Climate change, water supply and environmental problems of headwaters: the paradigmatic case of the Tiber, Savio and Marecchia rivers (Central Italy)

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Abstract

River headwaters, in spite of their importance for habitats and water supply, are often inadequately studied and managed. This study discusses the effects of the hydrogeological system and climatic variations on the environment of Monte Fumaiolo (Central Italy), which corresponds to the headwaters of the rivers Tiber, Savio and Marecchia. The area is a key system for supplying drinking-water and is also the habitat of amphibians such as the endemic and endangered *Bombina pachypus* and other amphibian species. Ongoing climate change is affecting the area: during the last 30 years, five prolonged droughts have occurred, against only one in the preceding 40 years. On all time-scales, there is a decrease in rainfall during the recharge period and an increase of temperature: these trends correspond to a decrease in water yield of about 12% over the last 30 years. The hydrologic system of the study area is composed of one basic aquifer and a few perched aquifers feeding springs. Their resilience to drought depends on their geological setting: study of some depletion curves helped us to understand the geological setting of the various types, and two promising sites for the habitat preservation of amphibians were identified. Study results indicate new approaches to the study and management of the environment and its water supply, which could be useful in similar areas.

Keywords: headwaters; climate change; spring depletion curves; river Tiber; endangered habitats; water budget.

1. Introduction

Springs feeding small watercourses in river headwaters areas represent the main source of downstream waters during dry seasons and periods of drought. Interactions among groundwater, springs and streams produce often substantial habitats and are responsible for the chemical and biological characteristics of streams (Alexander et al., 2007; Winter, 2007; Bae et al., 2016; Merriam and Petty, 2016). Although such watercourses are often small, their importance is great but, despite this, they often do not appear on official maps and only a few of them are mapped (Mayer et al., 2007; Rasmussen et al., 2013). According to Gomi et al. (2002), the roles played by headwater systems are typically underestimated and inadequately managed, in comparison with larger downstream systems. Knowledge of headwater areas, even if small in extent, requires specific conceptual and field studies, which are important in identifying emerging problems at an early stage of their development (Grip, 2000).

The main problems of headwater areas may be summarised as follows:

- As headwater regions are often among the last natural or poorly anthropised areas, they have high environmental value, which is in conflict with the increasing demand of land for agriculture, industry and tourism, etc; headwater regions generally provide the environment with high-quality waters. They can partly satisfy the increasing demand for drinking-water, which is a worldwide phenomenon. This may clash with the maintenance of wet habitats.
- Climate change, which severely affects the water cycle, increases all the problems of these fragile environments.
- Due to their marginal geographical position and consequent low economic and political status, headwater regions have received little attention, and research is hampered by proper lack of information and data (cfr. Haigh and Křeček, 1991).

Sadly enough, in spite of the importance of these environmental problems, the scarcity of hydro-meteorological data means that these spring areas have little appeal to hydrologists and hydrogeologists, and this often prevents even attempts at defining and solving problems. We believe that, if the problems are important, they should be investigated and solved as promptly as possible with available data and knowledge. Within this framework, the present work describes the problems of the Monte Fumaiolo Plateau (MFP), a typical small Mediterranean mountain headwater system, the problems of which, as well as the solutions, may be applied to other systems.

MFP is the headwaters of three important watercourses: the Savio, Marecchia and Tiber, the last being the river which flows through Rome. As the Tiber basin, including the area of Rome, is subject to frequent droughts and floods, there have been many studies focusing on droughts, floods, and the largest groundwater systems (e.g., Calenda et al., 2005; Di Matteo and Dragoni, 2006; Di Matteo et al., 2006; Romano and Preziosi, 2013; Bencivenga and Bersani, 2014; Barbetta and Moramarco, 2014; Maccioni et al., 2015; Behulu et al., 2016). However, the headwaters of all three of these rivers are much less well-known. As regards other mountainous areas of Central Italy, climate change, together with the increasing demand for water and anthropic pressures, is preparing a problematic future, from both environmental and water supply points of view (Dragoni, 1998; Bates et al., 2008; Dragoni et al., 2013; IPCC, 2014; Di Matteo et al., 2016). This is particularly important for the MFP, because it is a key hydrogeological system for drinking-water supply and habitat conservation. Four springs feed the main aqueducts serving a few towns in the North Apennines and along the Adriatic coast (Fig. 1): in addition, many small springs feed streams and ponds which are habitats of vital importance for amphibians and fish along the upper part of local watercourses (Lorenzoni et al., 2010; Franchi et al., 2014). Both in Europe and in Italy, the habitats and survival of endemic amphibians are in danger (Stagni et al., 2004; IUCN, 2013). Regarding this last point, the problem of maintaining wet habitats for the survival of peculiar and rare species is well-known worldwide, from humid mountain areas to arid or semi-arid ones (Enge, 1997; Ruiz et al., 2008; Surasinghe, 2009; Baker et al., 2011; D’Amen et al., 2011; Cole, 2014; Levison et al., 2014; EDGE, 2016). Throughout the Apennines, water withdrawal and interception of spring waters are the main threats for amphibian populations (Scoccianti, 1989; Stagni et al., 2004).

During the last few decades, increasing numbers of drought events have been documented, in general in the Mediterranean area and in particular for the Italian region, in the period 1991-2010 (e.g., Spinoni et al., 2015). Increases in the length and frequency of drought periods in the Central-Northern Apennines has affected the discharge of mountain springs, exacerbating the overall situation of both water supply and habitats (Di Matteo et al., 2013, 2016). Within this framework, and on the basis of hydrogeological field investigations, new measurements and analysis of available hydro-meteorological data, the main aims of the present work are the following:

- to investigate climatic variations in the MFP area, within the framework of on-going events in the Mediterranean basin;
- to hypothesise what might happen to the water resources of the MFP in the next few decades;
- to study the hydrogeological system and the effects of climatic variations on the regime of springs, to define management strategies to minimise the impact of climate change on drinking-water resources and the environment;
- to develop investigative approaches based on the depletion curves of springs, with possibly can be applied to other areas.

The overall results should be useful to approach similar problems in other small headwater areas with similar geological features. To improve the readability and significance of this work, the acronyms and symbols used in the text are listed in **Table 1**.

TABLE 1

2. Study area

2.1 Geographical characterisation

The Mount Fumaiolo plateau is located in Central Italy and covers an area of about 11 km² (43°47′21.12″ N, 12°4′17.76″ E). It is forested, with a maximum elevation of 1407 m a.s.l., and is located on the Apennine watershed divide between the Tyrrhenian and Adriatic seas (**Fig. 1**).Three important catchment areas are comprised in the MFP: Savio, Marecchia, and Tiber (**Fig. 1**). The first two drain towards the Adriatic and the Tiber towards the Tyrrhenian. The Tiber basin, the second largest in Italy (about 17,340 km^2), has a rather irregular hydrological regime, due to the hydrogeological features of its basin: in its upper part, rocks of low permeability (flysch) outcrop over most of the area. This characteristic is responsible for high, fast discharges during rainy periods (autumn and winter) and, more relevant to the aims of this paper, low or negligible flows during summer, which is the local dry season (**Fig. 2**). Although the area of the MFP is very small when compared with the Tiber catchment, its importance for water supply (springs exploited for drinking-water) and habitat preservation is very high: the MFP is a Site of Community Importance (SCI), i.e., the European Commission has declared it to be a protected area (code IT4080008) for the survival of endemic amphibians (e.g., *Bombina pachypus;* **Fig. 3**).

FIG. 1

FIG. 2

FIG. 3

2.2 Geological and hydrogeological setting

The geological setup of MFP is characterised by outcrops of Epi-Ligurian units (Conti et al., 2016): the Monte Fumaiolo Formation (MFU: calcareous sandstone, marly sandstone) and the San Marino Formation (SMN; limestones), characterised by medium to high permeability (**Figs. 4-5a**). The Epi-Ligurian units are deposited over the Ligurid nappes (Ricci Lucchi, 1986), composed of low-permeability mudstone (**Fig. 5b**).

The main aquifer is hosted in the Epi-Ligurian units. The hydrogeological system feeds 44 springs, most of which have a mean annual discharge of less than 5 l/s (Maccari, 2005). **Table 2** shows the mean monthly discharge of springs located in the study area, as resulted by a campaign conducted in 2004-2005. These are hitherto unpublished data, and no measurements on spring discharges are available, apart from qualitative historical information by Lotti (1915) and continual data from the Senetello spring (no. 22 in **Table 2**) monitored by the HERA Group, which is in charge of spring management: these data are presented below and discussed, taking into due account the climatic conditions of the area.

FIG. 4

FIG. 5

TABLE 2

3. Methods

3.1 Climatic characterisation

Climatic characterisation of the Monte Fumaiolo plateau (mean altitude approx. 1,250 m a.s.l.) was carried out on a monthly basis at the most reliable meteorological stations. As commonly occurs in other locations along the Apennines, there are only a few high-altitude meteorological stations and they are not always reliable (Cambi et al., 2010; Di Matteo et al., 2013). As within this framework only rainfall and temperature data were available (and most of them are not reliable), we used traditional empirical methods to estimate evapotranspiration, such as those based on the Thornthwaite-Mather (1957) and Turc (1963) equations. In situations similar to the MFP area, where data concerning radiation, air humidity, etc. - necessary to apply more modern methods - are not available, this approach is still useful (e.g., Shuttleworth, 2007, and refs. therein).

To meet criteria of reliability and uniformity, we chose only meteorological stations which had been operating from 1946 to 2013, and for which less than 10% of the rainfall and temperature data were missing: gaps in time-series were filled by applying multiple regressions based on the best-correlated data series (R^2>0.75) of the nearest rain gauges. Statistical analysis showed that only one station (Verghereto: 812 m a.s.l.; **Fig. 1**) had reliable temperature and rainfall data. The other stations in **Fig. 1** (Bagno di Romagna, Montecoronaro, Badia Tedalda) have no temperature measurements, rain time-series are not synchronous, and gaps are higher than the 10% threshold. The station of Montecoronaro (the nearest to the MFP) was moved to a new location in the late 1990s and closed, due to malfunctioning, in 2002. It thus turns out that the only reliable overlapping period of these stations is 1961-1990, which is not enough to calculate climatic evolution during more recent decades. **Table 3** shows the characteristics of the available meteorological stations.

TABLE 3

3.2 Climatic trends and drought assessment

The Mann-Kendall test (Mann 1945; Kendall 1975) was used to check the presence of significant temperature and rainfall trends at the Verghereto station on differing time-scales (annual, seasonal, etc.). For mountain areas, the World Meteorological Organization (WMO, 2008) recommends an optimal density of 1 rain gauge every 250 km^2, corresponding to an “influence radius” of about 9 km around each station. As the Verghereto station lies at about 5 km from the MFP, it is well inside the influence area of the rain gauge (**Fig. 1**). Within this framework, this rain gauge is well situated to assess climatic trends and drought conditions for MFP, without the need to consider other gauges which have no reliable data, much shorter data sets, or are far from the MFP. In order to check the occurrence and intensity of droughts, we used the Standardized Precipitation Index, SPI (McKee et al., 1993; Edwards and McKee, 1997). The available 68 years of rainfall data passed the test for gamma probability distribution according to Kolmogorov-Smirnov and Chi-square tests. In the SPI computation, the data - originally fitting gamma distribution - were transformed into normal distribution, so that the mean SPI for the location and desired period is zero and the variance is one (Edwards and McKee, 1997). SPI was computed by DrinC software (Tigkas et al., 2015) on varying time-scales (6, 9, 12 and 24 months). It should be noted that, in this procedure, a drought event is defined when the SPI is continuously negative and reaches a value of -1.0 or less. When the SPI reaches -2.0 or less, an extremely dry period occurs. In addition to the SPI, two other drought indexes, the WSVI (Water Surplus Variability Index) (Gocic and Trajkovic, 2015) and the RDI index (Reconnaissance Drought Index) (Tsakiris and Vangelis, 2005; Tsakiris et al., 2007; Tigkas et al., 2015) were also used. Both indexes are based on monthly precipitation (P) and potential evapotranspiration (PET). The latter was computed by the Thornthwaite and Mather method: as previously noted, other more reliable methods such as the FAO-56 Penman-Monteith equation (Ward and Robinson, 2000) were not used here, because of the lack of detailed weather and climatic data. The lack of any long time-series of springs or surface run-off data did not allow the use of drought indexes based on hydrological data such as the Streamflow Drought Index - SDI (Nalbantis and Tsakiris, 2009).

