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Effective infiltration variability in the Umbria-Marche carbonate aquifers of central Italy

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ABSTRACT - The spatial variability of the effective infiltration parameter within the recharge areas of the main aquifer complexes of the hydrogeological group of the Umbria-Marche ridge of Central Italy was assessed. This parameter usually varies with respect to lithology and the extent of precipitation in the investigated area. The average effective infiltration, expressed in millimeters/year, was directly computed by dividing the volume of water discharged on average from a hydrogeological basin by the extent of its recharge area. This method does not directly depend on the extent of precipitation, and therefore it is not biased by uncertainty in that value.

Effective infiltration was assessed for 15 hydrogeological units and ranges from 200 mm/year to 475 mm/year. The effective infiltration values for the "Scaglia" complex are always lower than those of the other aquifer complexes. The effective infiltration of the "Scaglia" complex increases southwards. This latitudinal spatial variation of effective infiltration is nearly independent of the precipitation distribution. Because this trend is much more pronounced in the "Scaglia" complex, it has been inferred that the spatial variability of the "Scaglia" fracturing is more significant than fracturing in any of the other calcareous lithotypes. The recharge area of the "Scaglia" complex is higher in the northern hydrostructures than in the southern structures because the two areas have different deformation styles. When added to the spatial fracture variability in the "Scaglia", the effects of this differentiation in deformation are responsible for the different water resource amount of the hydrostructures. The occurrence of wide outcrops of the "Scaglia" complex with reduced infiltration capability justifies the existence of less productive aquifers in the northern hydrostructures.

KEY WORDS: fractured aquifer, effective infiltration, central Italy

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INTRODUCTION

Carbonate aquifers are recharged by direct infiltration of water from atmospheric precipitation into rock masses. This water flows rapidly, and mostly vertically, through pores, fissures and fractures until it reaches the phreatic zone of the aquifer (Fig. 1). "Effective infiltration" is the parameter quantifying the amount of meteoric water that is involved in this phenomenon.

A reliable assessment of effective infiltration is conditional upon the scale of the investigation. This parameter expresses the capability of a given portion of a land area to absorb meteoric water and transmit it to the aquifer. Effective infiltration varies with lithology and morphology, and with the extent of precipitation in the investigated area.

Regional hydrogeological studies have been conducted on the Umbria-Marche carbonate Apennines. The most recent studies were high enough resolution to create a realistic reconstruction of the local distribution of effective infiltration (Boni et al., 2005; Mastrorillo et al., 2009). The average effective infiltration values into each of the identified hydrostructures and the specific values of effective infiltration assigned to the same hydrogeological complex are both variable.

The effective infiltration values reported in this paper were obtained using the "direct" computation method (Boni and Bono, 1982; Boni et al., 1986). This method does not require the assessment of meteoric precipitation, which is an advantage because the reliability of precipitation measurements depends on the level of optimization of temperature-precipitation monitoring networks. Other authors (Boila et al., 1983; Giaquinto and Mattioli, 1991; Cencetti et al., 1998; Di Matteo et al., 2009) consider the assessment of effective infiltration on the basis of the extent of meteoric precipitation to be more reliable. Even though the results obtained using the two methods do not always agree, they demonstrate the spatial variability of effective infiltration, and overshadow the prior classification of rock formations into permeability classes based only on their outcropping lithotypes. It is now common knowledge that the local ability of a fractured rock mass to absorb meteoric water, and thus favor aquifer recharge, depends not only on the geological formation present, but also on the local geometric and mechanical features of the fissures and fractures within the same formation (Scesi and Gattinoni, 2007).

In future quantitative hydrogeological studies, greater insight should be gained into the geological-structural and geological-technical features of the rock masses that act as recharge areas for carbonate aquifers. Further, specific surveys should be conducted in addition to the now well-established hydrogeological survey methods.

INVESTIGATED AREA

At present, the Umbria-Marche Apennines are one of the main focus areas for experimental studies on the direct

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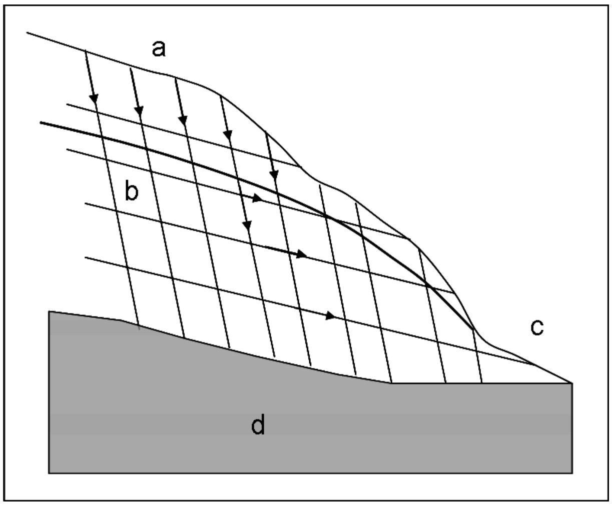

Fig.1 - Sketch of groundwater flow in a fractured rock mass.
a) infiltration zone; b) groundwater; c) discharge area; d) bedrock aquiclude (modified from Gattinoni & Scesi, 2007).

effective infiltration computation method and its application. This paper presents findings from the analysis of the spatial distribution of effective infiltration values in this region. These values were inferred from previous studies that offer a detailed hydrogeological characterization of most of the Umbria-Marche ridge hydrogeological systems (Boni et al., 1986).

The area that was investigated (Fig. 2) includes the following: the Umbria-Marche inner carbonate ridge (Calamita et al., 1991), its southern ramifications beyond the Colfiorito plain (in the Umbria carbonate ridges) as far as the Rieti plain, and the carbonate ridges of the Valnerina system. The carbonate outcrops in the area cover about 2600 km^2 and are the recharge areas for the aquifers identified in the study area.

