 2016-2017, respectively):

(S1) $R_{wb} = (P_{TOT} - ET) \times CPI$

where CPI is the Coefficient of Potential Infiltration that accounts for loss of recharge due to runoff and other minor processes (Civita, 2005) and ET is the annual evapotranspiration estimated using the Turc equation (Turc, 1951) (S2):

(S2) $ET = P_{TOT} / \sqrt{(0.9 + P_{TOT}^2/L^2)}$

where L is a “thermal indicator” that depends on mean annual air temperature (T) and is defined by (S3)

(S3) $L = 300 + 25 \times T + 0.05 \times T^3$

In order to estimate T over the catchments of Mt. Prinzera and Mt. Zirone, a linear relationship was identified in the two areas between the mean annual air T at a meteorological station and the elevation of the station (Fig. S5). Seven and six stations were selected for Mt. Prinzera and Mt. Zirone, respectively, among the ones active in the hydrological year of the survey (2012-13 or 2016-2017) (Fig. S2). The selected stations are located at different elevations between 104 and 834 m a.s.l. (Tab. S5). A mean annual air temperature was assigned to each altimetric belt (Tab. S6). The mean annual air T for the entire catchment was estimated as the average of mean annual temperatures assigned to each belt weighted on the belt areas (“averaged air T” in Tab. S6).

ET was estimated equal to 543 and 486 mm at Mt. Prinzera and Mt. Zirone, respectively, corresponding to the 54 and 77% of P_{TOT}.

Typical ranges of CPI are suggested by (Civita (2005)) for different lithologies. In the case of Mt. Prinzera, a CPI in the mid range of fissured plutonites (25%) allowed estimating a R_{wb} of 117 mm that fits well the R estimated in the main text (see Fig. S6). At Mt. Zirone, a much higher CPI (87%) had to be considered to obtain a good fit between R_{wb} and R, with R_{wb} of 127 mm. Such high value of the coefficient is uncommonly observed for the investigated lithologies. However, several reasons are discussed in the next Section 6 that would justify a much higher infiltration potential at Mt. Zirone compared to Mt. Prinzera.

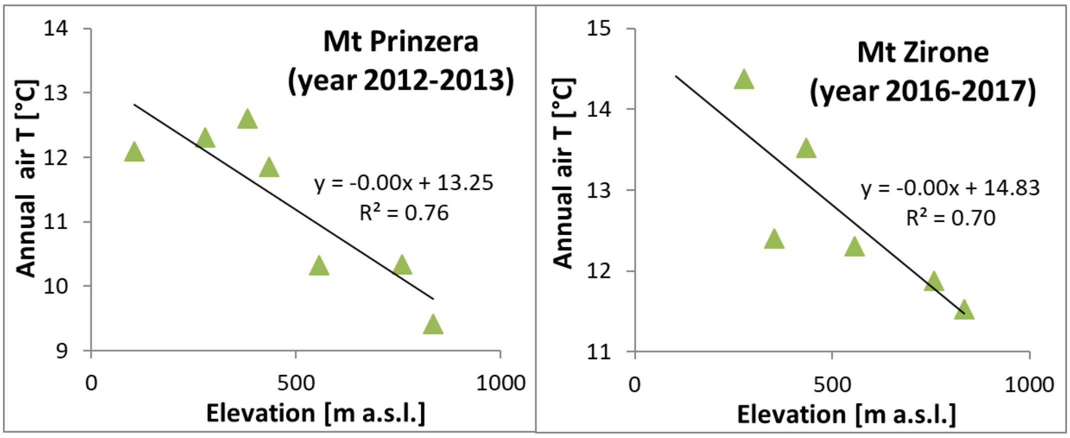

Figure S5 – Linear relationship between the elevation of the meteorological stations and the mean annual air temperature in the hydrogeologic year of interest.

	Meteorological station (ARPAE)	Elevation	T [°C]
Mt. Prinzera 2012-13	Pieve di Cusignano	277	12.30887
	Varano Marchesi	434	11.84751
	Mormorola	556	10.33055
	Berceto	758	10.3336
	Calestano	381	12.59756
	Medesano	104	12.09259
	Casaselvatica	834	9.409191
Mt. Zirone 2016-17	Pieve di Cusignano	277	14.37936
	Ostia Parmense	354	12.40505
	Varano Marchesi	434	13.52554
	Mormorola	556	12.3085
	Berceto	758	11.88294
	Casaselvatica	834	11.52532

* mean annual air temperature at the gauge

Table S5 – Ground elevation at the selected meteorological stations and mean annual air temperature during the hydrogeologic year of interest.