The drought indexes used here are generally closely correlated with the hydrological and hydrogeological indexes. According to Rimkus et al. (2013), SDI is analogous to the standardised precipitation index (SPI), which the WMO has declared to be an official meteorological drought index (WMO, 2009). As reported by Vicente-Serrano and López-Moreno (2005), robust relationships were found between the SPI time-scales on river discharges and reservoir storages in complex hydrological systems in mountainous regions and in the Mediterranean region. This viewpoint is well established: the same procedure (i.e., use of SPI, WSVI or RDI) has in fact been used quite frequently in the more recent literature on surface water, groundwater and climate change (e.g., Fiorillo and Guadagno, 2010; Bloomfield and Marchant, 2013).

3.3 Water budget

Knowledge of the total water yield (WYI) that a certain system can give is of paramount importance for integrated management of water resources and habitats. Within the framework of on-going climate change, the estimation of WYI evolution is of primary importance also.

The average yearly water budget of MFP is computed here according to Eq. (1), in which P, ETR and WYI are, respectively, average precipitation, evapotranspiration and total water yield of the MFP, i.e., surface water plus groundwater.

$$P = ETR + WYI \qquad (1)$$

Equation (1) implies that the only source of water in the MFP is precipitation (as confirmed by the geological setting) and that long-term storage variations are negligible, which is reasonable. Evapotranspiration was computed by the Thornthwaite-Mather method (Thornthwaite and Mather, 1955), with a field capacity of 150 mm, which gives good results in the forested mountain areas of Central and Southern Italy (Baiocchi et al., 2014). Similar results were obtained with the Turc equation (Turc, 1963): although empirical, these methods generally give good results in humid and temperate climates (cfr. Calvo, 1986; Bonacci and Andric', 2015). For the particular case of Central Italy, a detailed comparison of these methods with other more rigorous ones showed that the error involved in their use is smaller than the errors due to approximation of rainfall measures (Di Matteo and Dragoni, 2006).

3.4 Hydrograph analysis of springs

As in other hydrogeologic systems in Central Italy, and in general in mountain areas, the need to define the hydrogeologic scheme clashes with the scarcity of available data, especially in terms of discharge measurements and hydrogeologic information obtained from pumping tests (e.g., Cambi et al., 2010). Since the Mount Fumaiolo system is important for both environmental and water demand purposes, understanding its groundwater circulation from available data is of paramount importance, although the data are not as many or as reliable as they should be, and only provide knowledge on a "bulk" scale.

Analysis of spring discharges during recession periods, together with knowledge of the geological setting of the recharge area, is useful in understanding the characteristics of the hydrogeological system and its response to prolonged periods of drought. Depletion curves are particularly useful when specific information about hydraulic conductivity and specific yield data are missing, and in the case of hard rocks, where flow is controlled by the fracture network, as in the case considered here (Bonacci and Andric', 2015; Baiocchi et al., 2015; Dragoni et al., 2015). A depletion curve integrates the hydrogeological properties of the reservoir, and its shape can give information about these properties, at least in terms of average or equivalent values.

In the literature, several equations have been published to describe the recession curves of springs, using various conceptual models of the reservoir (Hall, 1968; Tallaksen, 1995; Dewandel et al., 2003). As is well-known, the exponential formula (Eq. 2 in **Table 4**; Boussinesq, 1877; Maillet, 1905) and the hyperbolic or quadratic formula (Eq. 3 in **Table 4**; Boussinesq, 1903) are extensively used in hydrogeological practice. In the following, we call the exponential equation EF and the quadratic formula QF. The EF and QF functions are based on Darcy's equation which, in theory, is not appropriate for karstic or fractured rocks, as in the case of the MFP: nonetheless, when hydraulic gradients and flow velocity are low, Darcy's equation gives good results. Thus, in these cases, EF and QF clearly describe the depletion process (Scanlon et al., 2003; Gattinoni et al., 2009; and Birk, 2010; Dokou and Karatzas, 2012; Dragoni et al., 2013).

Table 4 shows the main conceptual differences between EF and QF. Actually, in the case of springs with shallow water storage below the elevation of those springs (i.e., with a limited vertical component of the velocity vector), depletion curves can be simulated quite well by both EF and QF. This was stated by Dewandel et al. (2003) and confirmed by (still unpublished) results of many of our simulations, carried out with a finite difference model. It should also be emphasised that often the depletion process is described by more than one depletion coefficient. This may be explained by noting that, during a depletion period, the saturated thickness inside the reservoir decreases, so average hydraulic conductivity K and effective porosity n_e may differ; the geometric properties of the reservoir (size and shape) may also change (Bonacci, 1987; Fiorillo and Guadagno, 2010). Both EF and QF can easily be linearised (**Table 4**). Linearisation was used in the past to compute depletion constants α, while they are now often computed by numerical methods. Today the linearization is useful to check by visual inspection the depletion function generated by the spring reservoir, as it will be shown in a later section. It should be noted that, although Boussinesq's original formulation involved parallel flow, EF and QF also apply to converging flows, as in the case of punctual springs, as in the case of MFP.

TABLE 4

4. Results

4.1 Climatic analysis and trend

Analysis of the long-term series of temperature and rainfall data at the Verghereto station indicated that the study area matches the Mediterranean climate profile, with a mean rainfall of about 1345 mm/year and a mean annual temperature of 11°C. The recharge period is from October to May; dry months run from late June to September (**Fig. 6**). In order to check rainfall and temperature trends in the study area, statistical analysis was carried out, on a different time-scale, on monthly data from the Verghereto station (**Table 5**).

FIG. 6

TABLE 5

The data show a statistically significant negative precipitation trend during the January-April period (-1.35 mm/4months; significance > 94%, according to the Mann-Kendall test). Conversely, no significant rainfall trends (either positive or negative) occur in other months or seasons.

As **Table 2** shows, spring discharges are only a few liters per second, which indicates that the general reduction in rainfall during part of the recharge period can frequently reduce, during the dry season, the flow to zero. The effects on the water resources of precipitation trends are exacerbated by the significant positive annual temperature trend (+0.045 °C/year), which increases evapotranspiration.

4.2 Drought assessment

Figure 7a shows 12-month SPI values: for the last three decades, five severe droughts ($-2.0 \leq SPI < -1.5$), occurred in 1985-1986, 1988-1990, 1994-1995, 2006-2007 and 2011-2012. Conversely, there was only one main drought period between 1947 and 1982 (1973-1974 period). **Figure 7b-c** shows that the dry and wet periods indicated by the SPI generally match those identified by two other drought indexes, WSVI and RDI. In the last 30 years (according to the index used) the number of months with severe drought ranged between 25 and 30. It is interesting to note that, although moderate drought was identified by SPI for the 2001-2003 period, its intensity was less severe than that described in the Central-Eastern Apennines and Southern Italy in other authors (e.g., Polemio and Casarano, 2008; Fiorillo and Guadagno, 2010; Dragoni et al., 2015; Valigi et al., 2016).

FIG. 7

4.3 Water budget

Table 6 shows the water budget for two periods: 1947-1980 and 1981-2013. According to the water budget, the absolute value of the water yield (WYI) in the more recent period is about 12% lower than the previous one. The decrease in the WYI is due both to the slight decrease in rainfall and to the absolute increase in ETR, due to increasing temperatures (cfr. **Table 5**). As will be discussed later, the WYI decrease is consistent with results from the drought assessment. Further support of the validity of the estimated value of WYI comes from the fact that the sum of the available spring discharge is 502 mm/y (**Table 2**). This is about 25% lower than that obtained from the water budget of **Table 6**. This was to be expected: **Table 2** reports only one year of data, and considers only discharges from the main springs, neglecting surface runoff which, although low, is not zero: the WYI in **Table 6** accounts for both groundwater and surface run-off. In other words, all the available evidence indicates that the estimated water budget is not too far from reality.

TABLE 6

4.4 Analysis of recession curves of springs in MFP

As shown in **Fig. 4** and **Fig. 8a**, the Mount Fumaiolo system is characterised by small springs fed by perched aquifers hosted in the heteropic FMU and by base springs emerging at the contact between the SMF and UL units, the latter having a very low permeability. The Senatello spring has the greatest discharge (spring no. 22, mean discharge about 50 l/s). This spring, fed by the base aquifer, is located in the eastern part of the system, at the contact between SMF and UL at an altitude of about 1040 m a.s.l., and is the lowest outcropping elevation of the low-permeability boundary (**Fig. 4**). Along this contact, but at a higher altitude than the Senatello spring, there are other springs with average discharges of a few liters per second or less (e.g., springs 25, 26, 31, etc. in **Fig. 4**). In general, whenever an aquifer feeds two or more springs located at different elevations, as the piezometric surface is lowered, the hydrodynamic watershed moves towards the spring at high elevation, with reductions in the recharge area and the feeding volumes of the same spring (Cambi and Dragoni, 2000).

For the sake of simplicity, let us consider an aquifer drained by only two springs (**Fig. 9**), at different elevations above sea level, here defined as High Elevation Spring (HES) and Low Elevation Spring (LES) (**Fig. 9A)**. During prolonged drought periods, the response of an HES is quite different from that of a LES: when the volume feeding the HES spring falls drastically (**Fig. 9B**), its discharge decreases sharply, it no longer follows any of the "standard" depletion curves, and the spring dries up in a short time (**Figs. 9C, 9D**).

FIG. 8

FIG. 9

Fig. 10a shows the recession curves of the Senatello spring (no. 22 in **Table 2**). This spring is the lowest one fed by the base aquifer hosted in the SMN. Its depletion curve is well described by the EF (Eq. 2), with two exponential terms having depletion coefficients α_1 and α_2: the Mean Absolute Percentage Error (MAPE) between actual and predicted discharges is 0.62% and 0.45%, for the first and second exponential terms, respectively. As **Fig. 10b** shows, the recession curve of this spring is also well described by the QF (Eq. 3): the MAPE between actual and simulated discharge is 0.54% and 0.52% for the first and second quadratic terms, respectively. The fact that the depletion process is described by both EF and QF implies that the Senatello has some geological water storage below its elevation, like the lower spring shown in **Fig. 8a**. This information is consistent with the geological setting, which indicates a maximum depth of about 200 m for the aquiclude substratum under the outlet of the Senatello spring (cfr. geological section of **Fig. 4**).

Although the discharge data of the other springs listed in **Table 2** refer to a different observation period (2005), the recession curve of spring 25 (also fed by the base aquifer in SMN) can be adequately described by both EF and QF (**Fig.s 11a-b**): the MAPE values between actual and simulated discharges are 0.9% and 1% for EF and QF, respectively. Of interest is the behaviour of spring 26, located a few hundred metres NW of spring 25. The latter is also fed by the base aquifer, but is about 50 m higher than spring 25. As in spring 25, the recession curve of spring 26 (**Fig.s 11c-d**) is described by both equations (2) and (3): the MAPE values between actual and predicted discharges are 9% and 10% for both equations, respectively. As the recession period proceeds, about 32 days later, the discharges very rapidly approach zero. This phenomenon may be interpreted in the terms shown in **Fig. 9**, in which spring 26 is the upper one: the groundwater level drops below the spring outlet and discharge approaches zero in a finite time.