The lithological-stratigraphic setting of the Umbria-Marche Apennines consists of Lias age bedrock, which is a typical carbonate platform deposit ("Calcare Massiccio") and is significantly dislocated by extensional tectonic movements. The well-known Umbria-Marche pelagic carbonate succession was deposited on this bedrock until the Miocene.

This structural setting is typical in an E-dipping thrust and fold chain. The folds are strongly asymmetric and they are composed of narrow synclines and flat crested anticlines that have eastern sides arranged from vertical to reverse. The eastern side of the folds is also generally broken by overthrusts. In the northern and central sectors, the overthrust planes trend NW-SE- to NNW-SSE-and are solely compressional. In the southern sector, they trend NNW-SSE and are chiefly dextral transpressive overthrusts where the compressional tectonic regime combines with the effects of extensional tectonic processes that occurred in the Pliocene-Quaternary. These processes have downthrown wide carbonate sectors, giving rise to large intramontane basins inside the ridge. Subsequently, these basins were filled with fluvio-lacustrine deposits (Colfiorito, Castelluccio, Norcia and Cascia plains) (Cavinato and De Celles, 1999).

The stratigraphic relationships and structural features of the Umbria-Marche domain create a regional hydrogeological setting with separate aquifers of differing types; these aquifers may be in hydraulic communication with one another locally. The Umbria-Marche stratigraphic succession consists of alternating, dominantly calcareous formations (hydrogeological complexes that potential hold aquifers) and of marly-clays formations that act as aquicludes and aquitards (Fig. 3).

At the regional scale, two groundwater systems were identified. A deeper groundwater system was identified within the "Calcare Massiccio", "Corniola" and "Maiolica" formations, whereas a generally shallower groundwater system was identified within the "Scaglia calcarea" ("Scaglia bianca" and "Scaglia rossa") complex (Boni et al., 2005).

For a detailed hydrogeological description of the area, the reader is referred to the relevant literature (Boni & Mastrorillo, 1994; Mastrorillo, 1996; Caprari and Nanni, 1999; Mastrorillo, 2001; Boni et al., 2005; Nanni and Vivalda, 2005; Preziosi, 2007; Di Matteo et al., 2009; Mastrorillo et al., 2009; Nanni and Vivalda, 2009).

EFFECTIVE INFILTRATION AND INTEGRATED HYDROGEOLOGICAL BUDGET

The "direct" method calculation of effective infiltration is based on the principle that the amount of discharge from a hydraulically closed hydrogeological structure is equivalent to the average amount of water entering the recharge area (Boni et al., 1986). The average effective infiltration, expressed in millimeters/year, is calculated by dividing the average volume of water discharged by a hydrogeological structure by the extent of its recharge area; the latter is identified on the basis of a detailed reconstruction of the local geological-structural setting.

Detailed hydrostructural studies are used to identify the recharge areas of the individual springs, and the same method may be used to assess local effective infiltration of hydrogeological complexes that outcrop in the investigated area. In this way, effective infiltration data were collected for the individual hydrogeological complexes. However, the data corresponds to different outcrops that are scattered over the entire Umbria-Marche ridge.

Although the direct method of effective infiltration assessment is subject to errors in geological-structural interpretation, it yields reliable results. This result is not biased by uncertainty in the extent of precipitation because the method does not directly depend on these measurements. In the mountainous high-altitude areas of the Apennines (which are the chief recharge areas of the carbonate aquifers), the present temperature, rainfall and snowfall monitoring network coverage is not sufficient to ensure a reliable assessment of meteoric recharge.

The method selected here is very effective in regional hydrogeological studies over wide areas. However, it is less effective in more detailed studies, especially when the hydrostructures are hydraulically open and do not have known springs, but can accommodate deep groundwater outflows. In locations where springs that may be connected with groundwater flow from the investigated hydrostructure are not known, it is preferable to use other methods based on the analysis of the distribution of meteoric precipitation to calculate effective infiltration. However, the results obtained using these other methods must be validated by the computation of the integrated regional hydrogeological budget.

The integrated hydrogeological budget requires a quantitative comparison between inflows and outflows from each hydrostructure that takes into account water mixing between adjoining hydrostructures. In the investigated area, each supply deficit that is identified for a given hydro-

