The recharge - discharge process of the Peschiera spring system (central Italy)

Massimo V. Civita, Adriano Fiorucci

Abstract: The springs of Peschiera are situated in the Velino river valley, a few kilometres upstream of Cittaducale in the province of Rieti. They form the largest group of springs in the central Apennines with their 17 m^3/s environ average discharge, collected and diverted by ACEA to supply Rome and much of its hinterland. Our research presented herein had various purposes, including determination of the hydrogeological catchment area, the study of the hydrodynamics of the limestone aquifer and a complete hydrogeochemical study not only of the large springs in question but of all the many sources in the middle Velino valley. Various types of models were used: a numerical model quantified the aquifer's recharge-discharge process and verified its area; using various mathematical models, based on spring discharge data, we determined the regulating reserves and the renewal times of the resource and various other parameters useful for its sound management. Finally, analysis of the chemical and hydrodynamic properties highlighted the differences between the Peschiera waters and those of the other springs either side of the valley. Our study represents an integrated innovative approach that may be successfully applied to other large springs in the Apennines and Alps. It lends insights, on a mathematical basis, into the recharge-discharge process of limestone aquifers, which is of use to define the source protection zones concerned.

Keywords: limestones aquifer, spring recharge-discharge, groundwater age, mathematical models.

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Riassunto: *Le Sorgenti del Peschiera sgorgano in sinistra orografica della valle del F. Velino, qualche km a monte di Cittaducale in Provincia di Rieti. Si tratta del maggior gruppo sorgivo dell'Appennino centrale con i suoi 17 m^3/s di portata media, captati e derivati dall'ACEA per alimentare Roma e gran parte del suo hinterland. La ricerca che qui si presenta ha avuto vari scopi, tra i quali la determinazione della struttura idrogeologica che alimenta il gruppo, lo studio dell'idrodinamica dell'acquifero carbonatico e lo studio idrogeochimico completo, non soltanto delle grandi sorgenti in oggetto ma di tutte le numerose scaturigini della valle del medio Velino. Sono stati utilizzati diversi tipi di modelli: un modello numerico ha quantificato il processo ricarica - discarica dell'acquifero ed ha verificato la sua estensione; diversi modelli matematici, basati sui dati di portata sorgiva, hanno permesso di valutare le riserve regolatrici ed i tempi di rinnovamento della risorsa e diversi altri parametri utili per la sua corretta gestione. L'analisi delle caratteristiche chimiche e idrodinamiche ha, infine evidenziato, le differenze esistenti tra le acque del Peschiera e quelle delle altre sorgenti in destra e sinistra della Valle. Il lavoro rappresenta un innovativo approccio integrato che potrà essere applicato con successo alle altre grandi sorgenti appenniniche e alpine. Esso permette di comprendere, finalmente su una base matematica, il processo di ricarica e discarica degli acquiferi carbonatici, utile per delineare le aree di salvaguardia delle scaturigini stesse. L'alta valle del F. Velino percorre, a partire da Antrodoco, un'importante linea tettonica (linea Olevano – Antrodoco – Posta) che divide, dal punto di vista strutturale, l'Appennino meridionale da quello settentrionale. Nel tratto centrale, tra Posta e Cittaducale, il F. Velino riceve un notevole apporto da sorgenti poste in destra orografica e ancora maggiore in sinistra, dove sgorgano le sorgenti del F. Peschiera. Le sorgenti, captate in due riprese, alimentano Roma e l'alto Lazio con un'importante rete acquedottistica, integrata anche da altre fonti, gestita dall'ACEA che ha prestato la sua collaborazione, indispensabile per la ricerca, permettendo agli autori di rilevare i dati necessari presso le captazioni delle sorgenti medesime. Questo lavoro sintetizza uno studio durato diversi anni e che si è avvalso del telerilevamento multiscanner da aereo e da satellite, dei normali rilevamenti geologici ed idrogeologici, di una notevole massa di misure ed analisi chimico–fisiche e delle relative elaborazioni modellistiche che comprendono anche il bilancio idrogeologico dell'idrostruttura. L'idrostruttura in questione è una delle più vaste di tutto l'Appennino centrale.*

Introduction

The springs of Peschiera are situated in the Velino river valley, a few kilometres upstream of Cittaducale in the province of Rieti (Lazio, middle Italy) (Fig.1). They form the largest group of springs in the central Apennines with their env. 17 m^3/s average discharge, to supply Rome and much of its hinterland and most of northern-middle Lazio. Velino river valley, from Antrodoco, is situated on an important tectonic line (Olevano-Antrodoco-Posta) that separates Northern from Southern Apennines. Many springs situated in orographic right