FIG. 10

FIG. 11

The behavior of springs fed by perched aquifers is quite different from that fed by base aquifers. As shown in **Fig. 12a**, the recession curve of the Tiber spring (no. 8) is clearly described by QF: the MAPE between actual and predicted discharges is 1.42% (**Fig. 12**). A best fit with EF gives a much higher MAPE. This is consistent with the conceptual models of the quadratic formula and of perched aquifers: both imply nil or negligible thickness of the aquifer and also no storage below the outlet (cfr. **Fig. 8a**).

FIG. 12

5. Discussion

Within the framework of the environmental problems created by increasing water demand and climate change, this research examined one typical Mediterranean headwaters area.

As the MFP is isolated, i.e., it has no connections to other underground systems, the water budget was conceptually easy to estimate. This characteristic, despite few data, allowed us to assess the water yield evolution of the MFP over the last six decades. Both the water balance and analysis of reliable rain and temperature time series, revealed apparently previously unnoticed problems, i.e., an increasing number of drought periods, a clear-cut trend of increasing temperature, and a seasonal decrease in rainfall. All these occurrences can be interpreted as the effects of the ongoing world-wide climate change, which have now been acting for several decades. Both our study approach and its results could be extended to other areas having similar geological settings and climatic characteristics, i.e., hydrogeologically isolated systems, and areas where evapotranspiration can only be estimated from temperature and rainfall data.

The temperature trend found at the Verghereto station (i.e., on the MFP) is consistent with trends found in other meteorological stations in Central Italy. Our findings regarding rainfall are supported by a recent work by Antolini et al. (2016): in the region including the MFP, these authors found a decreasing trend in winter only. These results refine those of several previous works which, based on data-sets shorter than those considered here and with less accurate reliability analysis, indicate a more pronounced decreasing trend in rainfall (Di Matteo et al., 2006). The rainfall trend we detected during winter/early spring was weaker than that found in many stations in the river Tiber basin downstream from the MFP and in the eastern/southern Central Apennines (Vergni and Todisco, 2011; Di Matteo et al., 2013; Romano and Preziosi, 2013). These differences indicate great spatial variability in rainfall for the Central Apennines.

In the specific case of the MFP, there is great spatial variability of average yearly rainfall, even at short distance. This variability is demonstrated by the rainfall data from the Verghereto, Montecoronaro and Badia Tedalda stations in the 1961-1990 time-span (cfr. **Fig. 1** and **Table 3**). These thirty years are considered as a reference period in most works of the IPCC, the data of the three stations overlap and, as far as we can see, seem to be reliable. The stations are at most located 14 km apart, although the difference in elevation is not more than 150 meters: nonetheless, their mean yearly rainfalls differ by up to 14% (the difference between Montecoronaro and Badia Tedalda).

To preserve the environmental peculiarity of MFP and its capacity to supply drinking water, one of the aims of the present paper is to hypothesize what will likely happen to the water resources of the MFP during the next few decades. If this target is reached, Water and Environmental Agencies could prepare in advance the appropriate management strategies. In principle and considering the problem in general, i.e. at the world wide scale, General Circulation Models (GCMs) and Regional Circulation Models (RCMs) and their coupled approach - defined CMs by Mamalakis et al. (2017) - could solve the problem of generating reliable future climate scenarios. Up to this time, the modelling efforts demonstrated that it is "*virtually certain*" or "*extremely likely*" that anthropic greenhouse gas emission is the main driver of the atmosphere warming (e.g. IPCC, 2013 and 2014). At the same time, the modelling activity has shed much light on how the sub-systems composing the overall climate system react and influence each other while the atmosphere is warming up. However, from a practical point of view, the building of reliable future climatic scenarios, having a "small" uncertainty, is a complex problem. Up to the present day, this problem defied all the solution attempts, even using the most sophisticated CMs technics (for a similar point of view cf., for example, Beven, 2011). Practically all the papers about future climatic scenarios recognize this unpleasant situation. Just to be clear about this point, let us consider, among very many, the following examples, all related to the foreseeable fate of water resources. Guardiola-Albert and Jackson (2011), in a paper about the effects of climate change on the groundwaters of a major humid area in Spain, note that "*The results project that the change in climate by the 2080s, under a medium-high greenhouse gas emissions scenario, leads to a reduction in groundwater resources. The reduction in mean recharge ranges from 14%–57%*". These results are based on the output of 13 GCMs. More recently, Drouet et al. (2015) state: "*Many of the uncertainties surrounding climate change* *are difficult to quantify and depend on the judgement of experts and on the type of models used to generate future scenarios. Each model produces a distribution over the possible states of nature (e.g. cost of mitigation, temperature increase, or economic damages from climate change), and these distributions might differ from model to model*". In the introduction of a set of papers about the impacts of climate change in the Mediterranean, Ludwig and Roson (2016) write: "*However, it must be clearly stated that current uncertainties in climate projections and subsequent impact models, a yet incomplete understanding of the impact of a climate change signal on economic mechanisms or the lack of an elaborate and integrated human security conceptual framework are imposing strong limitations on water-related decision-making under conditions of climate change*". Finally, in a paper dedicated to the problem of "*bias correction and high-resolution downscaling of climate model rainfall*", Mamalakis et al. (2017), state: "*Despite the large number of GCM/RCM simulations currently available, and the many years of research dedicated in refining models' assumptions and conceptualization, CM results still exhibit considerable biases. This is especially true in the case of rainfall, as its intermittent character and highly variable nature at hydrologically relevant spatiotemporal scales challenge modeling attempts. ....* ". The last authors, among many others (e.g. Thompson et al, 2016; Stigter et al., 2012), list briefly the main reasons why the projections of future climate are so uncertain.

In the case of MFP, the spatial variability of rainfall adds further difficulty to the problem of generating reliable and narrow ranged future scenarios, as usually it happens in the case of orographically complex regions (Viviroli et al., 2011; Camera et al., 2016). If nothing else, this difficulty arises because GCMs and RCMs simulate rainfall scenarios as one single average over large areas, so that high spatial variability is lost (IPCC, 2001; Buytaert and De Bièvre, 2013; Dragoni et al., 2015). In our case, spatial variability is enhanced because MFP is located on the watershed between the Adriatic and Tyrrhenian seas. Both the basins of these two seas have a Mediterranean climate but differ in terms of winds and precipitation patterns. As in the Alpine ridge, which divides the Mediterranean and Atlantic or Continental climates, this situation clearly influences the spatial distribution of precipitation and future projections (Benitson and Stoffel, 2013). These difficulties may perhaps be overcome only by the use of high-definition RCMs, with rainfalls averaged over cells having sides of less than 10-15 km. In spite of all the uncertainties, the available studies about the future climate of western Mediterranean indicate a decrease of the water resources, at least in qualitative terms. Indeed, according to all the recent research, the temperatures of the western Mediterranean basin will continue to increase, while average yearly rainfall will, in general, decrease. For instance, the IPCC (2013) states: "...... *drying in the Mediterranean, southwestern USA and southern African regions are consistent with projected changes in the Hadley Circulation, so drying in these regions as global temperatures increase is likely for* *several degrees of warming under the Representative Concentration Pathway RCP8.5. Decreases in runoff are likely in southern Europe and the Middle East* " (IPCC, 2013). In an important paper focused on the Mediterranean climates, Alessandri et al., (2014) following a probabilistic approach and the Köppen and Geiger climate classification, conclude that by 2070-2100 the climate of Italy, Spain, Greece and Middle East very likely will evolve from Mediterranean to Arid.

In a more recent work, based on a multiple CMs approach, Bucchignani et al. (2016), built two scenarios of temperature and rainfall over Italy. Their two scenarios regard the period 2070-2100, compared to the period 1971-2000. These scenarios are based on the Representative Concentration Pathways RCP8.5 and RCP4.5, corresponding respectively to the highest and middle increase of greenhouse forcing agents forecasted by IPCC (2014). According to the results reported in the paper, in the area of MFP, the average linear gradient of temperature in the time interval 2000 - 2100 would be around +0.063 C°/year for RCP8.5 and +0.032 for RCP4.5. The rainfall would decrease of about 200 mm by 2100 under the RCP8.5, while there is no significant change under RCP4.5.

To have an idea of the future water resources in the MFP for the next thirty years, we carried out a water budget according to Eq. (1) and the Turc method, using the results of Bucchignani et al. (2016). We considered both the RCP8.5 and RCP4.5 scenarios and assumed the trends of rain and temperature to be linear. The RCP8.5, for the time interval 2014-2053, corresponds to a decrease of about 16% of the water available (WYI) in 1981-2013; the RCP4.5 corresponds to a decrease of about 5%. It is interesting to note that if we extrapolate the Verghereto series to the next three decades, assuming as in the past a temperature increase of 1.7 °C and no change in yearly rainfall, we obtain a WY1 decrease around 8%. This value is well within the range obtained from the modeling results of Bucchignani et al. (2016) and close the RCP4.5 scenario. These projections have a rather large range in terms of temperature, rainfall and water resources. If we had considered other papers, we would have even a wider range: for instance, according to the already mentioned work by Alessandri et al., (2014), by 2100 the climate in the region of MFP should be classified as Arid. This hypothesis is not consistent with the results by Bucchignani et al. (2016). In their paper, the worst scenario (for the temperature similar to the worst scenario of IPCC, 2013) would have an average temperature around 18.2 °C, and average rainfall and WYI around 1120 mm/year and 330 mm/year, respectively. By any means, these figures do not correspond to an arid or semiarid climate: just for example, let us consider the De Martonne Aridity Index (DMAI), as reported in Baltas (2007). This index, largely used, is given by the formula (4), where P and T are respectively average yearly precipitation (mm) and average yearly temperature (°C):

$$DMAI = P/(T+10) \quad (4)$$

A climate is classified semiarid if DMAI < 20 and arid if DMAI < 10: the worst projections of Bucchignani et al. (2016) correspond to a DMAI > 39, i.e. to a temperate-humid climate. Assuming that the increase in temperature will be as high as that of Bucchignani et al. (2016), i.e. similar to the worst projection of IPCC, the MFP climate would evolve to semi-dry only if the average rainfall on MFP drops around 570 mm/year. This dramatic scenario can appear unrealistic but cannot be excluded. This projection corresponds to a shifting of about seven hundred kilometers towards North of the present climate of Sicily, located about half way between the Italian peninsula and North Africa. In Sicily, most of the average yearly rainfall is less than 700 mm (Cannarozzo et al., 2006) and for the time interval 1921-2000, 78% of the years are classified semiarid or arid (D'Emanuele et al., 2010). In the western Mediterranean area, during warm periods, many pieces of evidence indicate the shifting of about one thousand kilometers towards North of the arid or semiarid southern climate (e.g. Dragoni, 1998; Ortolani and Pagliuca, 2009). The last authors, by archaeological, geological and palaeoclimatological data and using the Köppen and Geiger classification, studied the past climate variations in peninsular Italy. The conclusion was that in the Italian area, during the last two and half millennia and for natural causes, the semiarid areas expanded and contracted North-South a few times, with increasing aridity during the warm periods. Furthermore, these findings are consistent with the results obtained by Dragoni (1998): in peninsular and insular Italy, most of the meteorological stations show a statistically significant negative linear correlation between average yearly temperature and yearly rainfall. This correlation suggests that, over the western Mediterranean area, if the future temperature increases the average yearly rainfall will decrease in a significant manner. We have to conclude that, no matter if we use sophisticated approaches (i.e. CMs or complex statistics) or simple approaches (i.e. black box correlations, extrapolations of present trends and similitudes with local past climate changes) our quantitative knowledge about the future climate on the MFP remains uncertain. However, this scanty knowledge is not useless, as all the approaches indicate that there is a very high probability of having in the next future a further and significant decrease in water availability.