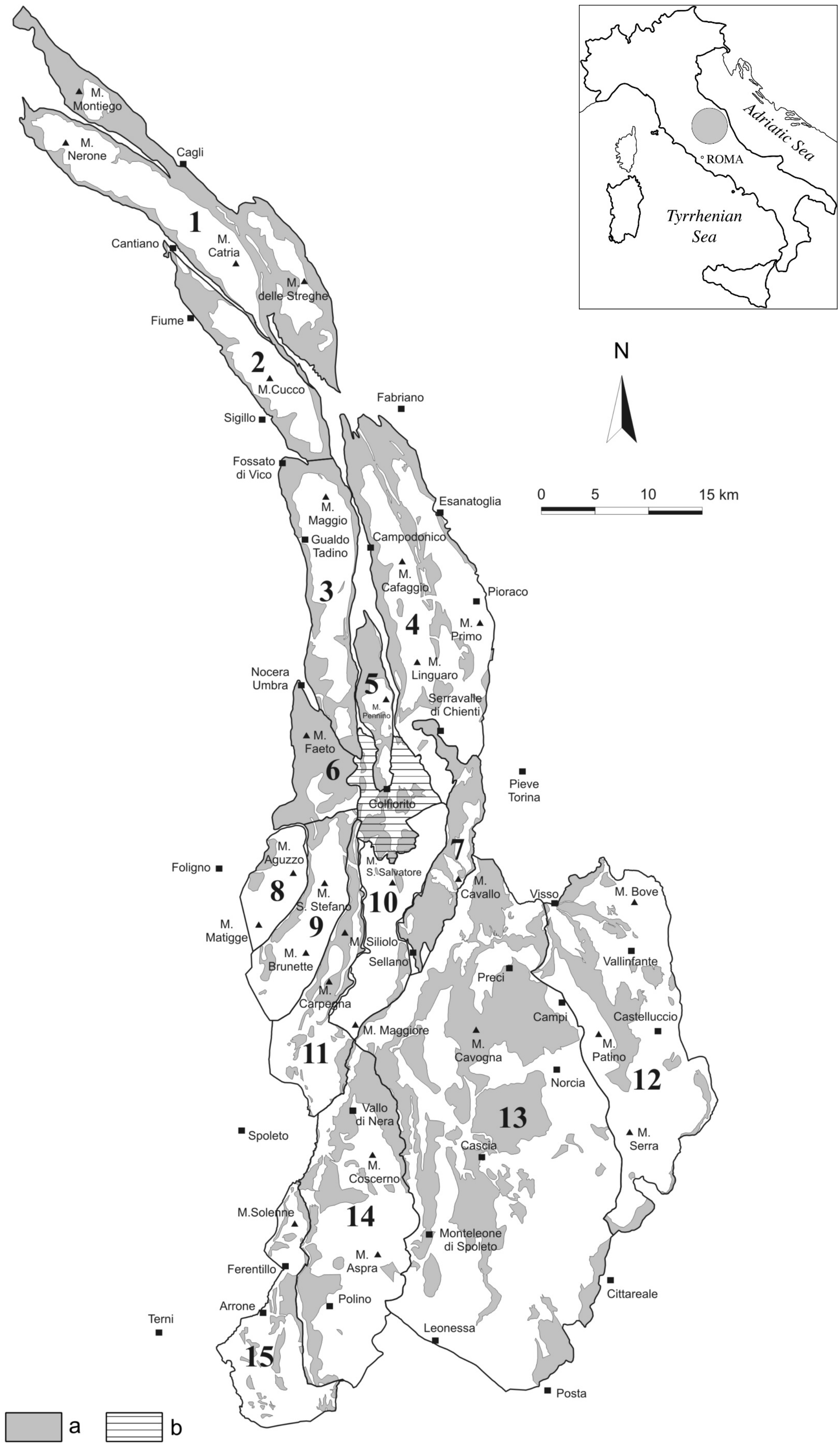

Fig. 2 - Study area and map of the hydrogeological units. Numbers refer to Tab. 1a) Scaglia complex outcropping; b) preferential recharge area of Colfiorito Plain.

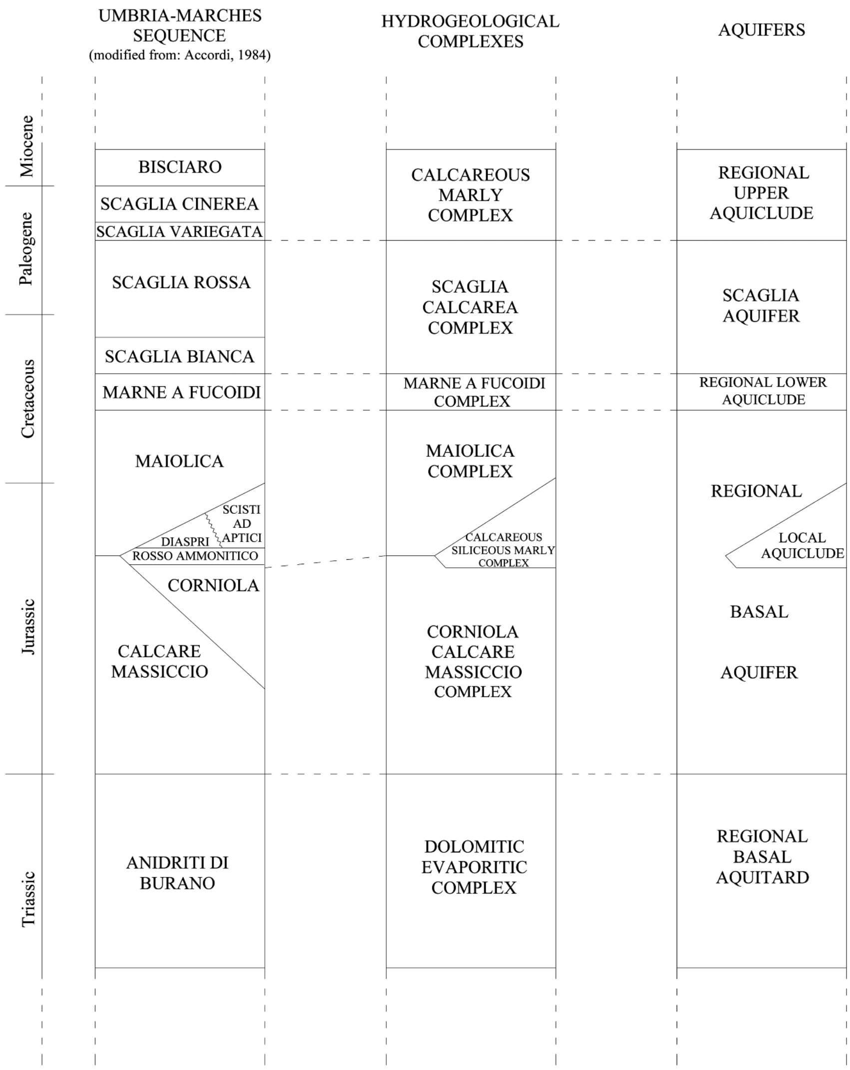

Fig. 3 - Sketch of relationships between stratigraphic sequence, hydrogeological complexes, and main aquifers in the Umbrian-Marchean domain (Mastrorillo et al., 2009).

