Hydrogeological study of data-scarce limestone massifs: the case of Gualdo Tadino and Monte Cucco structures (central Apennines, Italy)

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ABSTRACT This work presents a study on the geological framework and water budget of two limestone structures of the central Apennines (Gualdo Tadino Mountains and Monte Cucco, central Italy). Both massifs feed springs which supply high quality water. Since central Italy relies, to a large extent, on structures of this kind to meet water demand, understanding their groundwater circulation scheme is very important. Unfortunately, as in other cases, the need to define the hydrogeological scheme clashes with the scarcity of data available, especially in terms of discharge measurements. In the latest years, the realization of the importance of such data led the ARPA Umbria to equip some springs with new, continuous gauges that record the natural discharge. The new data available make the information more reliable than it was a few years ago, especially for the Gualdo Tadino Mountains. The work presented here is based on all the available instrumental measurements and on data coming from field surveys; although there is still a significant uncertainty on the discharge of several springs, the study allowed us to track the groundwater circulation scheme of the two massifs

1. Introduction

In temperate climates, mountain areas, particularly those composed of limestone, often contain significant amounts of high-quality groundwater, frequently exploited for drinking-water purposes. The need to protect mountain groundwater is currently a very real problem, due to widespread over-exploitation and pollution of other water resources. Furthermore, the need to protect groundwater in mountain areas is amplified by climatic variations; it is generally recognized that, in regions such as the Mediterranean, atmospheric warming is accompanied by a decrease in precipitation (Brunetti *et al.*, 2002, 2004a, 2004b; Di Matteo *et al.*, 2006; Trenberth *et al.*, 2006; EC, 2007; IPCC, 2007; Dragoni and Sukhija, 2008; Polemio and Casarano, 2008; Todisco and Vergni, 2008); such changes lead to a decrease in effective precipitation, which is expected to influence groundwater yield (Cambi and Dragoni, 2000; Dragoni *et al.*, 2003; Di Matteo *et al.*, 2009a). Despite this, both climatic and hydrogeological instrumental data are generally poor in mountain areas. However, for information on the best ways of managing their water resources, it is important to study their hydrogeological framework by using all available data; generally, despite certain uncertainties that can arise, the definition of a conceptual model is necessary even for systems for which the data are scanty, as noted by the EC Water Framework Directive, and reported by Gaus and Ó Dochartaigh (2000).

This work presents a hydrogeological study of Monte Cucco and the Gualdo Mountains, two contiguous limestone anticline structures within the Umbria-Marche Apennine chain (central Italy), that feed many high-quality springs exploited for drinking-water purposes (Fig. 1).

Although these structures are of strategic importance for supplying water to many areas of central Italy, they still do not have good hydrometeorological data. Nevertheless, according to the Italian law on the Environment (DM 152/2006), it is necessary to define both the hydrogeological scheme and a conceptual model of significant hydrogeological bodies and to evaluate their water balance. The study defines a conceptual hydrogeological model of the two strategic structures and evaluates their water budget analysing the available hydrometeorological data and examining the geological setting. This study highlights the main data deficiencies and suggests how data should be integrated to get more reliable quantitative information.

2. Experimental procedure

In the study areas, hydrometeorological data, understood as a continuous historical instrumental monitoring of temperature, precipitation and other weather parameters, and as spring and river discharge measurements, are generally scanty, as in most of the mountain areas of central Italy. A few precipitation and temperature stations are located within the study area, and just one of them (on Monte Cucco), which has been operating only since 1996, is located at the average elevation of the two structures (910 m AMSL for Monte Cucco and 1020 m AMSL for the Gualdo Mountains).

Nevertheless, the worst situation concerns the discharge measurements. As far as the Gualdo Tadino Mountains are concerned, the Capodacqua spring has the longest time series recording natural discharge, as it has been monitored continuously since 1997 by means of an ultra sound gauge, and the data are released at daily intervals. Due to the increasing awareness of the importance of knowing the natural spring discharge, in the past few years (starting from July 2007), the ARPA Umbria (Agenzia Regionale Per l'Ambiente) has equipped three more springs surrounding the Gualdo Tadino Mountains (Vaccara, Boschetto and Cappuccini) with gauging stations of the same kind as the one operating on the Capodacqua spring, which continuously measure the discharge rates, meant as the sum of the withdrawal and the surplus. Since 2003, another important spring called Santo Marzio has been equipped, with a trapezoidal thin-plate weir properly set up, on which a sound number of manual measurements of the natural discharge were collected. For other springs there are discharge measurements taken by various authors in different periods (Perrone, 1908; Boni *et al.* 1986, 1994; Lotti and Associati, 1989; Mastrorillo, 1994; Eco Tech Engineering and Servizi Ambientali, 2004; Cambi and Dragoni, 2006; Mastrorillo *et al.*, 2009). Although the data available are not comparable in terms of recording time interval, the existing information, integrated with those coming from field surveys carried out in different seasons, can give a sound idea of what the average springs discharge can be.