Due to the increase in temperature, the water crisis will be enhanced by the decreasing numbers of snowy days and by the anticipation of snowmelt. Both these phenomena will influence surface runoff and groundwater recharge, which will occur mostly in late winter rather than in spring so that the future dry season will be longer than at present (cf. for example, Kohler et al., 2014). This picture is worsened by the fact that most GCMs forecast for the same region an increase of temporal variability of precipitation, with an increase of extreme events (Iglesias and Garrote, 2014; IPCC, 2014; Thornton et al., 2014). This scenario is consistent with the fact that the number of droughts we observed in the MFP in the most recent decades is higher than in the previous ones: as the average yearly rainfall decrease is negligible, it follows that rainfall variability increases. The picture here presented, albeit not quantitative as desirable, is a serious caveat about the future of the environment and water resources of MFP. This scenario should stimulate projects and actions to minimize the impacts of the foreseeable evolution of climate. In our opinion, these actions should rely mainly on a proper management of the MFP groundwater: the following paragraphs discuss this issue in some detail.

The study of depletion periods, together with knowledge of the geological setting, identified various types of springs: those fed by perched aquifers and others fed by the base aquifer. The latter, in turn, may be a High Elevation Spring (HES) or Low Elevation Spring (LES). For the former, as the recession period proceeds, discharge will approach zero in a finite time. The springs most sensitive to drought are those fed by perched aquifers and those of HES type. Instead, resilient springs are those of LES type, which have live water storage larger than the other two types (**Fig. 8a**). In addition, LES type springs also have large permanent water storage, i.e., water stored below the elevation of the spring outlet. This water does not flow out when the piezometric head in the reservoir drops below the spring elevation, and it is not naturally available for man and the surface environment. This type of spring is a key resource for water management, in both terms of drinking-water supply and habitat conservation, in the MFP and in all other similar hydrogeological settings. When the water demand is larger than the natural spring discharge, even if the discharge is nil, more water can be temporarily obtained from pumping wells located upstream of the spring outlet. This may satisfy the demand for water, but it lowers the piezometric head much more than natural discharge, and can also remove water from permanent storage. Nonetheless, water obtained during drought can be regained during the following recharge period, if artificial removal is halted. These actions correspond to regularising the spring discharge. Rather than using wells, a better approach for obtaining water would be to use sub-horizontal drains tapping the aquifer zone below the spring outlet, so that the permanent storage area can be exploited through gravity flow (cfr. **Fig. 8a-b**). This solution is an improvement on the usual vertical wells, because no energy is required to pump out the water. It is not efficient in the case of springs fed by perched aquifers, which do not have any significant water storage below their elevations (**Fig. 8b**). Exploiting aquifers and regularising springs using sub-horizontal drains, is far from new (cfr. Coffield, 1947; Boni, 1968; Welchert and Freeman, 1973; Celico et al., 1980; Kullman, 1984; Stevanovic, 2010). The advantages of the sub-horizontal drains, when there is a significant permanent groundwater storage, and the geological and topographical features are favourable, are well known. For instance, Kullman (1984), describing the Biele Vody spring in Slovacchia, exploited by one horizontal drain, stated that the drain regularized the discharge, with advantages for the water supply and the environment. At present, notwithstanding the advantages, using wells is much more frequent than using horizontal drains, even when the geological setup is favourable to the second option. The main reason for the little use of sub-horizontal drains is that their drilling cost is higher than that of vertical wells: this is not a rational choice as in the long term the sub-horizontal drains are cost-effective.

We would like to point out here that our investigations have shown that examination of the depletion processes of a spring can give good information about its hydrogeological structure and suitability for being managed by means of gravity-flow schemes. This information is important because it can help to reduce the expense of other direct or indirect geological investigations. To avoid over-exploitation, it is essential to use drains only during drought periods: permanent sustainable management will in fact require continual analysis of the spring water budget, with the aim of extracting water, on average, in quantities no larger than the average yearly recharge (Stevanovic, 2010; Boni and Petitta, 1994).

It is interesting to note that, in the case of the MFP and similar geological structures delimited by no flow boundaries and punctual springs, setting the maximum average total water output from the base aquifer to the average yearly recharge corresponds to sustainable water management. This statement rests on two main reasons. The first is that the approach can consider both water supply and habitat conservation requirements. The second is that changes made by the proposed management will only involve the regimen of local base springs and will not influence other contiguous water systems, as might occur in other areas with more complex hydrogeological settings than the MFP. This last point is a topic of active research (cfr. as an example among many, Gorelick and Zheng, 2015). The management approach suggested here is useful both for water supply and for the protection of habitats of endemic species. As reported by EU Habitats Directive 92/43/EEC, EU Member States must take measures to ensure long-term conservation of the habitats of these species. In areas like that of Monte Fumaiolo, knowledge of the response of springs to climate is an inevitable step in trying to ensure the survival of threatened amphibian species, such as *Bombina pachybus, Salamandrina terdigitata, Triturus carnifex* and *Ichthyosaura alpestris*. According to Silva et al. (2007), in the Mediterranean region, due to the lack of consideration in land-use decisions, ponds are frequently damaged or destroyed when the landscape is modified. This carelessness is a worldwide problem, noticed by several authors (Zektser et al., 2005). Ponds often are temporary, since they experience annual dry periods and are subject to substantial inter-annual hydrological fluctuations; up to a certain extent and as long as the agriculture activity does not involve the wet area (temporary dry), amphibians are adapted to such changes (Silva et al., 2007). The artificial water management of ponds proposed here, thanks to the drains which would shorten the no-water periods, can be particularly useful to remember the existence of the ponds and to protect them. In fact, to maintain and restore the landscape and environmental features, water on small rivers and ponds should also be ensured during prolonged periods of drought (Canestrelli et al., 2014).

Of the many potentially eligible areas in which to dig ponds, two promising sites (**Fig. 13**) are located in the north-eastern part of the MFP (near spring 25, sites A and B) and along the stream on the north-western boundary of the system (west of spring 31, Site C). In these areas, thanks to water emerging from punctual or linear springs and fed by the base aquifer, some small ponds could be created and/or maintained which, thanks to sub-horizontal drains, would not dry up frequently in summer or even during prolonged periods of drought. A similar approach could also be applied to other areas worldwide and in particular in the Mediterranean region, assuring the maintenance of wet habitats during prolonged drought and reducing landscape modifications.

FIG. 13

6. Conclusions

On the basis of the results of study carried out, we can draw the following conclusions:

- Analysis of MFP climatic data indicates a significant increasing trend in temperatures on various time-scales (from annual to seasonal). As regards rainfall, no significant trend at annual scale has been identified; however, a significant negative rainfall trend occurs in the recharge period (JFMA), as in many areas of Mediterranean basin.
- The SPI, WSVI and RDI indexes show a notable increase in the length and frequency of droughts. The most severe have occurred during the last two decades.
- The general reduction in rainfall during the recharge period and the increase in temperature both affect the water availability of the MFP. In fact, according to estimated water budgets, the total water yield of the last 30 years is about 12% lower than that of the previous three decades. The high spatial variability of precipitation, even on a scale of 30-year averages, is a problem to be addressed in future research and interventions. This problem, important within the framework of climate change studies, is common to many other mountain areas of the Mediterranean basin.
- Careful study of the depletion period of springs allows convenient and economical identification of the hydrogeological structures suited to mitigate periods of drought by sub-horizontal drains. These springs should be accurately monitored.
- If the future water crisis is severe, as all the evidence indicates, conflicts will arise between the environment and water supplies. To minimise such conflicts, water management plans must be activated well in advance, before the crisis is precipitated.

Lastly, we believe that it is important to note, again, the importance of many reliable and continuous hydrometeorological data. These data are often missing, especially in mountain areas: in spite of official worries about climate change and high-level debates, in many areas of the world the number of measuring stations is decreasing (Lorenz and Kunstmann, 2012). If this problem is not properly addressed, the possibility of dealing effectively with the impact of climate change on water resources is rather poor.

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Figures and Tables

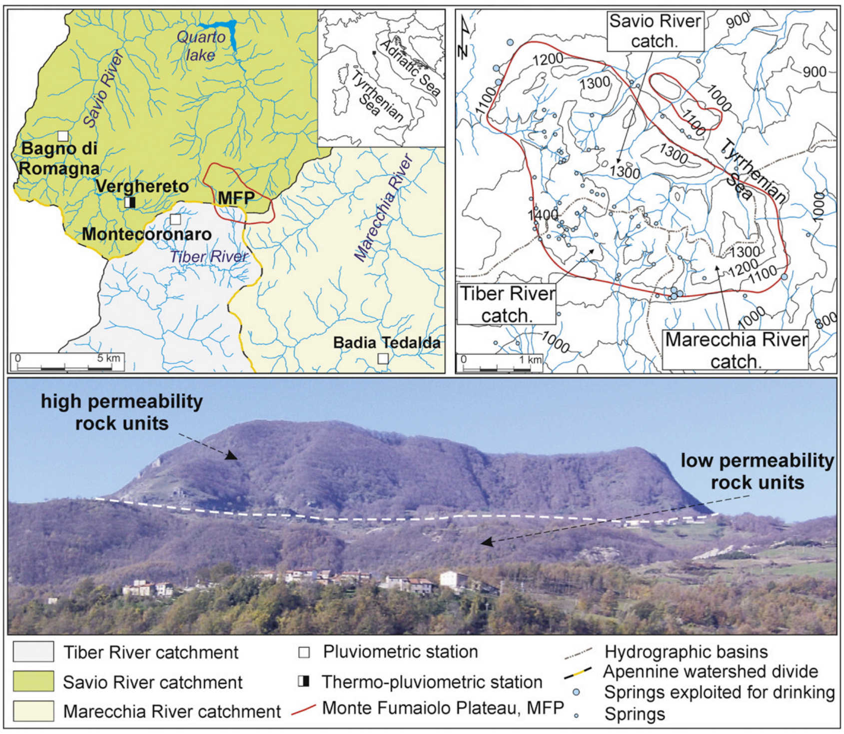


Fig. 1. Location of Mount Fumaiolo Plateau (MFP) with thermo-pluviometric stations and springs. Panoramic photo taken from SSE.

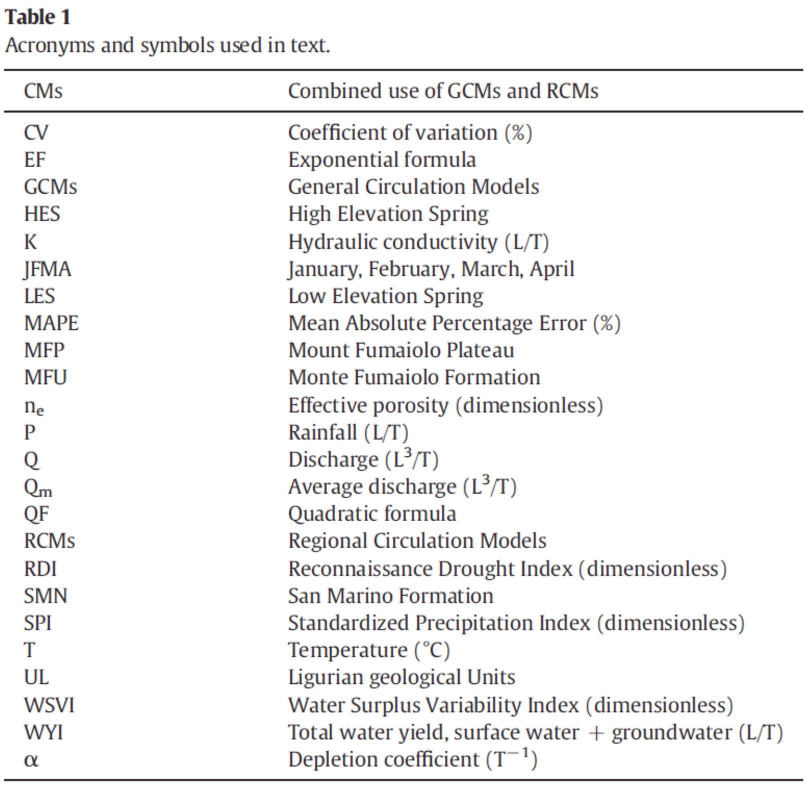


Table 1
Acronyms and symbols used in text.