ID	HYDROGEOLOGICAL UNIT	A	Ds	T	D_{TOT}	EI		F
						(a)	(b)	
1	Mt. Nerone - Mts. della Strega	265	1680	0	1680	200	1680	0
2	Mt. Cucco	87	690	0	690	250	690	0
3	Mt. Maggio	122	1850	0	1850	410	1585	265
4	Mt. Linguaro - Mt. Primo	264	3595	0	3595	415	3470	125
5	Mt. Pennino	35	420	0	420	380	420	0
6	Mt. Faeto	61	720	80	800	415	800	0
7	Mt. Cavallo	64	860	0	860	425	860	0
8	Mt. Aguzzo	44	0	640	640	460	640	0
9	Mt. Santo Stefano	96	1845	0	1845	460	1400	445
10	Mt. San Salvatore	82	1345	0	1345	470	1220	125
11	Mt. Siliolo - Mt. Carpegna	91	290	1040	1330	460	1330	0
12	Mt. Bove	266	4300	0	4300	510	4300	0
13	Mt. Tolentino - Mt. Cavogna	754	10640	0	10640	445	10640	0
14	Mt. Aspra - Mt. Coscerno	241	3630	0	3630	475	3630	0
15	Mt. Solenne	107	1610	0	1610	475	1610	0

Tab. 1 - Integrated hydrogeological budget. ID) id of each hydrogeological unit; A) total area in km^2; Ds) Spring discharge in L/s; T) Groundwater seepage towards surrounding hydrogeological units; DTOT: total discharge of the unit; EI) Effective infiltration (net recharge) in mm/year (a) and L/s (b); F) groundwater seepage from surrounding hydrogeological units (modified from Mastrorillo et al., 2009).

structure corresponds to a similar surplus in the adjoining hydrostructures (Mastrorillo et al., 2009).

The budget analysis, described above (Tab. 1), made it possible to reliably assess the effective infiltration, even for hydraulically open hydrogeological units. For these structures, the calculated infiltration value is the ratio of the average outflow volume (the sum of the average flow from the springs and of deep, mixed water flows towards the exterior) to the hydrostructure recharge area extent.

Each hydrogeological unit has a recharge area equivalent to its extent and is enclosed between geological-structural hydraulic boundaries. In general, the hydrostructures correspond to morphologically clearly demarcated anticlinal ridges. Along their western edge, these structures are hydraulically limited by contact with lower permeability complexes. Along their eastern edge, they are hydraulically confined by compressional tectonic lines. The original features of the rock masses have been altered and have evolved into continuous mylonitic belts. These belts generally act as no-flow boundaries (Boni et al., 2005). Possible deep water mixing between adjoining hydro-structures mostly occurs at their northern and southern boundaries, where it is not easy to assign the hydraulic limit to specific geological-structural features.

Theoretically, the recharge area of each hydrostructure coincides with the extent of hydrogeological complexes outcropping that have actual infiltration capability. Along the sides of the ridges, the tectonic folding style gave rise to outcrops of markedly calcareous complexes with good infiltration capability ("Scaglia calcarea", "Maiolica" and "Corniola-Calcare Massiccio" complexes) alternating with marly complexes where surface runoff is dominant (calcareous-siliceous-marly, "Marne a Fucoidi" and calcareous -marly complexes). In the study areas, outcrops of the dominantly marly hydrogeological complexes contribute to effective infiltration into the topographically underlying calcareous complexes. These outcrops may be considered as an integral part of the recharge area, and the outcrop extent corresponds to the overall hydrostructure extent.

REGIONAL ASSESSMENT OF THE EFFECTIVE INFILTRATION

In the investigated area, the effective infiltration was assessed for 15 hydrogeological units. Tab. 2 shows the effective infiltration values that were calculated for each hydrostructure; these values range from 200 mm/year for the Mt. Nerone-Mt. delle Streghe unit to 475 mm/year for Mt. Solenne.

For some units, effective infiltration was assessed separately for the "Scaglia calcarea" hydrogeological complex and for the undifferentiated "Maiolica-Corniola-Calcare Massiccio" complexes (seen in the last two columns of Tab. 2). When assessing effective infiltration, the "Maiolica" complex was not differentiated from the "Corniola-Calcare Massiccio" complex because the "Corniola-Calcare Massiccio" outcrops are generally of limited extent and insufficient to carry out a significant assessment of this parameter.

In all of the investigated hydrostructures, the values of effective infiltration for the "Scaglia calcarea" complex are always clearly lower than those attributed to the "Maiolica" and "Corniola-Calcare Massiccio" complexes. The infiltration capability of the "Scaglia calcarea" complex proves to be 80%-20% lower than that of the underlying calcareous complex.

This difference may be caused by the higher marly content in the "Scaglia" compared to the "Maiolica and Corniola-Calcare Massiccio" (APAT-CNR-Commissione Italiana di Stratigrafia, 2007). In general, the different lithology implies a different response to deformation stresses. Often, the faults

ID	HYDROGEOLOGICAL UNIT	As	Am	EI	EIs	EIm
1	Mt. Nerone - Mts. della Strega	137	105	200	50	430
2	Mt. Cucco	34	37	250	170	435
3	Mt. Maggio	47	54	410	345	470
4	Mt. Linguaro - Mt. Primo	80	134	415	370	590
5	Mt. Pennino	21	9	380	380	n.d.
6	Mt. Faeto	50	1	415	410	n.d.
7	Mt. Cavallo	47	8	425	n.d.	n.d.
8	Mt. Aguzzo	5	25	460	n.d.	n.d.
9	Mt. Santo Stefano	17	51	460	400	490
10	Mt. San Salvatore	5	56	470	n.d.	n.d.
11	Mt. Siliolo - Mt. Carpegna	30	30	460	370	n.d.
12	Mt. Bove	67	91	510	395	490
13	Mt. Tolentino - Mt. Cavogna	260	177	445	380	485
14	Mt. Aspra - Mt. Coscerno	72	112	475	420	545
15	Mt. Solenne	21	32	475	n.d.	n.d.

Tab. 2 - Outcropping area and effective infiltration (net recharge) of the hydrogeological units and of the hydrogeological complexes .ID) id of each hydrogeological unit; As) outcropping area of Scaglia complex in km^2; Am) outcropping area of Maiolica and Corniola-Calcare Massiccio complexes in km2; EI) effective infiltration (net recharge) average of hydrogeological unis in mm/year; EIs) effective infiltration (net recharge) of Scaglia complex in mm/year; EIm) effective infiltration (net recharge) of Maiolica and Corniola-Calcare Massiccio complexes in mm/year.

observed in the "Calcare Massiccio" do not propagate into the formations overlying the "Maiolica", indicating a different mechanical response to deformation (Barchi et al., 1991). The lower part of the largest competent sequence is stiff and develops extremely localized deformations in response to the applied stress field. Conversely, the overlying pelagic multilayer, which is less competent, has a relatively more ductile behavior and exhibits deformations distributed over larger zones.