	Altimetric belt	annual air T [°C]	Belt area [m^2]	averaged air T [°C]
Mt. Prinzera 2012-13	A1 (400-500)	11.41	27721.00	
	A2 (500-600)	11.00	324291.00	
	A3 (600-700)	10.59	372578.00	
	A4 (700-735)	10.18	46888.00	10.76
Mt. Zirone 2016-17	A1 (400-500)	13.03	32000.00	
	A2 (500-600)	12.63	290000.00	
	A3 (600-700)	12.23	210000.00	
	A4 (700-707)	11.83	2000.00	12.49

Table S6 – Estimation of averaged air T at Mt. Prinzera and Mt. Zirone as the average of the mean annual temperature at different elevations weighted on belt areas of the same elevation.

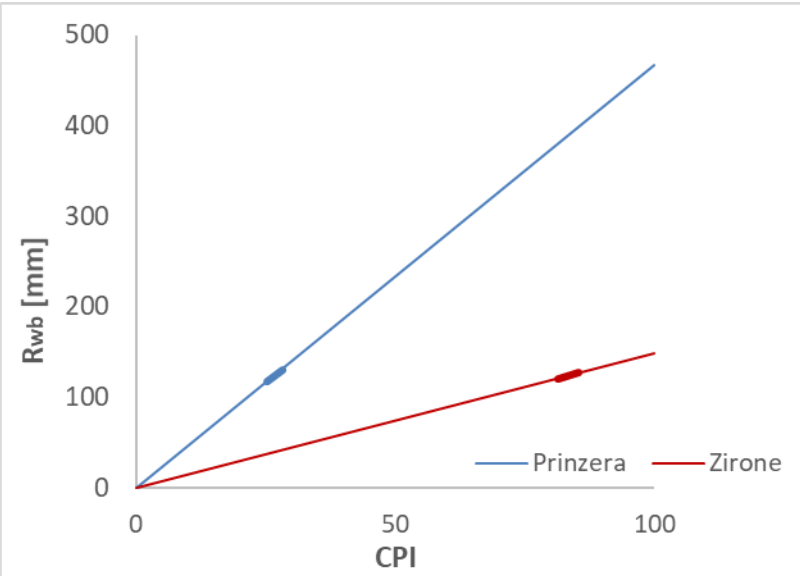

Figure S6 – R_{wb} variation at varying CPI. The thicker segments identify the R values estimated in the main text.

S6. Surface evidences for the infiltration potential at Mt Prinzera and Mt. Zirone

Filed observations on surface morphology, Quaternary cover and fracturing were conducted at Mt. Prinzera and Mt. Zirone providing insights into the infiltration potential of the two aquifers.

The surface of Mt. Zirone is interested by a large number of rock slope deformations (sensu Hungr et al., 2014) likely set on the preexisting tectonic structures (Fig. S7). Such generalized stress-release condition is expected to enhance infiltration of recharging water from the topographic surface into the aquifer. Infiltration is likely exacerbated due to the low thickness of the aquifer (up to 150 m, which is half the maximum thickness of Mt Prinzera aquifer). In contrast, the olistolithe of Mt. Prinzera appears rather intact, with only two rock slope deformations in its northernmost and southernmost edges (Fig. S7). The different degrees of structural relaxation characterizing the two areas are also well discernible in the field, where the fractures at Mt. Zirone appear much wider than that of Mt. Prinzera (Fig. S8). The above observations suggest a lower infiltration potential at Mt Prinzera compared to Mt Zirone.

Preliminary structural surveys were performed at Mt. Prinzera and Mt. Zirone in summer 2014 and 2015, respectively, along two 20 m long scan lines. Whereas the total number of fractures along the scan line was similar in the two cases (1961 at Mt. Prinzera and 2443 at Mt. Zirone), the aperture and persistence of fractures was much lower at Mt. Prinzera, corroborating the hypothesis of higher infiltration potential and overall higher permeability at Mt. Zirone (Fig. S9).

The Quaternary covers in the areas of Mt. Prinzera and Mt. Zirone were analyzed during a field survey from March 2011 to October 2011, using the Technical Regional Map as a base map (1:5000), integrated with aerial photographs (Tab. S7). The results allowed refining the available geological map (Di Dio et al., 2005) based on CARG (Italian Geological Cartography Project) data. The Quaternary deposits consist of eluvial and colluvial deposit, residual cover, active and dormant landslide and mass movements. The woodland cover mostly consists of scattered oak trees and juniper shrubs (Corticelli et al., 2011). The areas not intersected by woodland or Quaternary covers were classified as bedrock outcrop and assumed as the areas contributing most actively to groundwater recharge due to easier recharge infiltration. The overall lower percent of bedrock outcrop over the total aquifer surface at Mt. Prinzera (60%) compared to Mt. Zirone (69%), may contribute to the hypothesized higher infiltration at Mt. Zirone.