As for the Monte Cucco Massif, the available instrumental data are poorer, since continuous measurements are only available for the Scirca spring, whose natural discharge has been measured daily since 1942 by means of a broad crested weir, equipped in 2007 with an ultra-sound gauge. For the other springs, a large set of discharge data coming from the literature is available (Perrone and Zoppi, 1899; Perrone, 1910; Centamore *et al.*, 1975; Boila *et al.*, 1983; Lotti and Associati, 1989, 1995; Mastrorillo, 1994; Dragoni and Valigi, 2006; Mastrorillo *et al.*,

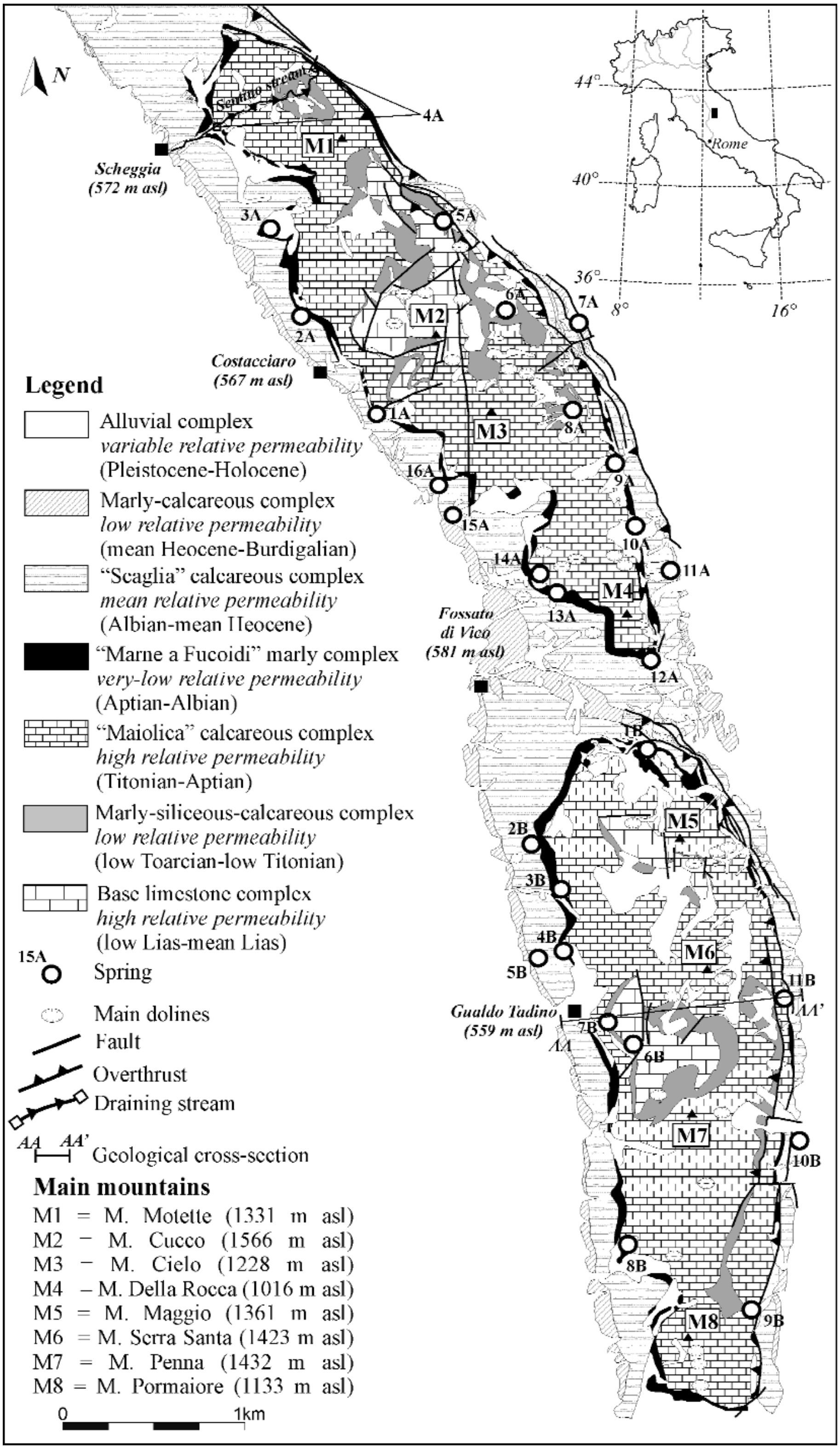

Fig. 1 - Hydrogeological map of studied massifs.

2009; Nanni and Vivalda, 2009); it has been, therefore, possible to compare the average discharge evaluated on the basis of field surveys carried out in different seasons with such data.

For the purposes of this study, the mean annual discharge of springs was taken as the average of all the instrumental measurements, where available, and as the mean of discharge measurements taken during two or three field surveys carried out in springtime (maximum annual discharge), at the end of the summer (minimum annual discharge) and, in some cases, in autumn. The discharges evaluated on the basis of the field surveys, were compared with data from the literature to verify whether they match.