Moreover, the occurrence of different stylolithic surface systems within the "Scaglia Rossa" indicates the dominance of chemical pressure-solution deformation in this lithotype. Particular stress conditions associated with geochemical situations that are likely to occur and that are conducive to $CaCO_3$ precipitation have favored the deposition of calcium carbonate within the fractures (Brilli et al., 2000; Invernizzi, 2008). Therefore, the "Scaglia calcarea" complex is not only less fractured than the "Maiolica" and "Corniola-Calcare Massiccio" complexes, owing to its different deformation response, but it also has a lower effective infiltration capability because portions of the existing fractures are obstructed by dissolved and recrystallized calcite.

SPATIAL VARIABILITY OF THE EFFECTIVE INFILTRATION

In a previous, smaller scale study (Mastrorillo, 2001), the significant difference in effective infiltration between the northern sector and the southern sector of the inner Umbria-Marche ridge was correlated with the occurrence of two areas, separated by the "Fossato di Vico-Gole della Rossa" line, that have different deformation styles (Ambrosetti et al., 1981). Close to this line, the fold axes abruptly shift from a NW-SE direction to a meridian direction (Centamore et al., 1979). In the northern sector, folds with large radius of curvature are dominant. Conversely, in the southern sector, overlaps and overthrusts dominate and the calcareous formations are more fractured (Cencetti, 1964).

To perform a more thorough analysis of the spatial variability of effective infiltration and to obtain preliminary quantitative assessments, it was necessary to test the assumption of a relationship between the geographic position of the investigated hydrostructures and the respective average values of yearly effective infiltration.

Fig. 4 shows the average effective infiltration of each investigated hydrogeological unit vs. its average latitude. The average latitude is defined as the latitude that corresponds to the middle point of the longitudinal extent of the hydrostructure. The functional relationship between average effective infiltration values and average latitude is shown by the linear regression curve. The R^2 value of 0.78 validates a linear correlation model.

The distribution of points in the graph confirms the sharp difference in effective infiltration between hydrostructures located north and south of the "Fossato di Vico-Gole della Rossa" line (Mastrorillo, 2001). The distribution also shows that, in both sectors, the investigated parameter gradually increases southwards.

This effective infiltration trend increases from N to S. This result is confirmed by analysis of the parameter values calculated using different methods and is attributed in the literature to be due to the undifferentiated "Scaglia" and "Maiolica" complexes. Caprari and Nanni (1999) reported an effective infiltration of 200 mm/year for the Mt. Catria-Mt. Nerone ridge, whereas Boni et al. (1994) reported 380 mm/year for the Mt. Maggio-Mt. Penna ridge. The infiltration into the Foligno Mts. was ranges between 420 and 520 mm/year (Boni and Mastrorillo, 1993) and Cencetti et al. (1989) assigned a value of 450–550 mm to the Nera valley. The effective infiltration at the Fiori mountain was reported at 610 mm/year (Montroni et al., 1999).

Theoretically, the upward trend of average effective infiltration depends on the variation of two independent variables:

- extent of precipitation;
- lithological features (e.g., marly content) and structural

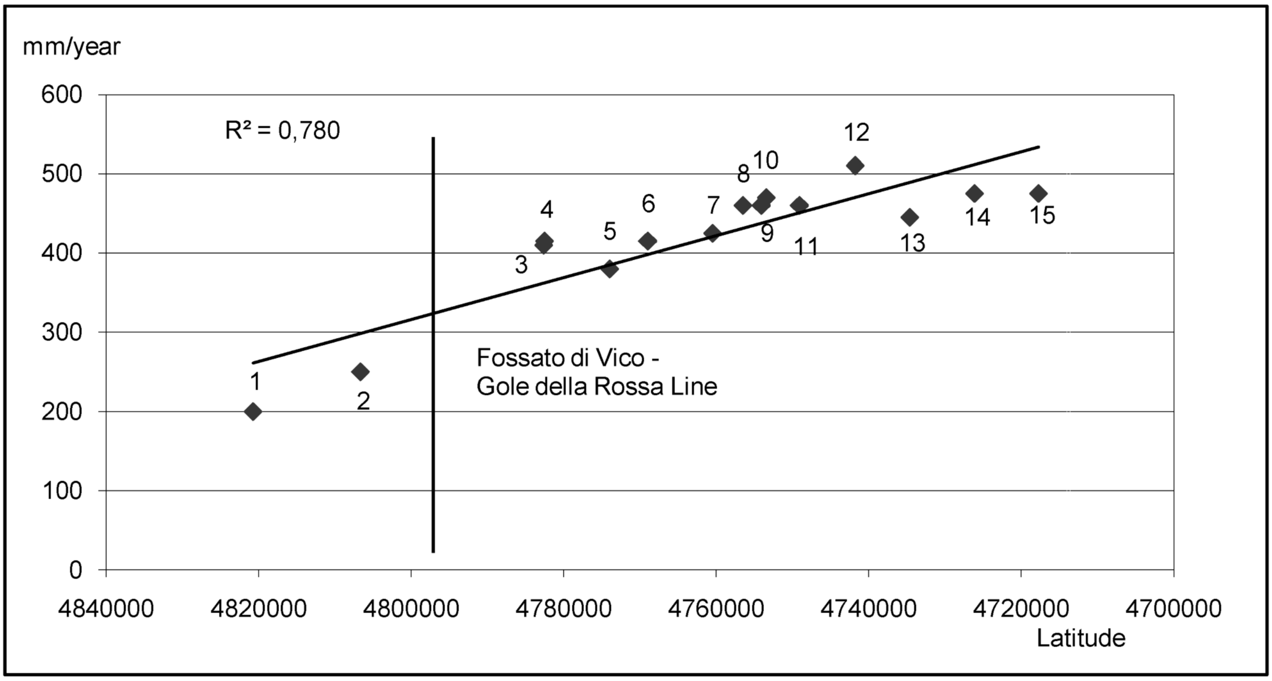

Fig. 4 - Mean effective infiltration distribution related to the latitude of the hydrogeological units. (Geografic System WGS84-Monte Mario Italy2).