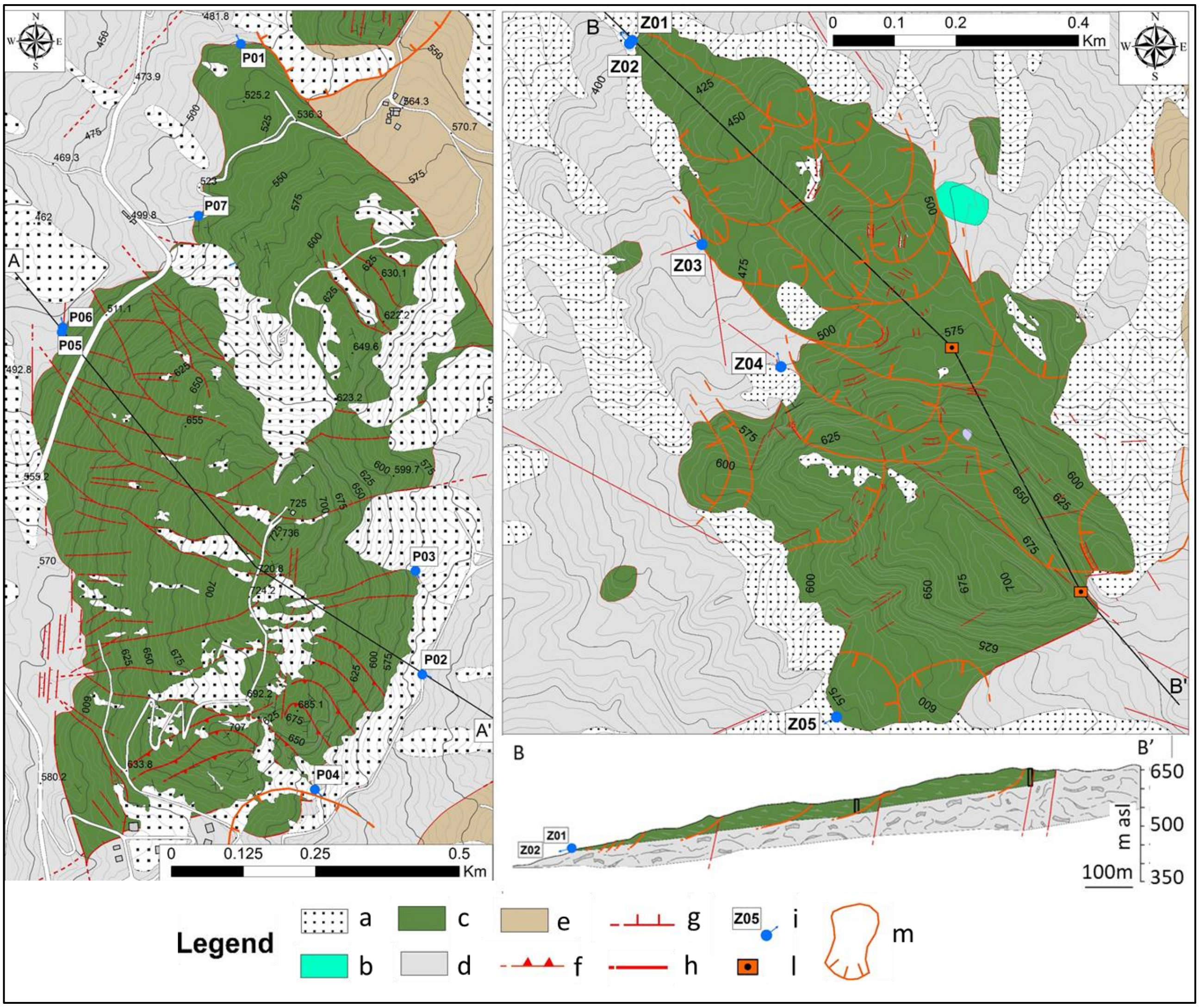

Figure S7 - Geological sketch maps of Mt. Prinzera (left) and Mt. Zirone (right) a: Quaternary deposits; b: Calpionella limestones; c: ophiolite hard-rock aquifers; d: polygenic breccias in clay matrix (aquitard); e: Helminthoid flysch; f: thrust; g: fault (the teeth indicates the downwards moved side); h: tectonic contact; i: perennial spring; l: borehole; m: rock slope deformation boundary (the teeth indicates the downwards moved side).