Precipitation and temperature on the two massifs were estimated according to historical data recorded in meteorological stations located as close as possible to the study area. Thirty meteorological stations have been analysed, of which only the ones with less than 20% data missing, and operating in the same time interval (1959-2007), have been accounted for.

Although some uncertainties arose from the lack of meteorological stations located at high elevations, the literature shows that, in Italy, when long time periods and relatively small areas are considered, there is generally a good linear relationship between elevation and mean annual precipitation and temperature (Boila *et al.*, 1983; Cencetti *et al.*, 1989; Ardizzone *et al.*, 1999; Dragoni *et al.*, 2003; Fabbrocino and Perrone, 2009). Defining these linear relationships seemed to be a suitable way of estimating mean annual temperature and precipitation in the two structures. Hydrometeorological data furnished enough information to evaluate the water budgets of the two massifs, which, together with a careful study of the geological and structural framework, allowed us to prepare a hydrogeological scheme of the systems.

3. Geological and hydrogeological characteristics of Monte Cucco and the Gualdo Tadino Mountains

Monte Cucco and the Gualdo Tadino Mountains are located on the western border of the main ridge of the Umbria-Marche Apennines (central Italy), a compressive Miocene/Pliocene arc-shaped fold-and-thrust belt, with eastward vergence and convexity, later affected by Quaternary extension (Colacicchi and Pialli, 1967; Passeri, 1971; Lavecchia and Pialli, 1980, 1981a, 1981b; Barchi and Lavecchia, 1986; Menichetti and Pialli, 1986; Calamita *et al.*, 1991; Boscherini *et al.*, 2005; Ciaccio *et al.*, 2005). Both structures are east-vergent, asymmetric anticlines, bounded to the east by a thrust-fault system, which is the main expression of compressive tectonics. Their rocks belong to the Umbria-Marche sequence, consisting of Jurassic–Miocene carbonates and marls, in which fractured and/or stratified limestones host aquifers separated from each other by marl aquicludes.

In this work, several hydrogeological complexes made up of various formations which are similar in terms of age and relative permeability are defined, as shown in Fig. 1.

The main aquifers are located in the low-Jurassic “Base Limestone” Complex, made up of Corniola and Calcare Massiccio, a fractured, highly permeable shelf limestone, and in the Maiolica Complex, a Lower Cretaceous Formation made up of pelagic limestones. The Marly Complex made up of the Marne a Fucoidi Formation is the main aquiclude of the area and bounds the structures almost continuously, except to the east, where it is involved in the already-mentioned thrust-fault system. In the Umbria-Marche Apennines the thrust system represents an

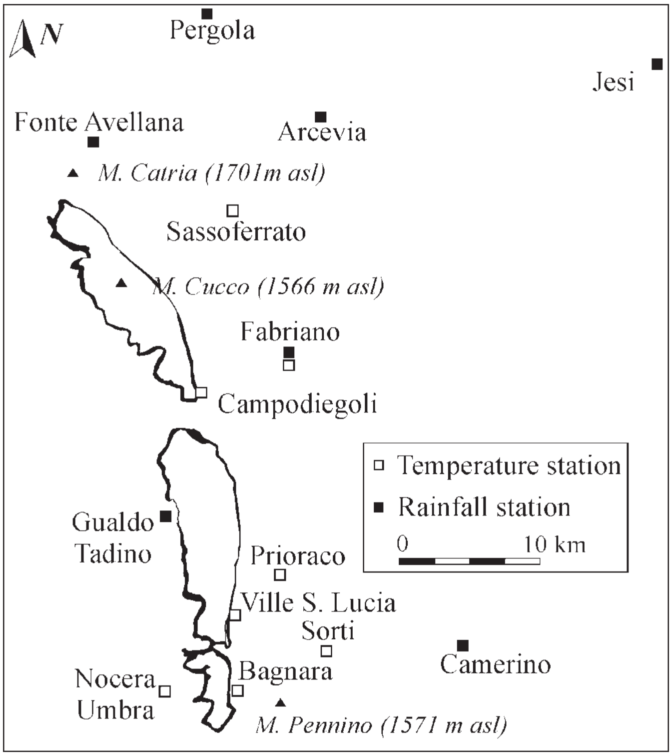

Fig. 2 - Location of meteorological stations.

impervious boundary almost everywhere, such as the Marne a Fuciodi Formation. This formation and the thrust system together, define a "belt" around each structure. Many springs emerge between this belt and the Maiolica Formation where they come into contact (Fig. 1).

Major normal faults in the anticline cores, particularly well-developed on Monte Cucco, are the main expression of the Quaternary extension; in some areas these faults constitute a tectonic contact between the Calcare Massiccio and Maiolica. Well-developed karst structures and caves are present in the Calcare Massiccio of Monte Cucco, whereas they are of less extent in the Gualdo Tadino Mountains. Dye tracing tests in streams and caves made it evident that normal faults act as conduits and represent important flow paths (Bertuccioli *et al.*, 1975; Menichetti *et al.*, 1992).