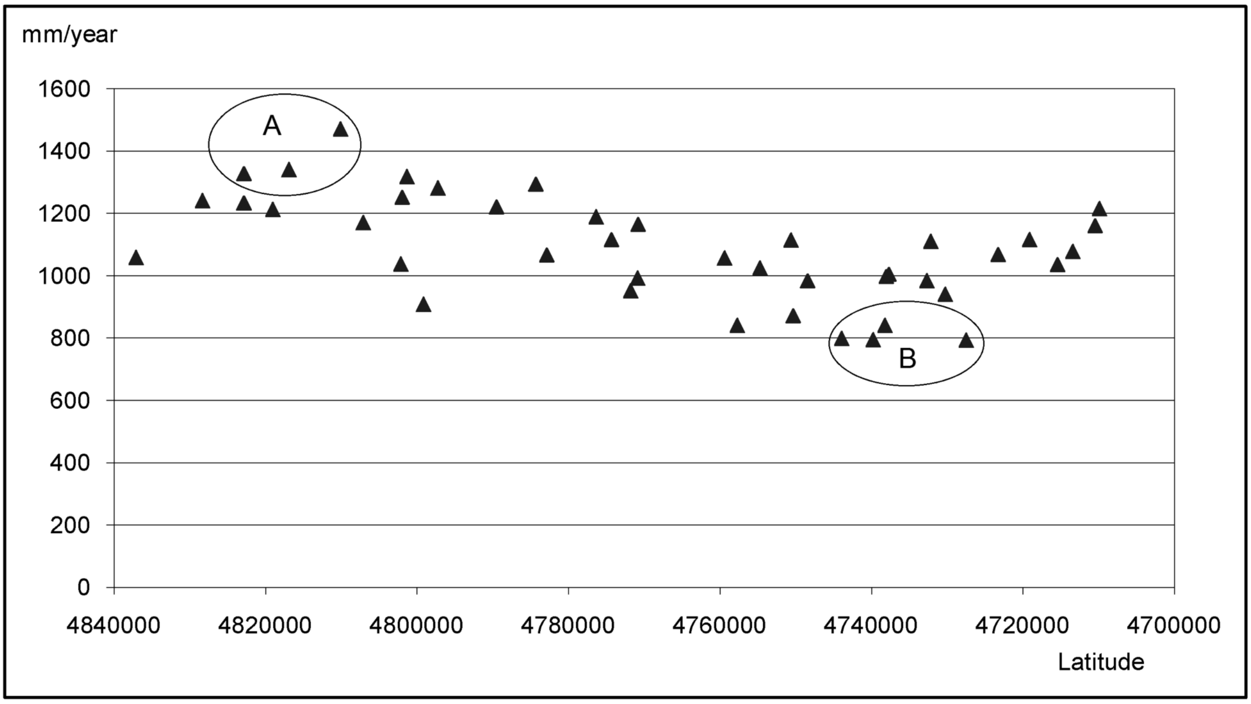

Fig. 5 - Mean yearly rainfall distribution (Boni et al., 1986) related to latitude of the rain station (Geografic System WGS84-Monte Mario Italy2).

features (e.g., extent of fracturing) of the calcareous rocks outcropping in the recharge areas.

The influence of vegetation on the spatial variability of effective infiltration is negligible because the vegetation characteristics in the study area are uniform. In fact, the whole Umbria-Marche Apennine region is included in the geobotanical Eurosiberian region where broadleaf forests are prevalent. Historically, human impacts have lowered the wood limits to elevations lower than 1700 m asl, favoring the diffusion of the mountainous grassland areas on the ridge tops (Pedrotti, 2002).

The spatial distribution of average effective infiltration was directly compared with average yearly precipitation in order to assess the influence of each of the investigated variables.