CMs	Combined use of GCMs and RCMs
CV	Coefficient of variation (%)
EF	Exponential formula
GCMs	General Circulation Models
HES	High Elevation Spring
K	Hydraulic conductivity (L/T)
JFMA	January, February, March, April
LES	Low Elevation Spring
MAPE	Mean Absolute Percentage Error (%)
MFP	Mount Fumaiolo Plateau
MFU	Monte Fumaiolo Formation
n_e	Effective porosity (dimensionless)
P	Rainfall (L/T)
Q	Discharge (L^3/T)
Q_m	Average discharge (L^3/T)
QF	Quadratic formula
RCMs	Regional Circulation Models
RDI	Reconnaissance Drought Index (dimensionless)
SMN	San Marino Formation
SPI	Standardized Precipitation Index (dimensionless)
T	Temperature (°C)
UL	Ligurian geological Units
WSVI	Water Surplus Variability Index (dimensionless)
WYI	Total water yield, surface water + groundwater (L/T)
α	Depletion coefficient (T^{-1})

Table 1. Acronyms and symbols used in text.

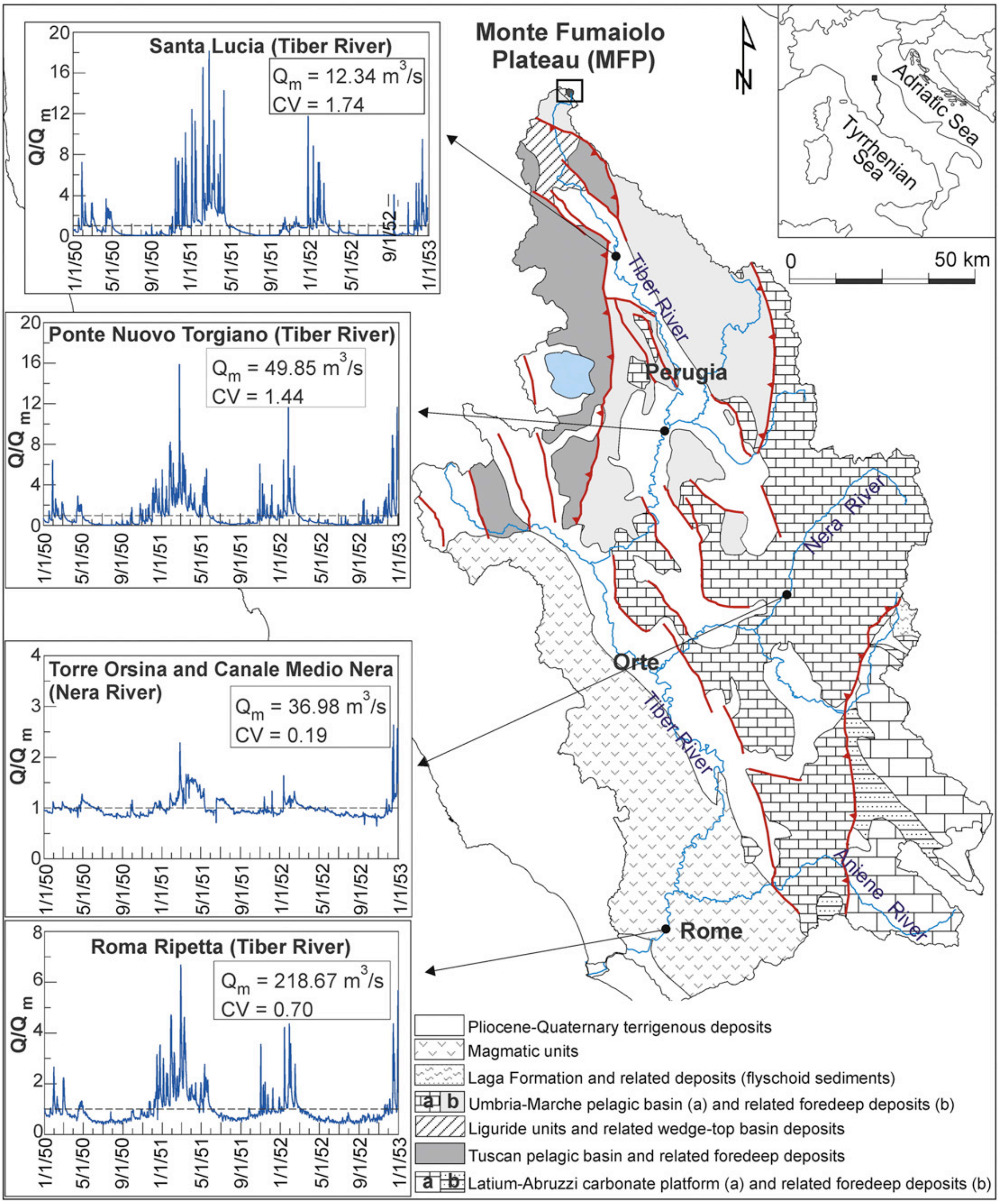


Fig. 2. Geological map of Tiber basin (modified from Butler et al., 2004, and Boni and Bono, 1982). River discharges refer to 1950-1953 (before two large dams, Corbara and Montedoglio, were built). Upper part of Tiber catchment characterised by rocks of low permeability; middle-lower part contains limestone and magmatic rocks of medium to high permeability.

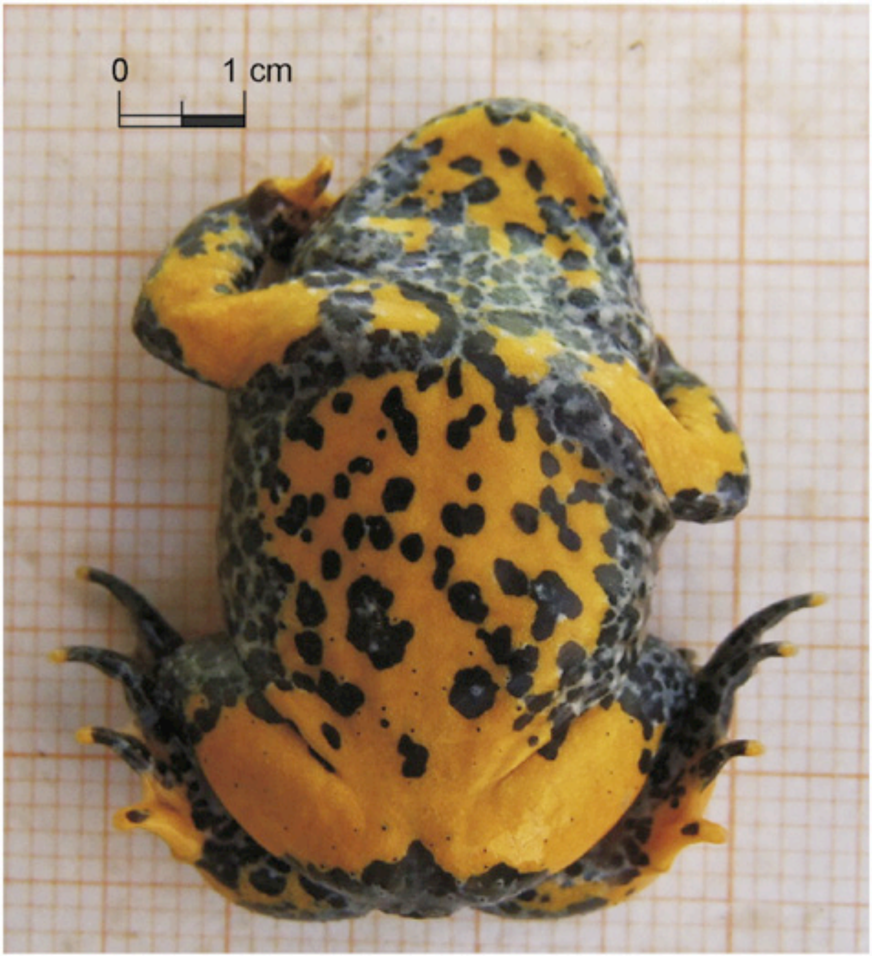


Fig. 3. *Bombina pachypus* in ventral view (photo by Lorenzo Talarico, University of Rome Tor Vergata, Italy).

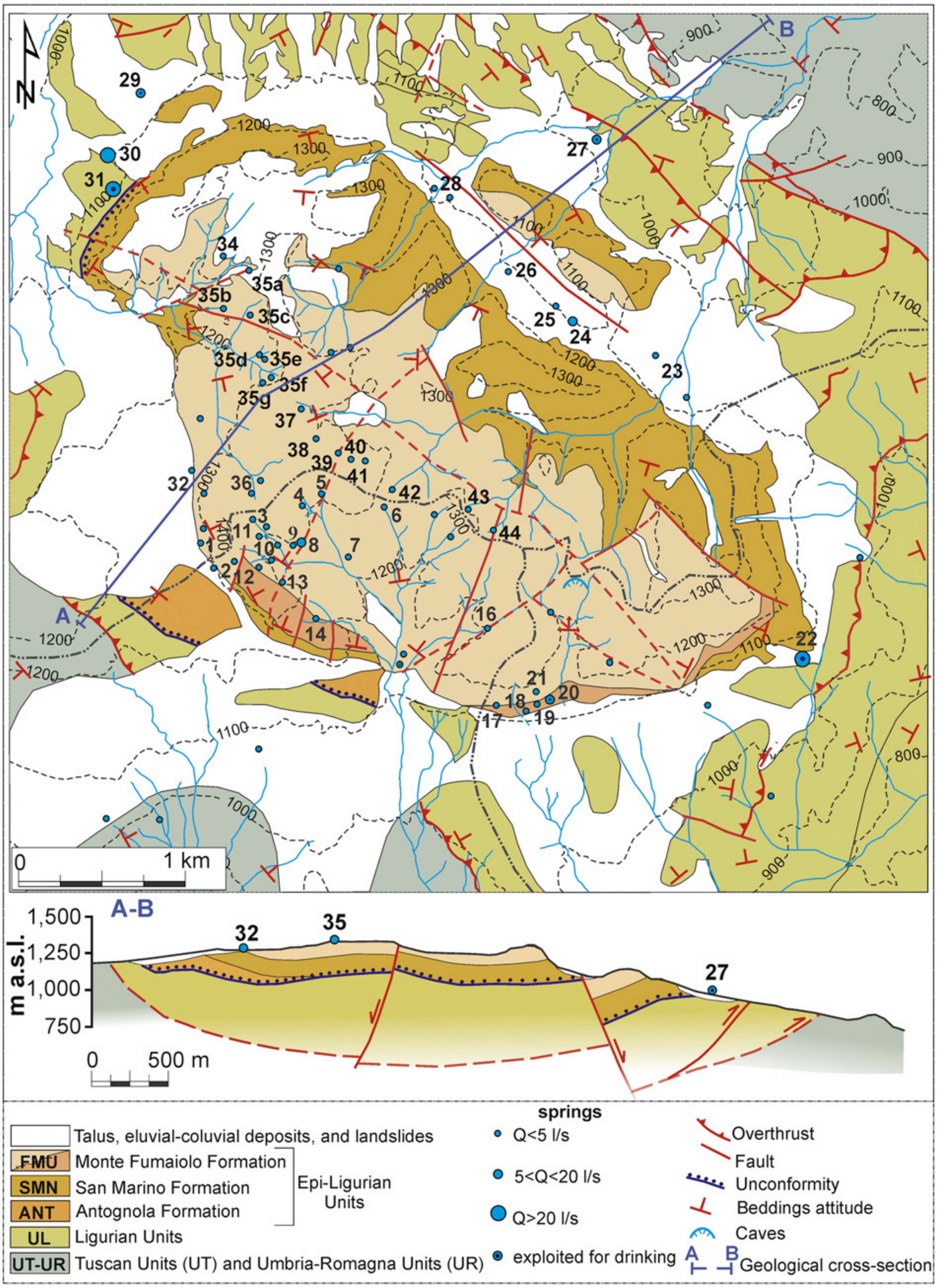


Fig. 4. Geological map of study area, with location of springs and geological cross-section approximately oriented NE-SW. Adapted from CARG geological maps CARG (2009). FMU = calcareous sandstone and sandy marl (medium relative permeability); SMN = limestone (high relative permeability); ANT = marl (low relative permeability); UL = marly clay (very low relative permeability); UT and UR = marly clay (low relative permeability).