The analysis carried out in this study concerns the areas surrounded by the impervious "belts", respectively 42 km^2 and 50 km^2 wide in Monte Cucco and the Gualdo Tadino Mountains.

4. Climatic setting

In order to define the main climatic characteristics of the two structures, 30 time-series recording mean annual temperature and precipitation in the surrounding areas were analysed carefully. In order to meet criteria of reliability and uniformity, of the 30 stations analysed, only those operating between 1959-2007, where less than 20% data were missing, were chosen (Fig. 2). The temperature and rainfall data recorded in this period have been used to define the temperature/elevation and rainfall/elevation relationships.

Table 1 - Mean annual temperature at stations examined.

Station	Elevation (m AMSL)	Period of recording	Percentage of missing data (%)	Mean annual temperature throughout the period (°C)
Pergola	306	1959-2007	2	13.4
Fabriano	357	1959-2007	0	13.1
Iesi	96	1959-2007	2	14.3
Camerino	664	1959-2007	18.4	12.3
Fonte Avellana	689	1959-2007	8.2	12.0
Arcevia	535	1959-2007	10.2	13.0
Gualdo Tadino	535	1959-2007	22.4	12.8

4.1. Mean annual temperature and precipitation

Table 1 shows the temperature data used to define the elevation/temperature relationship (Fig. 3).

Table 2 shows the precipitation data used to define the elevation/precipitation relationship.

Although the elevation/precipitation relationship is not generally as good as the elevation/temperature, in this case the correlation coefficient is quite high, as shown in Fig. 3.

In Fig. 3, the oversized squared dots represent mean annual temperature and precipitation at the average elevation of Monte Cucco (910 m AMSL) and of the Gualdo Tadino Mountains (1020 m AMSL), estimated by extrapolating the trends defined by the linear relationships. Mean annual temperatures were estimated at 11.4 °C and 11 °C, and mean annual precipitation values were 1517 mm/y and 1620 mm/y respectively for Monte Cucco and for the Gualdo Tadino Mountains.

5. Mean annual discharge of the two massifs

As previously mentioned, the two structures studied here feed many high-quality springs, most of which are located along the belt defined by the contact between Maiolica and Marne a Fucoidi

Table 2 - Mean annual precipitation at stations examined.

Station	Elevation (m AMSL)	Period of recording	Percentage of missing data (%)	Mean annual precipitation throughout the period (°C)
Fabriano	357	1959-2007	20	940
Campodiegoli	507	1959-2007	10.2	1193
Sassoferrato	312	1959-2007	18.4	1017
Ville S.Lucia	664	1959-2007	14.3	1260
Pioraco	441	1959-2007	14.3	1055
Sorti	716	1959-2007	16.3	1392
Bagnara	620	1959-2007	12.2	1197
Nocera Umbra	548	1959-2007	10.2	1161

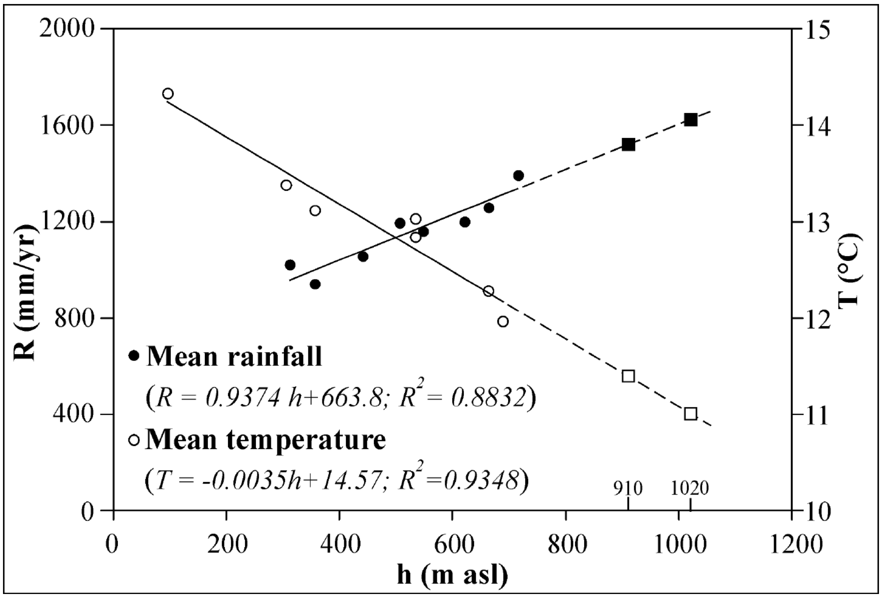

Fig. 3 - Elevation/precipitation and elevation/temperature relationships. Squares: extrapolation at average elevation of Monte Cucco (910 m AMSL) and Gualdo Tadino Mountains (1020 m AMSL).