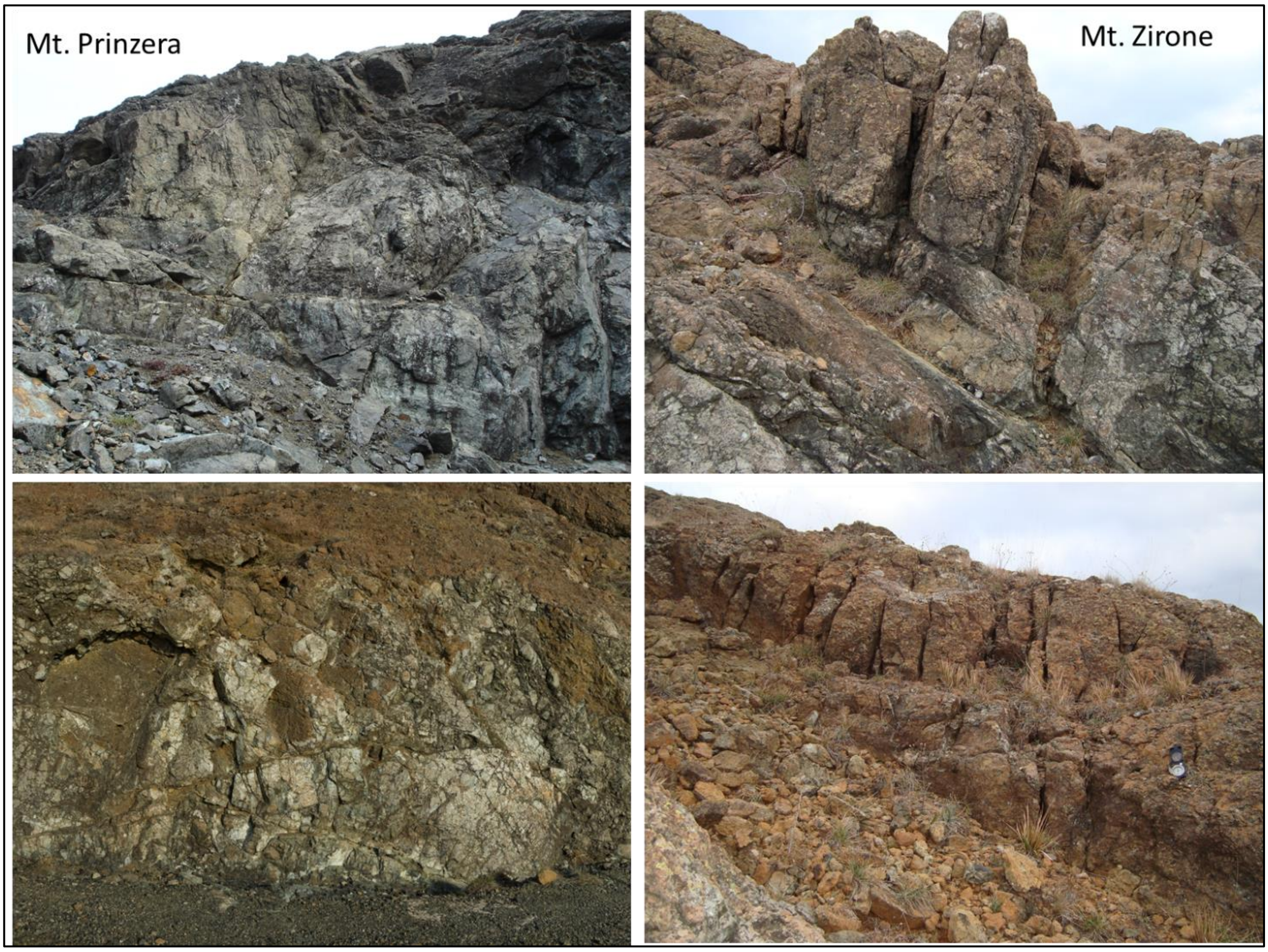

Figure S8 – Pictures from Mt. Prinzera (left) and Mt. Zirone (right) highlighting different stress-release conditions.