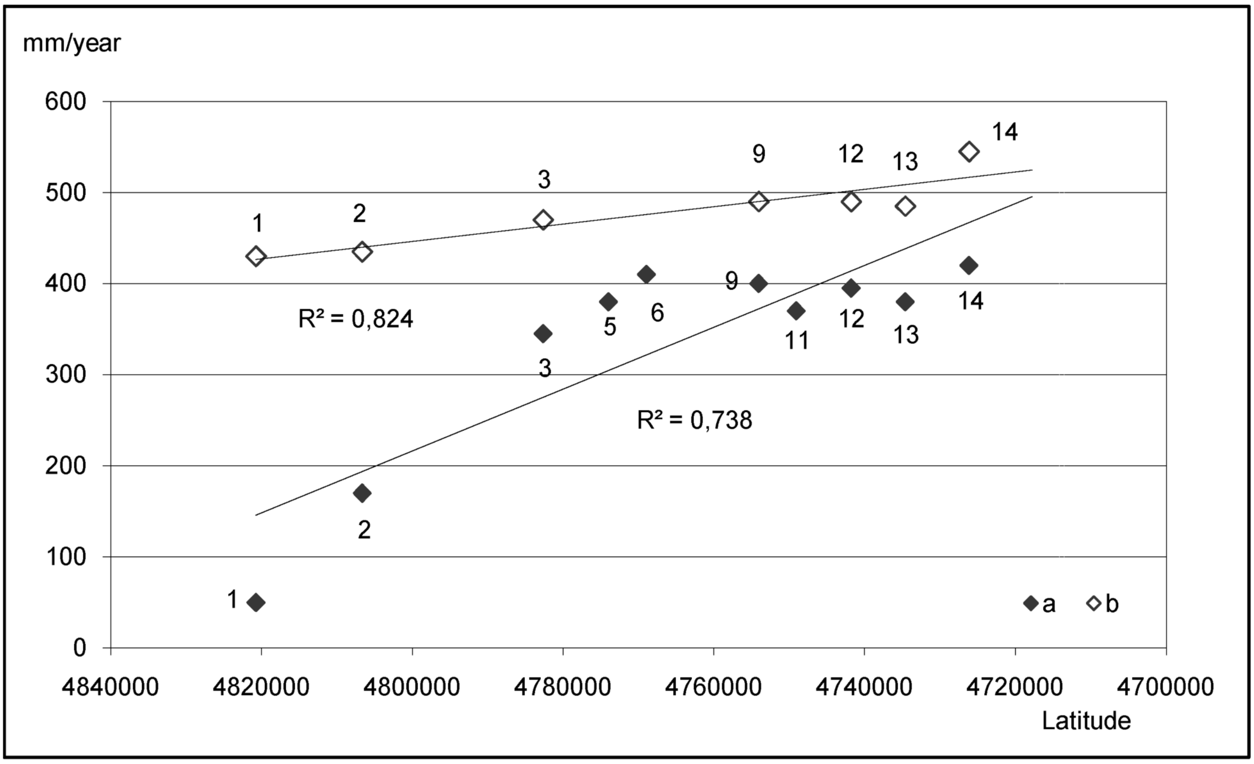

Fig. 6 - Mean effective infiltration distribution of the Scaglia complex (a) and of the Maiolica, Corniola-Calcare Massiccio complex (b) related to the latitude of some of the hydrogeological units (Geografic System WGS84-Monte Mario Italy2).

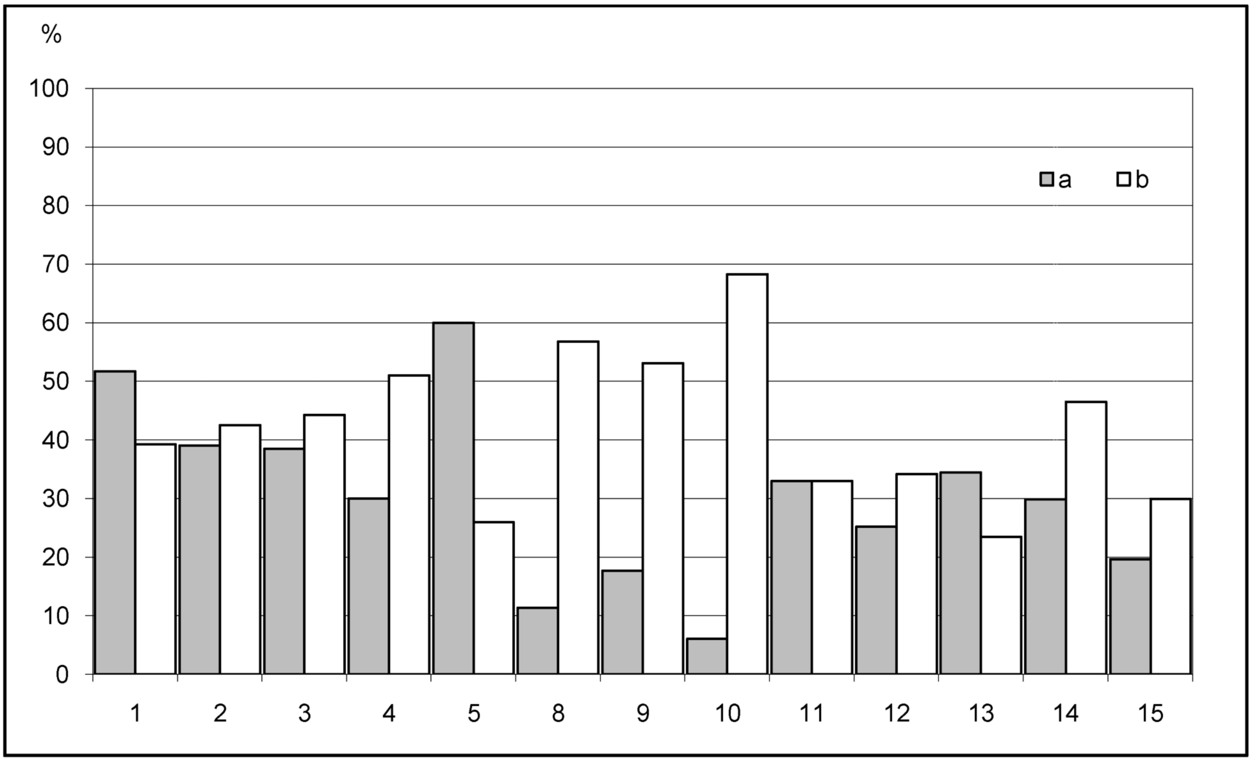

Fig. 7 - Comparison between percentage outcrop of the Scaglia complex (a) and of the Maiolica, Corniola-Calcare Massiccio complex (b) in each hydrogeological units, numbered referring to Tab.1.

Fig. 5 shows the distribution of the yearly average precipitation values (measured by the rain gauge stations in the investigated area) (Boni et al., 1986) vs. latitude.

The measured yearly precipitation ranges from about 800 mm to 1,500 mm, with an average value of roughly 1,090 mm.

The distribution of precipitation values does not suggest a clear variation with latitude. Local countertrends, in terms of the distribution of effective infiltration, were observed. Indeed, the highest yearly average precipitation values were measured by some of the northernmost stations (A in Fig. 5), which are located at hydrostructures with the lowest effective infiltration values. The four rain gauge stations where the lowest yearly average precipitation was recorded (B in Fig. 5) fall within the recharge area of the Mt. Tolentino hydrogeological unit. Here, the average effective infiltration value has the pattern shown in Fig. 4.

Comparison of the two graphs indicates that the spatial variation of effective infiltration is not dependent on the distribution of precipitation values. Therefore, other explanations related to the lithological and structural variation in the recharge areas of the hydrogeological units may be more appropriate.