formations and/or between Maiolica and the thrust system. In order to estimate the total mean annual discharge of the two structures, it was necessary to evaluate the discharge of each spring. The mean annual discharge of the five springs equipped with continuous gauging stations (1A Scirca, 3B Vaccara, 4B Cappuccini, 8B Boschetto, 9B Capodacqua) has been considered as the mean of all the available instrumental data. For the Santo Marzio Spring the average annual discharge has been calculated as the mean of 51 measurements taken at the thin-plate weir mentioned above. For the springs that are not equipped with discharge gauging stations, the discharge has been estimated as the average between two or three measurements taken in springtime (close to the maximum discharge), at the end of the summer (close to the minimum discharge) and in autumn. Each of these measurements included both the withdrawn water and the surplus released in streams. Tables 3 and 4 show the mean annual discharge of all springs examined. The mean annual estimated discharges match the values measured by the authors quoted in chapter 2. The total mean annual discharge of the springs fed by Monte Cucco is lower than that of the Gualdo Tadino Mountains, where most of the springs supply several dozen l/s.

6. Results

6.1. Water budget

The mean annual infiltration over the two massifs was evaluated according to the above hydrometeorological data. Mean annual precipitation and temperature were estimated by applying the elevation/precipitation and elevation/temperature relationships of Fig. 3. Starting from these values, evapotranspiration (ETR) was computed with Turc's formula and then used to estimate the water surplus (S), taken here as the difference between precipitation (P) and

Table 3 - Mean annual discharge of springs surrounding Monte Cucco. The * symbol indicates the presence of a discharge gauge, with year of initial operation.

Hydrogeological System	Number of measures	Q nat (l/s)
1A Scirca stream*(1942)	21318	190
2A Il Rio ditch	2	12.6
3A Chiasciolo ditch	2	2.1
4A Increase along the Sentino River	2	115.7
5A Delle Prigioni stream	2	49
6A Rio Freddo stream	2	31.3
7A Paccone ditch	2	3.6
8A Delle Pianelle ditch	2	13.4
9A Vallina ditch	2	10.3
10A Maggiore ditch	2	36.2
11A S. Martino ditch	2	2.3
12A Campodiegoli ditch	2	6.3
13A Canovine ditch	2	16.8
14A Vetorno ditch	2	38.7
15A Sodo stream	2	40.6
16A Delle Gorghe stream	2	4.7
Total discharge from springs	_	573.6

evapotranspiration (S = P – ETR). Although the validity of Turc’s formula is often questioned, it was chosen because the lack of specific meteorological data made it impossible to use sounder methods, such as that of Penmann-Monteith (see Ward and Robinson, 1999). It should be noted that, in areas with temperate climates such as Europe, Turc’s formula is widely used and gives reliable results. In particular, as regards central Italy, instrumental data are comparable to those supplied by Turc’s formula: this can be seen from the fact that the evapotranspiration estimated using Turc’s equation is quite close to that calculated as the difference between the mean annual precipitation and the mean annual discharge of low-permeability gauged catchments (Di Matteo and Dragoni, 2006). As infiltration in catchments of this kind can be considered as nil, in practice this difference corresponds to mean annual evapotranspiration. Di Matteo and Dragoni (2006) also give other examples, showing that evapotranspiration computed with Turc’s formula is close to the value derived from instrumental measurements. Other examples of the validity of Turc's formula can easily be found in the literature (Bono, 1993; De Felice *et al.*, 1993; Strzepek and Yates, 1997; Bonacci, 1999; Krüger *et al.*, 2001).

Table 5 shows the components of the water budget computed in the two structures.

The Maiolica was considered separately from the Base Limestones, since different coefficients were assigned to each complex, in order to calculate effective infiltration (I). Infiltration coefficients of 0.7 and 0.9 were assigned respectively to the fissured Maiolica and to the karstified Base Limestones. These values fall in the ranges proposed by Civita (2005), which are 0.5÷0.85 for fissured limestones and 0.75÷1 for karstified ones. The alluvial complexes have

Table 4 - Mean annual discharge of springs surrounding Gualdo Tadino Mountains. The * symbol indicates the presence of discharge gauges, with year of initial operation.

Hydrogeological System	Number of measures	Q nat (l/s)
1B Giano spring	3	31.9
2B P. Mancinelli spring	3	44.1
3B Vaccara*(2007)	255	99.1
4B Cappuccini spring*(2007)	482	19.5
5B Rumore spring	2	119.8
6B S. Marzio spring	51	86.8
7B Rocchetta spring	Mean well withdrawal	16.5
8B Boschetto spring*(2007)	441	119.4
9B Capodacqua spring*(1999)	2707	102.8
10B – Torre/S.M. Maddalena spring	3	30
11B – Belvedere/Montenero spring	3	109.2
Total discharge from springs	--	779.1

been considered as having the same infiltration coefficients as the underlying formations.

The effective infiltration values estimated for each structure were compared with the total discharge from the springs, as shown in Table 6.