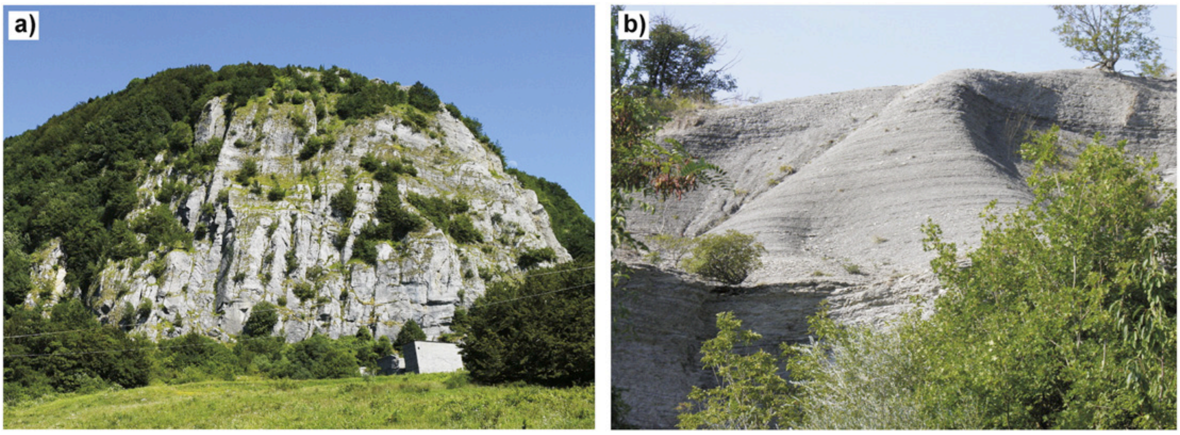
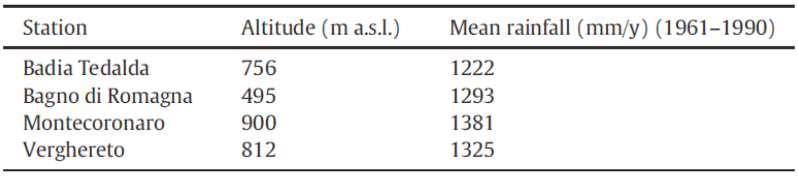


Fig. 5. a) Outcrop of Epi-ligurian Units in NW part of Mount Fumaiolo plateau (high-permeability rocks of San Marino Formation, SMF); b) very low permeability rocks belonging to Ligurian Units (UL). The latter acts as an aquiclude of groundwaters in upper formations (i.e., Epi-ligurian Units).

n.	Jul-04	Aug-04	Sep-04	Oct-04	Nov-04	Dec-04	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Year
1	0.14	0.10	0.10	0.17	0.32	0.44	0.41	0.21	1.09	0.94	0.25	0.21	0.37
2	0.05	0.04	0.03	0.04	0.23	0.32	0.32	0.07	0.35	0.36	0.13	0.06	0.17
3	0.02	0.01	0.01	0.04	0.09	0.25	0.25	0.02	0.11	0.28	0.05	0.03	0.10
4	0.10	0.05	0.01	0.03	0.88	0.45	0.45	0.31	1.36	0.63	0.27	0.05	0.38
5	0.18	0.15	0.11	0.19	0.26	0.19	0.21	0.15	2.00	1.14	0.71	0.34	0.47
6	0.08	0.00	0.00	0.00	0.34	0.16	0.16	0.11	0.55	0.22	0.10	0.06	0.15
7	0.09	0.02	0.02	0.14	0.41	0.62	0.61	0.39	1.79	1.52	0.19	0.15	0.50
8	0.93	0.41	0.38	0.59	3.02	13.61	13.45	1.23	6.92	14.35	6.38	2.78	5.34
9	0.78	0.57	0.53	0.60	0.81	1.79	1.77	0.25	1.29	2.76	2.19	1.14	1.21
10	0.41	0.23	–	0.31	1.48	3.17	3.13	0.73	3.72	0.73	0.54	0.43	1.35
11	0.10	0.08	0.06	0.05	0.46	1.34	1.32	0.91	4.68	1.25	0.25	0.18	0.89
12	0.01	0.00	0.01	0.02	0.03	0.03	0.03	0.01	0.02	0.04	0.02	0.01	0.02
13	0.00	0.00	0.01	0.04	0.14	0.24	0.24	0.09	0.48	0.32	0.10	0.09	0.15
14	0.15	0.10	0.09	0.10	0.43	0.49	0.49	0.26	1.80	2.19	0.47	0.43	0.58
15	0.30	0.18	0.14	0.61	1.78	1.94	2.49	1.68	4.74	2.10	0.69	0.43	1.42
16	0.80	0.40	0.20	0.83	1.90	2.80	2.77	1.62	8.30	5.60	2.90	1.31	2.45
17	0.04	0.01	0.01	0.01	0.01	0.21	0.33	0.34	0.32	0.26	0.15	0.08	0.15
18	0.29	0.27	0.24	0.22	0.27	0.16	0.26	0.27	0.25	0.19	0.26	0.28	0.25
19	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.06	0.06	0.05	0.05	0.05	0.05
20	7.20	6.80	6.48	5.93	7.25	4.42	6.41	7.43	6.81	5.14	7.12	7.25	6.52
21	–	–	–	–	–	–	–	–	–	–	–	–	0.93*
22	–	–	–	–	–	–	–	–	–	–	–	–	50*
23	3.10	2.30	2.10	2.30	5.20	5.20	5.10	3.60	5.60	6.00	5.10	3.70	4.11
24	0.24	0.01	0.00	0.02	4.76	5.82	5.75	1.53	7.83	6.85	1.83	0.81	2.95
25	7.34	5.60	4.95	5.45	12.42	12.39	12.24	8.46	13.41	14.35	11.59	8.94	9.76
26	0.98	0.22	0.00	0.00	0.71	1.92	1.90	0.44	2.27	2.88	1.91	1.38	1.22
27	14.89	11.51	10.21	17.12	24.58	25.51	19.47	12.30	17.87	28.48	22.62	18.10	18.56
28	0.44	0.16	0.00	0.00	0.54	1.07	1.06	0.52	2.69	3.41	2.26	1.06	1.10
29	–	–	–	–	–	–	–	–	–	–	–	–	19*
30	–	–	–	–	–	–	–	–	–	–	–	–	35*
31	–	–	–	–	–	–	–	–	–	–	–	–	
32	0.03	0.02	0.02	0.05	0.12	0.22	0.22	0.06	0.17	0.18	0.09	0.06	0.10
33	0.17	0.15	0.15	0.15	0.15	0.15	0.15	0.13	0.13	0.18	0.14	0.13	0.15
34	0.06	0.06	0.05	0.05	0.06	0.05	0.06	0.05	0.06	0.06	0.06	0.06	0.06
35	1.10	0.28	0.22	1.28	6.61	10.30	11.60	3.80	19.30	14.20	8.00	1.97	6.56
36	0.05	0.05	0.03	0.08	0.18	0.25	0.25	0.12	0.61	0.47	0.12	0.08	0.19
37	0.00	0.00	0.00	0.04	0.05	0.20	0.20	0.08	0.40	0.32	0.14	0.05	0.12
38	0.36	0.25	0.16	0.42	1.44	2.10	2.32	0.47	2.43	2.50	1.32	0.59	1.20
39	0.02	0.01	0.00	0.10	0.21	0.21	0.20	0.02	0.11	0.29	0.26	0.04	0.12
40	0.11	0.05	0.03	0.12	0.21	0.21	0.21	0.08	0.43	0.50	0.35	0.18	0.21
41	0.05	0.01	0.01	0.07	0.07	0.08	0.08	0.05	0.33	0.37	0.26	0.08	0.12
42	0.03	0.00	0.00	0.00	0.50	0.23	0.23	0.16	0.80	0.32	0.14	0.07	0.21
43	0.10	0.04	0.00	0.02	1.18	0.55	0.54	0.37	1.90	0.76	0.33	0.24	0.50
44	0.03	0.00	0.00	0.00	0.68	0.31	0.31	0.21	1.10	0.43	0.18	0.09	0.28
											l/s		~175
											Mm^3		5.52
											WYI (mm/year)		502

Table 2. Mean monthly and yearly discharge of springs (Q, l/s) in Monte Fumaiolo hydrogeological system: springs 1-16 belong to Tiber catchment, 17-22 to Marecchia catchment, 23-44 to Savio catchment. Springs are shown on geological map (Fig. 4). Data provided by HERA Group.



Station	Altitude (m a.s.l.)	Mean rainfall (mm/y) (1961–1990)
Badia Tedalda	756	1222
Bagno di Romagna	495	1293
Montecoronaro	900	1381
Verghereto	812	1325

Table 3. Characteristics of available meteorological stations (for locations, see Fig. 1).

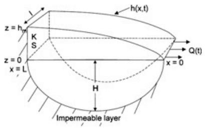
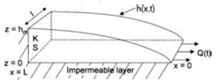
Name	Model	Formula	Linearization
EF Boussinesq (1877)		$Q_{(t)} = Q_0 \cdot e^{-\alpha \cdot t}$ (2)	$\ln Q_{(t)} = \ln Q_0 - \alpha \cdot t$ (2a)
QF Boussinesq (1903)		$Q_{(t)} = \frac{Q_0}{(1+\alpha \cdot t)^2}$ (3)	$\frac{1}{Q_{(t)}} = \frac{1}{\sqrt{Q_0}} + \frac{\alpha}{\sqrt{Q_0}} \cdot t$ (3a)

Table 4. Common conceptual models used for spring recession analysis (modified from Dewandel et al., 2003). Symbols: K = hydraulic conductivity; S = effective porosity; α = depletion coefficient; $Q_{(t)}$ = spring discharge at time t; Q_0 = initial flow rate at the beginning of the depletion period; l and L = width and length of system; H = depth under outlet level; h = hydraulic head.

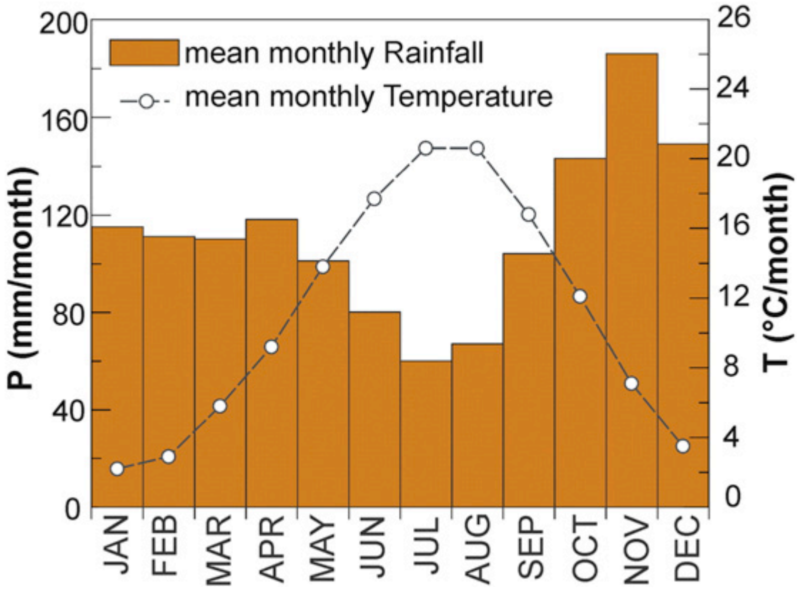
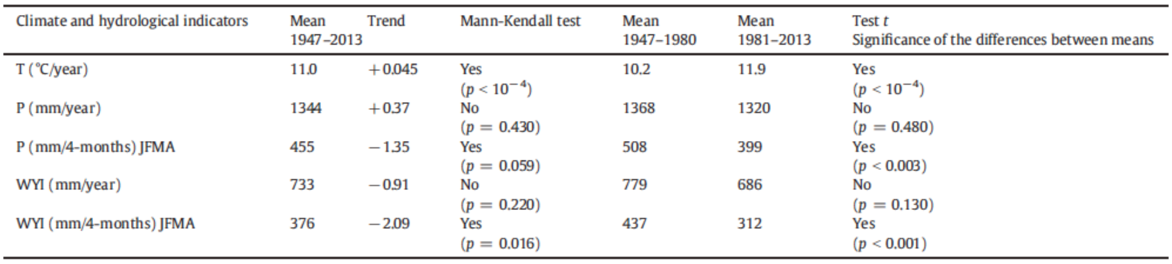


Fig. 6. Mean monthly rainfall, temperature and water yield according to data from Verghereto meteorological station.