The values of effective infiltration that were calculated for the investigated complexes were analyzed separately. Fig. 6 shows the spatial distribution of effective infiltration in the "Scaglia calcarea" complex (in black) and in the undifferentiated "Maiolica, Corniola-Calcare Massiccio" complex (in white) vs. latitude. Effective infiltration increases with decreasing latitude, and this trend is much more pronounced in the "Scaglia" complex. The lowest values are in the northern sector, and effective infiltration reaches values close to those of the "Maiolica" and "Corniola-Calcare Massiccio" in the southern sector.

Using the statistical-structural method of Kiraly (Kiraly, 1969; Kiraly et al., 1971), Caprari et al. (2002) calculated the hydraulic conductivity of the lithotypes outcropping in the Mt. Catria-Mt. Nerone, Cingoli and Fiori mountain ridges on the basis of geostructural data. The purpose of this calculation was to reconstruct the main groundwater flowpaths. From this, the spatial distribution of the values shows that the hydraulic conductivity of the "Scaglia" increases from N to S. The hydraulic conductivity in the "Scaglia" of Mt. Catria-Mt. Nerone has a peak value of ~10^{-7} m/s. In contrast, progressively higher orders of magnitudes are obtained trending southward for the Cingoli ridge (10^{-6} m/s) and for the Fiori mountain ridge (10^{-5} m/s). No significant hydraulic conductivity spatial variations were observed for the other calcareous lithotypes of the Umbria-Marche succession.

The results described so far indicate that the "Scaglia" fracturing has a greater significant spatial variation than other calcareous lithotypes. In particular, it is necessary to check whether the progressive increase of effective infiltration that proceeds southwards is accompanied by an increase in the values characterizing the fracturing. Unfortunately, the current lack of geological-technical data collected specifically with this hydrogeological purpose in mind makes this type of verification difficult.

In the investigated area, the outcrop percentage of the "Scaglia" complex and the "Maiolica-Corniola-Calcare Massiccio" complex of each hydrostructure was correlated with latitude variation (Fig. 7).

Consideration was only given to the hydrogeological unit where outcrops of both complexes are present. This neglects the Mt. Faeto and Mt. Cavallo hydrogeological units, which have recharge areas almost entirely composed of outcrops of the "Scaglia" complex.

The recharge area by the "Scaglia calcarea" complex is wider in the northern hydrostructures than in the southern ones, where the exposure of the "Maiolica-Corniola-Calcare Massiccio" complex increases (Fig. 7). This trend may be attributed to the fact that the two areas have different deformation styles and are separated by the "Fossato di Vico-Gole della Rossa" line (Ambrosetti et al., 1981). The overlaps and overthrusts that are prevalent in the southern sector may have favored greater uplift of the anticline cores, resulting in subsequent erosion of larger volumes of "Scaglia" and a wider exposure of the underlying and more ancient lithotypes.

Differentiation effects add to the spatial variability of fracturing in the "Scaglia" and are responsible for the differing amounts of water resources in the hydrostructures. The occurrence of wide outcrops of the "Scaglia" complex with reduced infiltration capability explains the existence of less productive aquifers in the northern hydrostructures (Mt. Nerone and Mt. Cucco). The wider exposure of the "Maiolica-Corniola-Calcare Massiccio" complex, concurrent with the peak effective infiltration capability, favors the higher water potential of the southern hydrostructures (Mt. Solenne and Mt. Aspra-Coscerno).

CONCLUSIONS

The spatial variability of the effective infiltration parameter was assessed in the recharge areas of hydrogeological units belonging to the hydrogeological group of the Umbria-Marche ridge. The qualitative and quantitative results from the data analysis serve as a starting point for additional, more detailed studies.

The regional-scale analysis highlighted the following things:

- the yearly average value of effective infiltration, calculated for the investigated hydrostructures, increases progressively from north to south;
- the spatial variability of this parameter does not depend on the distribution of precipitation. Rather, it depends on the differing extent of fracturing of calcareous outcrops in the recharge areas. The possible spatial variation of the marly content of the calcareous outcrops (another factor that has an impact on the variability of effective infiltration) was not analyzed in this study;
- the values of effective infiltration of the "Scaglia calcarea" complex are always lower than those of the "Maiolica" and "Corniola-Calcare Massiccio" complexes. The difference between the values is a maximum (80%) in the northerly hydrostructures and decreases progressively, to 20%, in the more southerly structures;
- in the recharge areas, the exposure of the "Scaglia calcarea" complex is higher in the northern hydrostructures. In the southern hydrostructures, outcrops of the "Maiolica" and "Corniola-Calcare Massiccio" complexes are prevalent;
- the upward trend of effective infiltration with decreasing latitude is more marked in the "Scaglia" complex, indicating a higher spatial variability of fracturing in the "Scaglia" than in other types of calcareous lithotypes.

The above features control the regional hydrogeological setting and the different water resources in the hydrogeological units. The northerly complexes (Mt. Nerone and Mt. Cucco), with recharge areas dominated by outcrops of the "Scaglia" complex with less intense fracturing, have less productive aquifers. In the southern hydrostructures, the larger "Maiolica" and "Calcare Massiccio" complex exposures that have more intense fracturing favor the recharge for more productive deep regional aquifers (Mt. Aspra-Coscerno, Mt. Solenne).

To better understand the above phenomenon, the results of regional, quantitative hydrogeological studies should be integrated with specific geological-technical surveys of the hydrogeological complexes that are exposed in the recharge areas of the Umbria-Marche carbonate aquifers. During the surveys, particular emphasis should be placed on the geological-technical parameters that affect the infiltration process of water recharge into a fractured aquifer. In effect, the dominant vertical component of the infiltration flow suggests that the degree of opening and filling of discontinuities is particularly significant and that particular attention should be attached to the study of the variation of this characteristic with depth (Gattinoni et al., 2005; Gattinoni and Scesi, 2007).

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