Comparisons between the two values show that the total spring discharge is almost 40% lower than the annual effective infiltration on Monte Cucco and about 35% lower than that in the Gualdo Tadino Mountains. Although some non-negligible uncertainty arises, due to the scarcity of hydrogeological and meteorological data, differences of such magnitude between infiltration and discharge cannot be justified by considering only these uncertainties. It has to be noticed that, even assigning the lowest infiltration coefficients proposed by Civita (2005) for fissured and karstified limestones (0.5 and 0.75) to the Maiolica and to the Base Limestones, the amount of mean annual infiltration estimated for the two structures remains higher than the total discharge coming from the spring surrounding them. Since karst phenomena are highly developed in the base limestones, especially on Monte Cucco, and some karst phenomena are also present in the

Table 5 - Water budget of study massifs. T = mean annual temperature, P = mean annual precipitation, ETR = mean annual evapotranspiration, I = mean effective infiltration, Mai = Maiolica, Base L = Base Limestones.

System	Recharge area		Elevation of recharge area (m AMSL)		Mean annual hydrogeological balance									
					T (°C)		P (mm)		ETR (mm)		I (mm)		I (mm)	I (l/s)
	Complex		Complex		Complex		Complex		Complex		Complex		Whole structure	Whole structure
	Mai	Base L	Mai	Base L	Mai	Base L	Mai	Base L	Mai	Base L	Mai	Base L		
Monte Cucco	36.70	7.20	861	1102	11.6	10.7	1471	1697	614	593	600	994	665	926
Gualdo Mountains	46.10	4.83	1002	1066	11.0	10.8	1603	1663	600	595	702	961	727	1174

Table 6 – Comparison between mean annual infiltration and total spring discharge

System	Mean annual effective infiltration (l/s)	Total springs discharge (l/s)
Monte Cucco	926	573.6
Gualdo Mountains	1174	779.1

Maiolica formation, it seems however more likely that the infiltration coefficients are higher than the minimum.

6.2. Hydrogeological scheme of the two massifs

Computation of the water balance gives the same indications for both massifs, which are open hydrogeological systems, where the infiltration feeds not only the spring located around them but also a "hidden", deeper groundwater flow.

This hypothesis is strengthened when considering the geological and structural characteristics of the two massifs, which consist of two asymmetric anticlines both bounded to the east by a low-angle thrust system plunging westwards. Normal faults cutting the anticlines, mainly located around the cores or on the western side, and particularly well-developed on Monte Cucco, are the expression of the Quaternary extensive tectonics and act as groundwater conduits, as proved by tracer tests. The sedimentary sequence and structural setting suggest that there are no boundaries capable of isolating the two structures from the hydrogeological point of view, and indicate that effective infiltration feeds not only springs located around the massifs but also a deeper regional flow, the development of which is due to the lack of impervious limits under the anticlines and to the presence of karst systems and well developed normal faults. Since the west-plunging thrust systems must be considered as an impervious limit, regional flow is expected to be directed westwards, as shown on the sample cross-section of Fig. 4.

The presence of normal faults on the western side helps the development of the deep flow. Similar hydrogeological schemes have been proposed for analogous hydrogeological structures such as Monte Pennino (Fig. 5), where estimated recharge exceeds discharge (Cambi and Dragoni, 2000), and Monte Subasio (Chiodini *et al.*, 1991; Mastrorillo *et al.*, 2009).

The hypothesis of a deep flow directed westwards matches other hydrogeological and hydrogeochemical data from contiguous areas. In particular, the Renano deep well (P51), drilled in the Monte Subasio area (Fig. 5), has intercepted the Base Limestones aquifer (Umbra Acque and Regione Umbria, 2006). As reported in Frondini (2008), the salinity of this well (TDS up to 1292 mg/l, electric conductivity up to 2020 μs/cm) cannot be explained by assuming that the water comes from the nearby Monte Subasio, but only that it comes from the Apennines structures further east. This would explain the high salinity, due to the long residence time of the water and to a flow circuit influenced by the Triassic evaporitic rocks lying below the Base Limestones.

One more indication of the fact that the Apennines chain is made of open hydrogeological structures, seems to be the high discharge of the saline base spring of Stifone, which, according to recent studies, is partly fed by the Apennines chain, located about 100 km east (Di Matteo *et*