Climate and hydrological indicators	Mean 1947–2013	Trend	Mann-Kendall test	Mean 1947–1980	Mean 1981–2013	Test *t* Significance of the differences between means
T (°C/year)	11.0	+0.045	Yes ($p < 10^{-4}$)	10.2	11.9	Yes ($p < 10^{-4}$)
P (mm/year)	1344	+0.37	No ($p = 0.430$)	1368	1320	No ($p = 0.480$)
P (mm/4-months) JFMA	455	−1.35	Yes ($p = 0.059$)	508	399	Yes ($p < 0.003$)
WYI (mm/year)	733	−0.91	No ($p = 0.220$)	779	686	No ($p = 0.130$)
WYI (mm/4-months) JFMA	376	−2.09	Yes ($p = 0.016$)	437	312	Yes ($p < 0.001$)

Table 5. Statistical analysis, on differing time-scales, of several climatic and hydrological indicators (climate data from Verghereto station). JFMA: January, February, March, April.

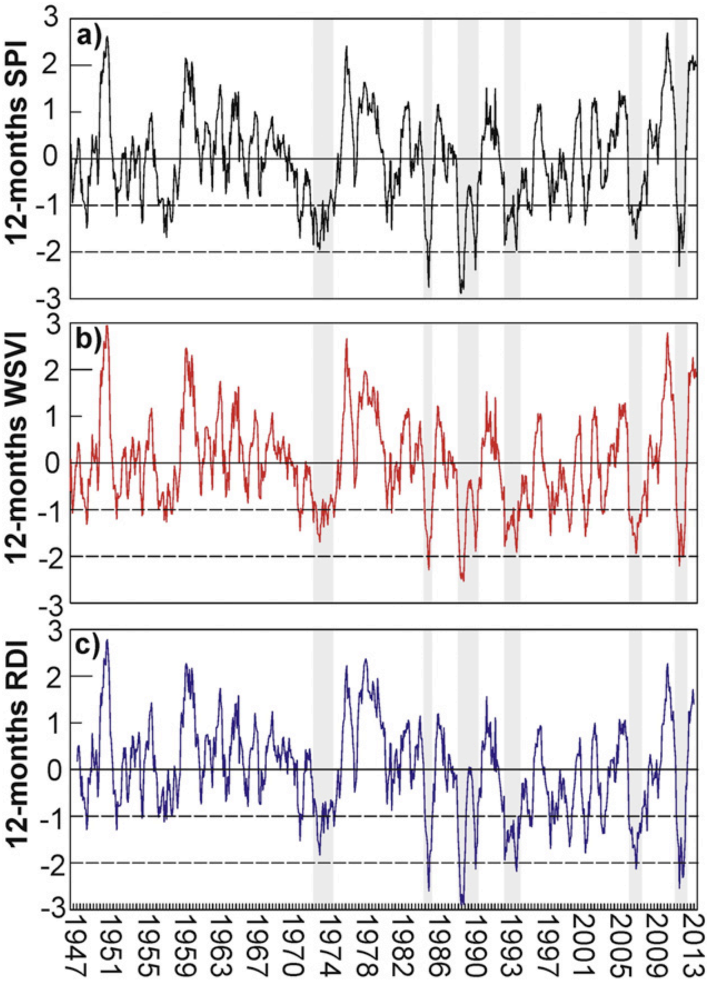
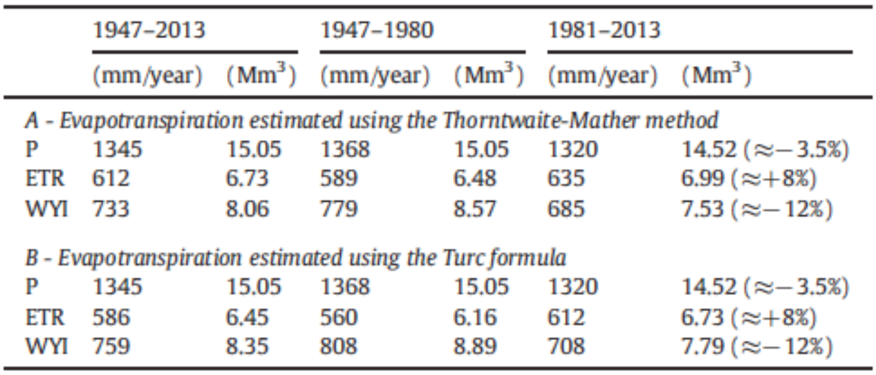


Fig. 7. a) 12-month SPI; b) 12-month WSVI; c) 12-month RDI, calculated from meteorological data of Verghereto station. SPI and RDI values calculated by DrinC software (Tigkas et al., 2015).



	1947–2013		1947–1980		1981–2013	
	(mm/year)	(Mm^3)	(mm/year)	(Mm^3)	(mm/year)	(Mm^3)
A - Evapotranspiration estimated using the Thorntwaite-Mather method						
P	1345	15.05	1368	15.05	1320	14.52 (≈−3.5%)
ETR	612	6.73	589	6.48	635	6.99 (≈+8%)
WYI	733	8.06	779	8.57	685	7.53 (≈−12%)
B - Evapotranspiration estimated using the Turc formula						
P	1345	15.05	1368	15.05	1320	14.52 (≈−3.5%)
ETR	586	6.45	560	6.16	612	6.73 (≈+8%)
WYI	759	8.35	808	8.89	708	7.79 (≈−12%)

Table 6. Simplified water budget of MFP, according to equation (1). Table A modified from (Di Matteo et al., 2016).

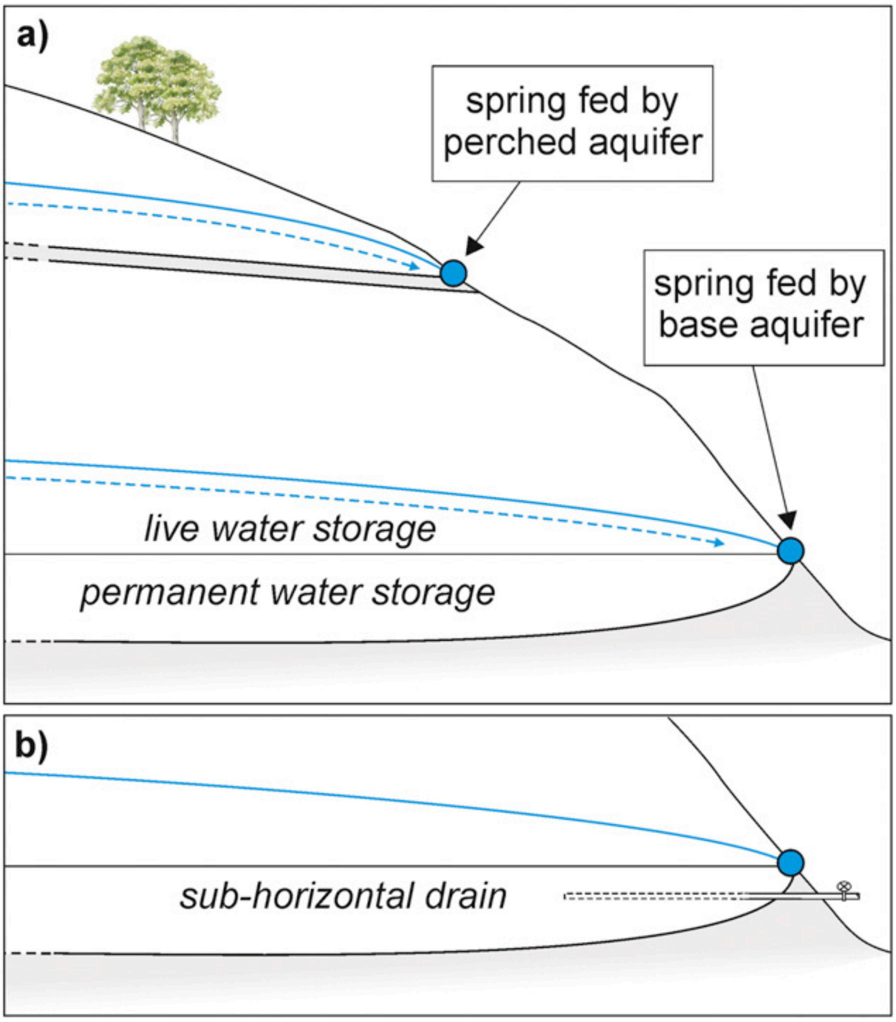


Fig. 8. a) Sketch of perched and base aquifers characterising Mount Fumaiolo hydrogeological system. b) Sketch of sub-horizontal drain fed by the permanent storage would regularize the spring yield (see the Discussion section).

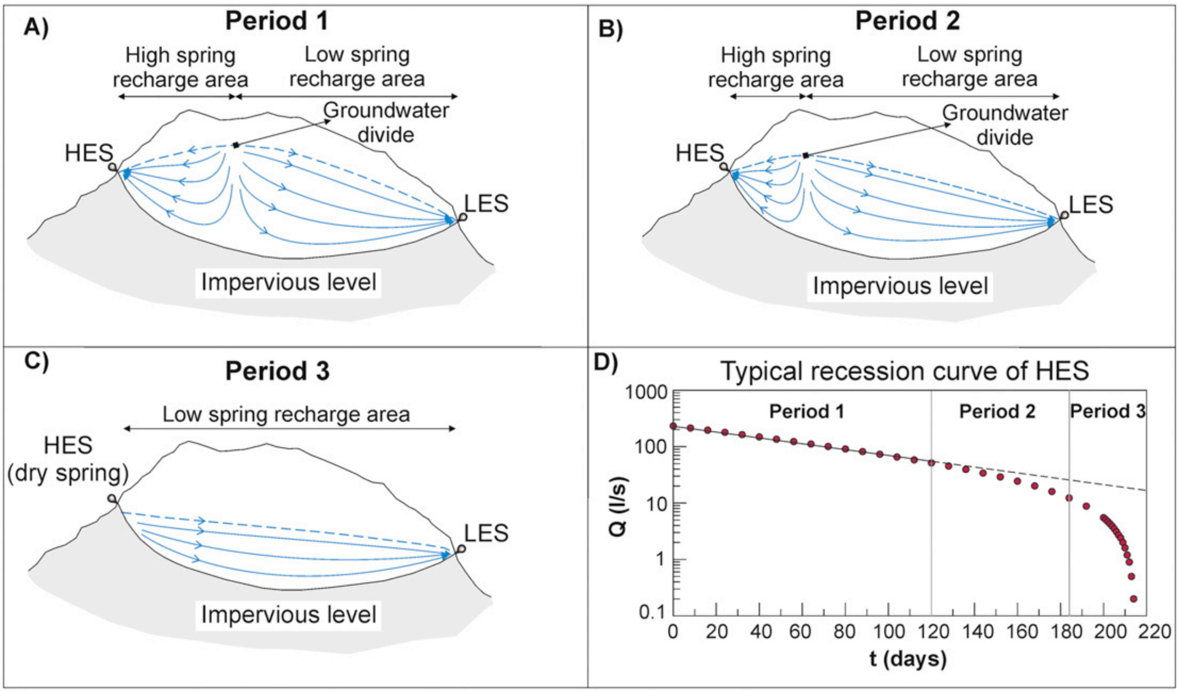


Fig. 9. Conceptual model of an aquifer feeding two springs, the recharge areas of which are divided by a hydrodynamic boundary. A) onset of depletion process; B) as water level falls, HES recharge area becomes smaller; C) when level drops below threshold, discharge of LES reaches zero; D) conceptual recession of HES spring. Modified from Cambi and Dragoni (2000).