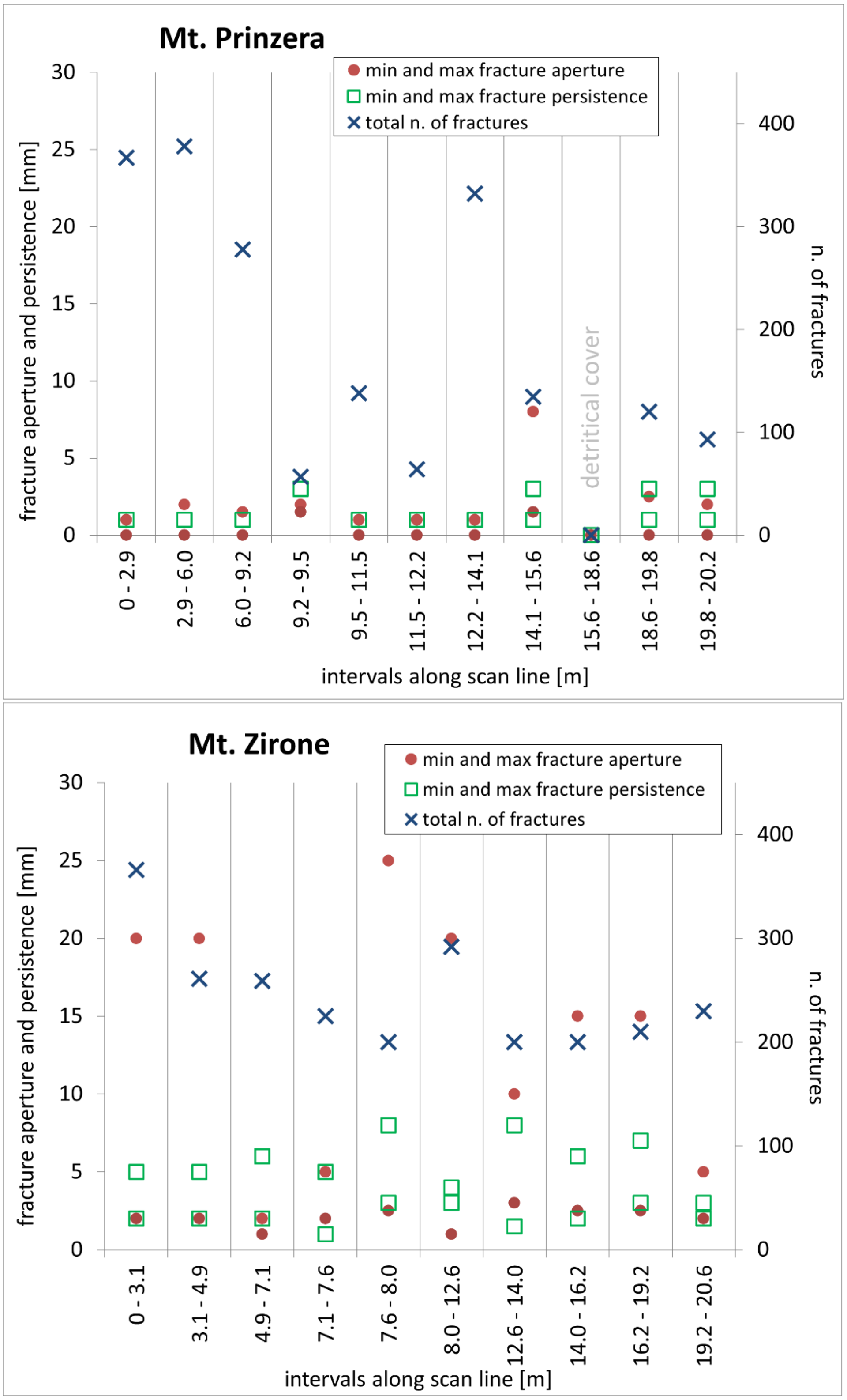

Figure S9 – Results of a preliminary structural survey along 20 m long scan lines at Mt. Prinzera and Mt. Zirone.

			% of total area		% of covered area	
	Mt. Prinzera	**Mt. Zirone**	**Mt. Prinzera**	**Mt. Zirone**	**Mt. Prinzera**	**Mt. Zirone**
Aquifer area (m^2)	771478	534000				
Bed rock outcrop or scattered trees (m^2)	462427	367726	59.94	68.86		
Total cover (m^2)	309051	166274	40.06	31.14		
Quaternary deposit cover (m^2)	148691	25730	19.27	4.82	48.11	15.47
Woodland cover (m^2)	160360	140544	20.79	26.32	51.89	84.53

Table S7- Woodland and Quaternary covers and bedrock outcrop at Mt. Prinzera and Mt. Zirone.

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