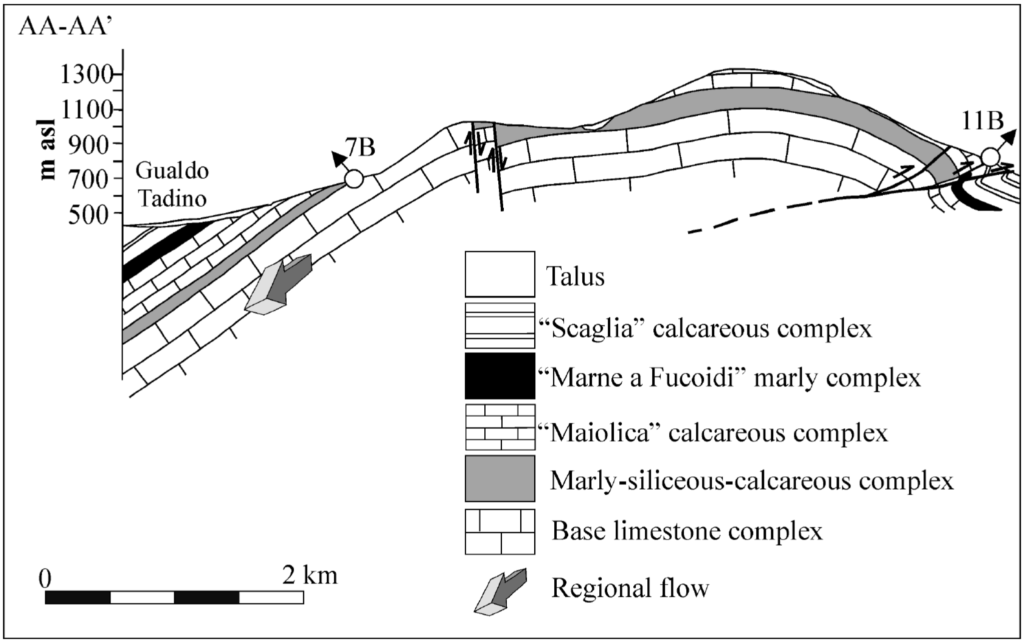

Fig. 4 - Hydrogeological cross-section through Gualdo Tadino anticline.

al., 2009b).

6.3. Considerations on hydrogeological setting

In view of the hydrogeological scheme described above, in both massifs, springs represent the "spill-over" of the deep regional flow. The recharge areas of springs and deep flow are separated by dynamic groundwater divides, which move horizontally as the water table falls or rises. In the hypothesis of a drop in the water table, which can be expected in periods of low rainfall when the recharge is low, the piezometric divides moves towards the higher springs, where the recharge area shrinks, allowing the recharge area of the deep flow to widen (Cambi and Dragoni, 2000). Many authors agree that in central Italy a general tendency towards a decrease in rainfall and an increase in temperature, which has already affected some hydrogeological systems (Cambi and Dragoni, 2000; Dragoni *et al.*, 2003; Di Matteo *et al.*, 2009a), has been detected. The groundwater recharge decrease expected in this situation would influence the spring discharge of the studied structures more severely than it would if the massifs were considered isolated, as assumed by Mastrorillo *et al.* (2009). If the structures were closed, the spring recharge areas would not shrink with the fall in the piezometric surface, and the only cause of a discharge lowering would be the decrease in recharge. Instead, in the case of open structures, with dynamic piezometric divides, the negative effect of decreased recharge would be combined with that of shrinkage of recharge areas.

It should be noted that, in the case of piezometric surface lowering, the springs, that release high-quality drinking-water, would be more influenced than the deep regional flow, the quality of which is much lower, due to longer residence times and interactions with evaporitic rocks. If the