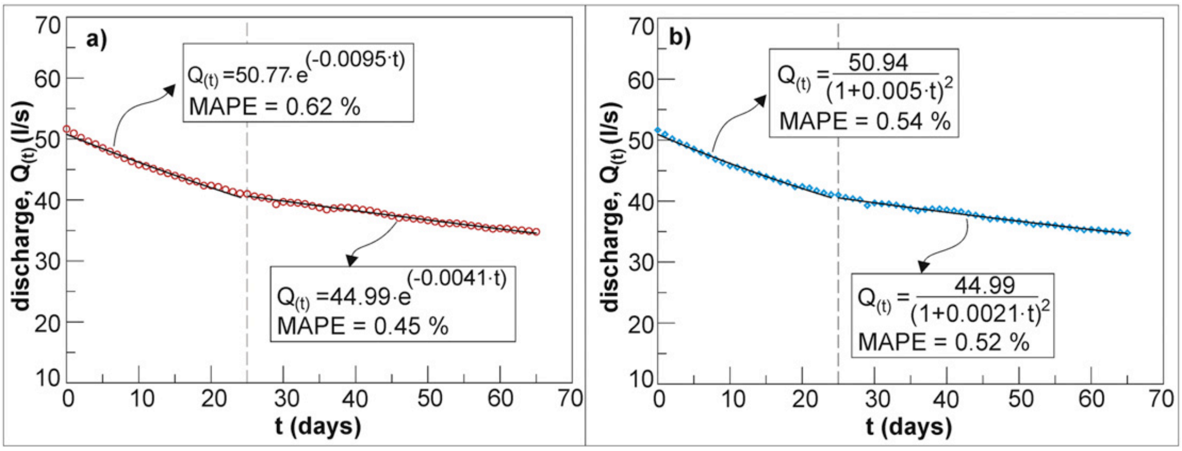


Fig. 10. Recession curve of Senatello spring 22 (2011) fed by base aquifer: a) depletion as described by EF, with two exponential terms; b) depletion as described by QF with two quadratic terms. Black dots: simulated data; red and blue dots: measured data.

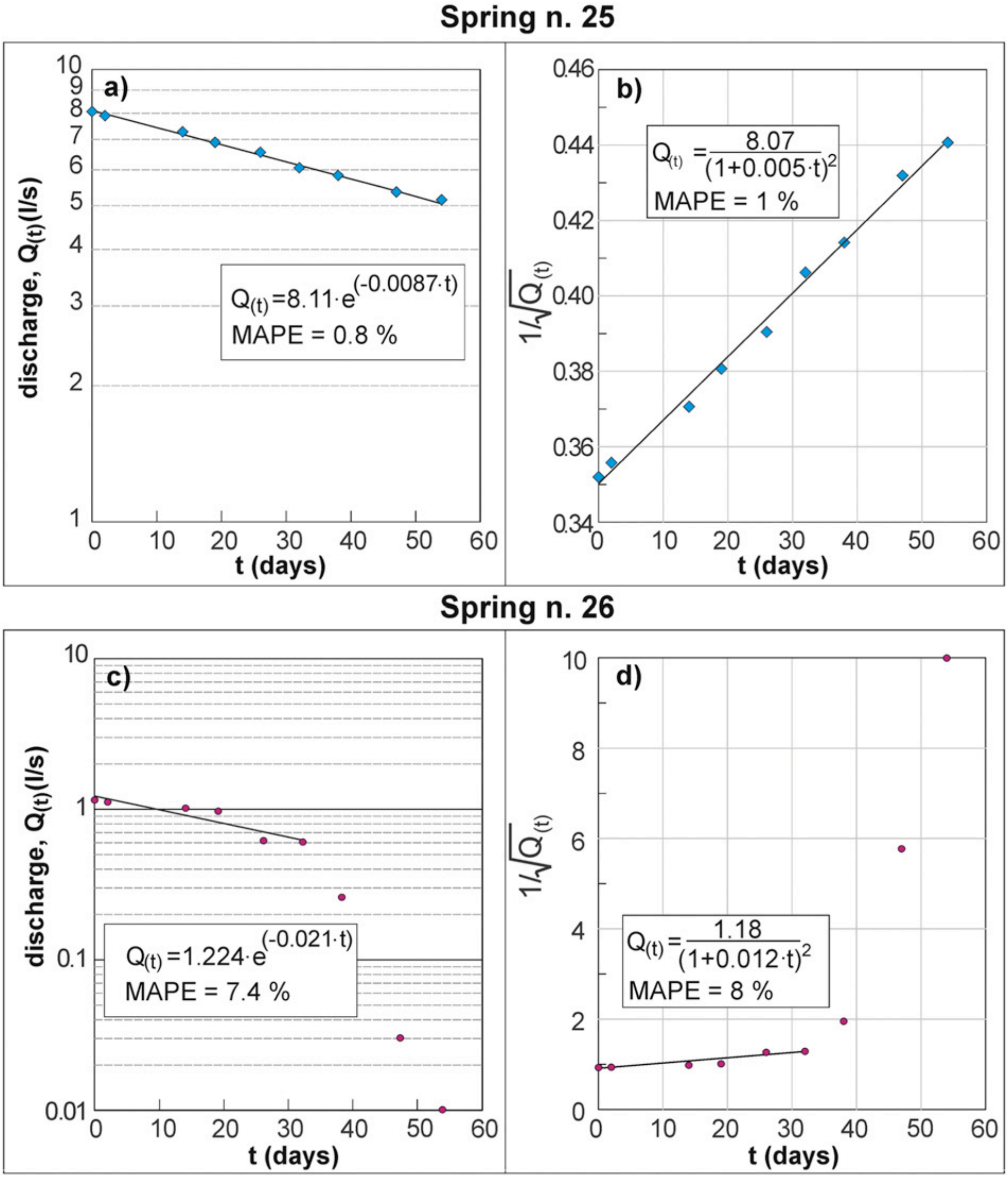


Fig. 11. Recession curves of springs 25 and 26, both fed by base aquifer; discharge was measured on the same days in 2005. Both springs (located a few hundred meters from each other) are described quite well by EF and QF: a) depletion of spring 25, fitted by EF; b) depletion of spring 25, fitted by QF; c) depletion of spring 26, fitted by EF; d) depletion of spring 26, fitted by QF. Note that, in spring 26, as recession period proceeds, after day 32, discharge is not described by EF as well as by QF, and in fact approaches zero. This is because spring 26 lies about 25 m higher than spring 25 (cfr. general sketch in **Fig. 9**).

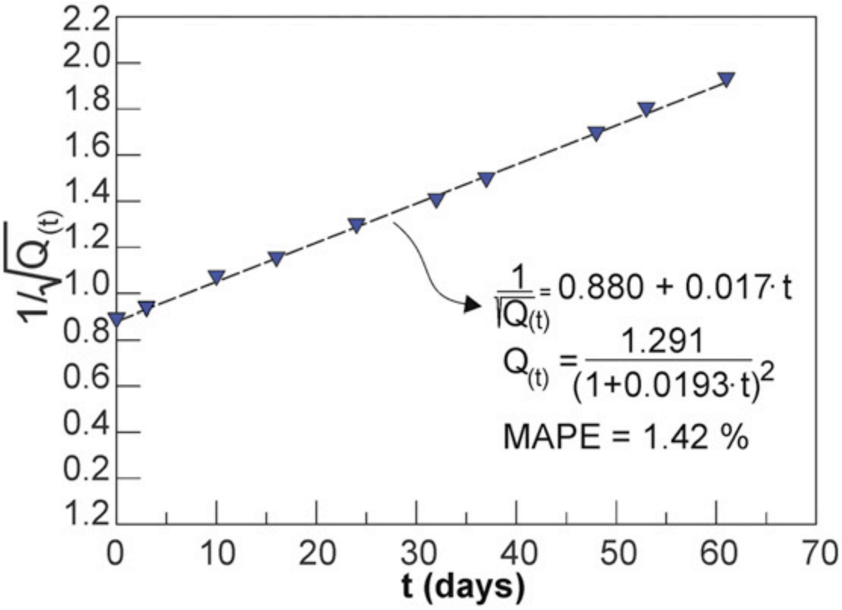


Fig. 12. Recession curve of the Tiber spring (n. 8) fed by perched aquifer as described by QF (**Table 4**).

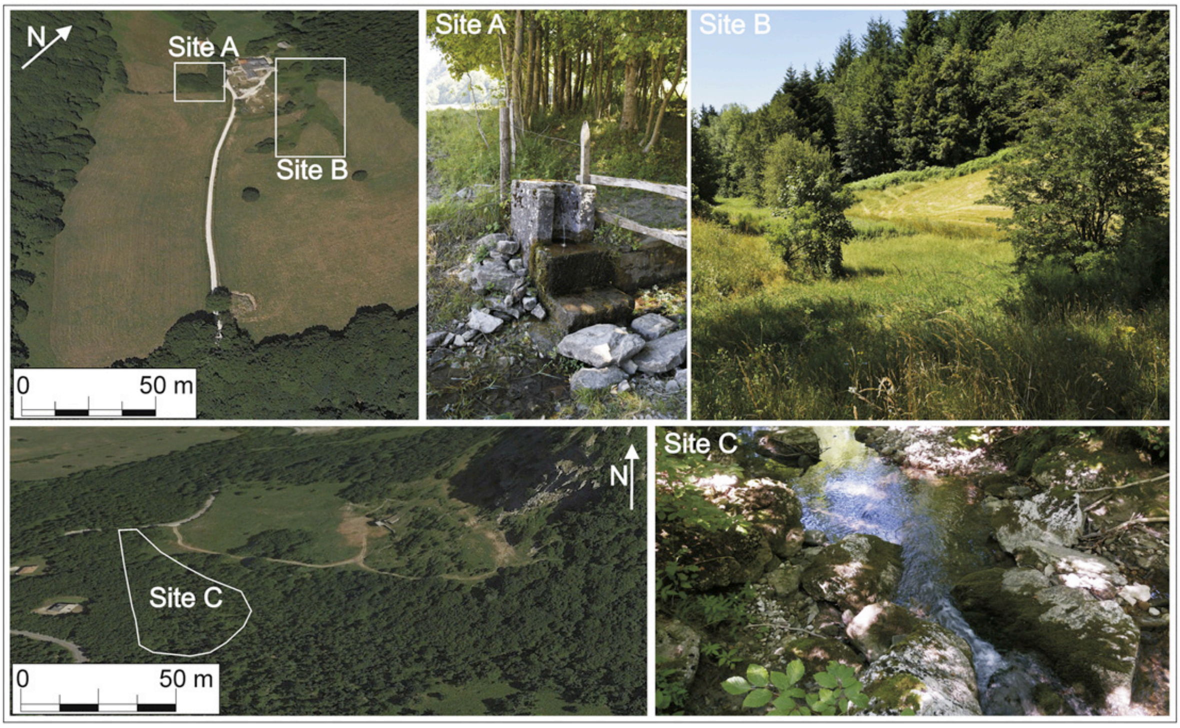


Fig. 13. Promising identified sites for restoration and habitat conservation: Sites A and B are close to spring 25 (**Fig. 4); ** Site C is located west of spring 31 (**Fig. 4**).