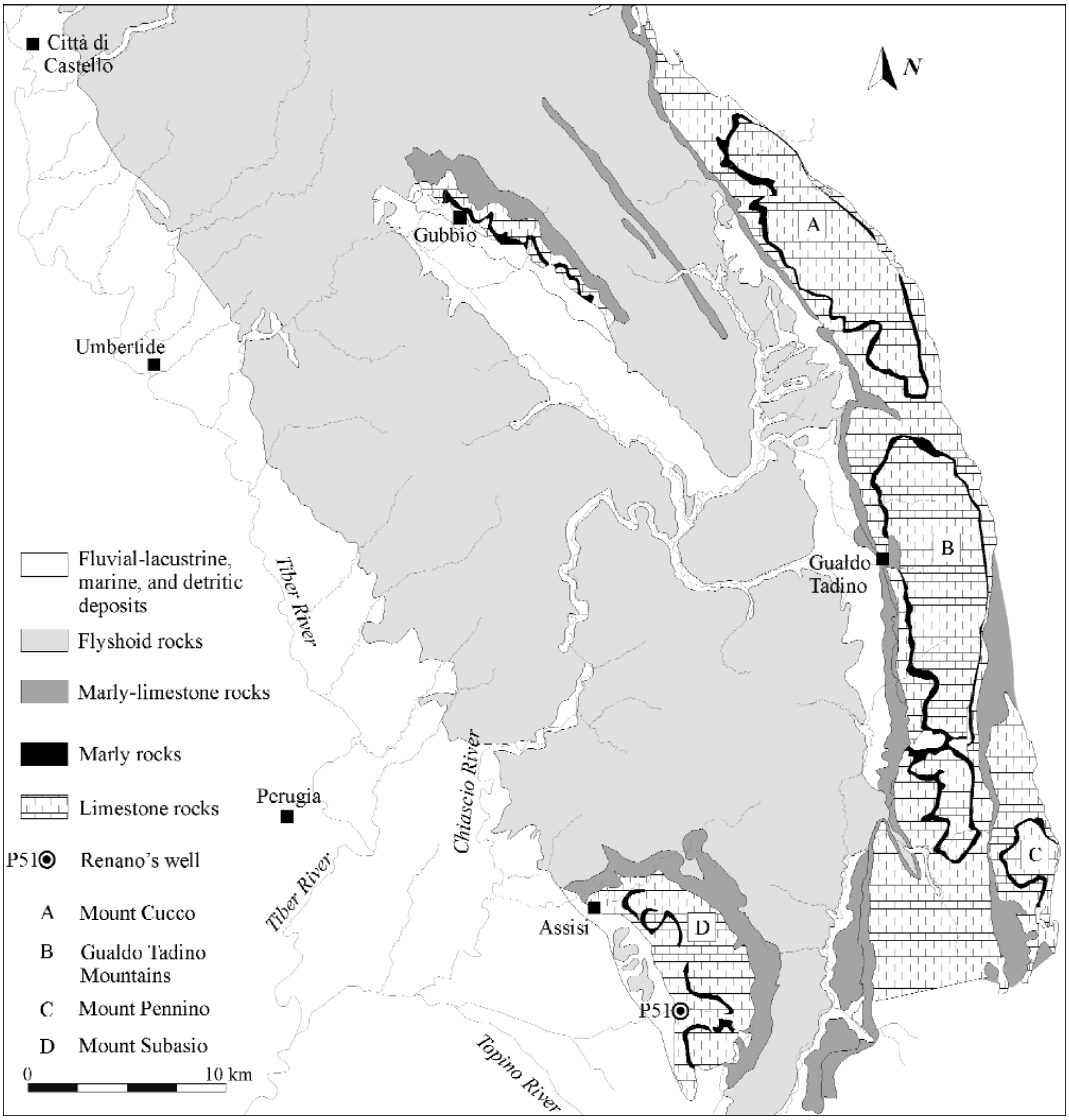

Fig. 5 - Regional geological map.

groundwater recharge would decrease severely, the regional flow discharge, which is currently lower than that of the springs, may even be expected to exceed it.

Numerical modeling of each system would allow the evaluation of variations in springs and deep flow discharge by changing the annual recharge, and also estimation of the recharge value below which the spring discharge would become lower than that of regional flow. This kind of approach has already given good results in the modeling of a spring fed by Monte Pennino, just south of the Gualdo Tadino Mountains (Cambi and Dragoni, 2000) and is also to be used in the near future for the systems studied here, to get quantitative information on the effects of a low recharge on structures of this kind.

7. Discussion

Despite the scarcity of hydrometeorological data in the study area, this study allowed us to demonstrate that Monte Cucco and the Gualdo Tadino Mountains are open hydrogeological structures feeding both the high-quality springs located around them and a regional flow, directed westwards and characterized by high salinity, the recharge area of which is separated by the recharge areas of springs by dynamic piezometric divides. This result is based also on recent good quality data on the discharge rates of some springs which were not available until recently when, at least for the Gualdo relief, recharge of the regional aquifer was considered small or negligible (Cambi *et al.*, 2008).

It is to be pointed out that, still, in some cases the average discharge of springs has been assumed equal to that detected throughout a short period, or equal to the mean of a few measurements. Such assumption gives rise to uncertainties since, in some cases, the discharge can be deeply different over short periods from its mean, which is calculated over a long time span, because of the strong variability of rainfall to which the discharge is strictly related (Deffenu and Dragoni, 1978).

The study clearly shows that the discharge measurements are particularly poor on the Monte Cucco Massif, and on the eastern slope of the Gualdo Tadino Mountains. The collected data show that, as for the unmonitored springs of the Gualdo Tadino Mountains, their discharge is of the magnitude of 30 l/s or more, and the springs would deserve a continuous monitoring, also according to the management and planning strategies for water systems defined by the Italian law on the Environment (DM 152/2006). On the Monte Cucco structure, due to the presence of many smaller springs, in order to get more reliable information on the water balance of the whole structure, it seems that the continuous monitoring of all the springs with estimated discharge higher than 10 l/s would be necessary.

The need for having more reliable data has already been partially met for the Umbrian springs, most of which are presently equipped with continuous discharge gauges. On the contrary, continuous measurements of the natural discharge are still missing for the springs of the Marche region, for most of which only the withdrawal is monitored.

According to the proposed hydrogeological scheme, in times of low rainfall and recharge, or in the hypothesis of a decrease in groundwater recharge due to climatic variations, the consequent average lowering of the water table will cause the spring recharge area to shrink, so that the spring discharge will be more severely affected by decreased recharge than would be the case if the structures were considered isolated. The spring discharge appears to be more greatly influenced by recharge scarcity than that of the deep flow. This is an indication that in the near future it will become essential to develop new techniques to capture the groundwater feeding the regional flow before its salinity becomes too high for drinking-water purposes.

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