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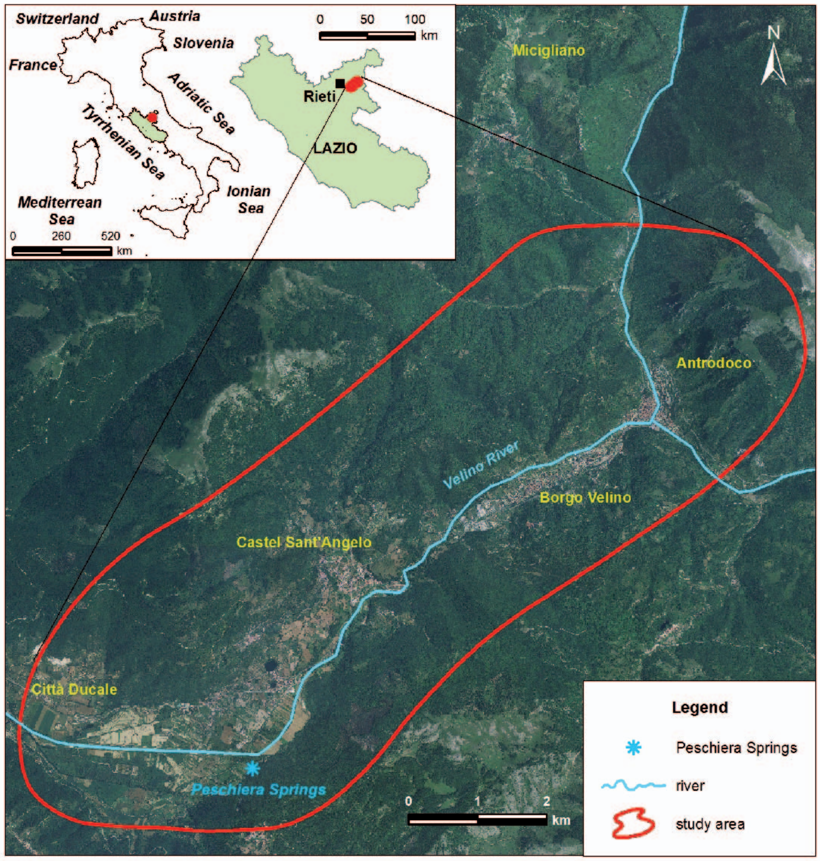

Fig. 1: *Location of the study area.*

and left, where there are the springs of Peschiera, yield Velino River, in the middle part, between Posta e Cittaducale. The spring tapping, on two times, and other springs are collected and diverted by ACEA to supply Rome and much of its hinterland. This paper summarizes a job that lasted several years. It bases on multiscanner Airborne and Satellite Remote Sensing, geologic and hydrogeologic surveys, a lot of dates and chemical and physical analysis to make a numerical model that include ground water balance of the hydrostructure. This hydrostructure is one of the wider in the middle Appennines.

The spring discharge area

The chief aim of this work is to dispel doubts concerning the size of the catchment area and establish the hydrogeological separation from the adjacent structures of Mt. Terminillo to the NW and Mt. Sirente to the SE, catchment areas for regionally important sources. The most critical part for understanding the hydrostructure that feeds the Peschiera springs is its western boundary, where there is the largest number of springs feeding the River Velino between Posta and the Spa of Cotilia (Castel S. Angelo, immediately upstream of Cittaducale - Fig. 2). The characteristic data of all the springs are reported in Table 1. In the study area, we used landsat-tm satellite and **MIVIS**[1] aerial prospecting to obtain the heat inertia index pixel by pixel. The relative map highlighted concealed springs and underground reservoirs. With this support we were able to carry out a targeted campaign of discharge measurements.

The first sources of any importance on the left side of the Velino appear at 510 m a.s.l. in the area of Cascinesi, a few km upstream of Antrodoco on the eastern front of the Mt. Giano substructure, with major variations in discharge (from over 0.5 m^3/s to 0 m^3/s). Hydrogeochemical prospecting carried out in Spring 2010 highlighted a good similarity between the Fontanelle springs (S02), on the right-hand side of the Velino (q = 456 m a.s.l., Q = 0.46 m^3/s), those of Canetra (S03, q = 434 m a.s.l., Q = 1.38 m^3/s) and that detected at Briglia di Canetra (S15). Between the Fontanelle group and the Canetra group in the Velino channel are the springs Campodoro 1 (S04) and Campodoro 2 (S05) fed by the same aquifer as the above two groups. The River Velino downstream of Canetra has considerable discharges (2 - 3 m^3/s). Besides the already abundant Canetra springs there is the contribution of other springs, whose outflow at the Briglia was measured at 0.133 m^3/s.

Farther downstream in the area of Sant'Erasmo, close to the emergence zone of the Peschiera springs, are some sources, known in the local dialect as Paulle. Two of these are sulphureous, Paulla bassa (S08) and Paulla 3 (S10). The former has a modest discharge, while the latter reaches 0.04 m^3/s. In the same area, there are more important springs at Paulla Alta (S09), where a discharge of 0.08 m^3/s has been measured, and Sant'Erasmo (S11), with a discharge of 0.115 m^3/s (Tab. 1). On the opposite side of the Velino (right), other water points have been detected, the largest being the spring of Mulino di Vasche (S12), with a discharge of 0.085 m^3/s.

As regards chemical properties, the springs Campodoro 1 (S04) and Campodoro 2 (S05), located on the left side, are similar to those of Monte Canetra (S17) and Mulino di Vasche (S12), showing the possible drainage of the same aquifer. The various diversion branches of the Peschiera springs have very similar chemical properties.

[1] **MIVIS** *is an airborne scanner (102 channels), used at heights of 2500 m (4 passes) and 4300 m (6 passes). In processing, 12 channels were used, between visible and thermal infra-red.*

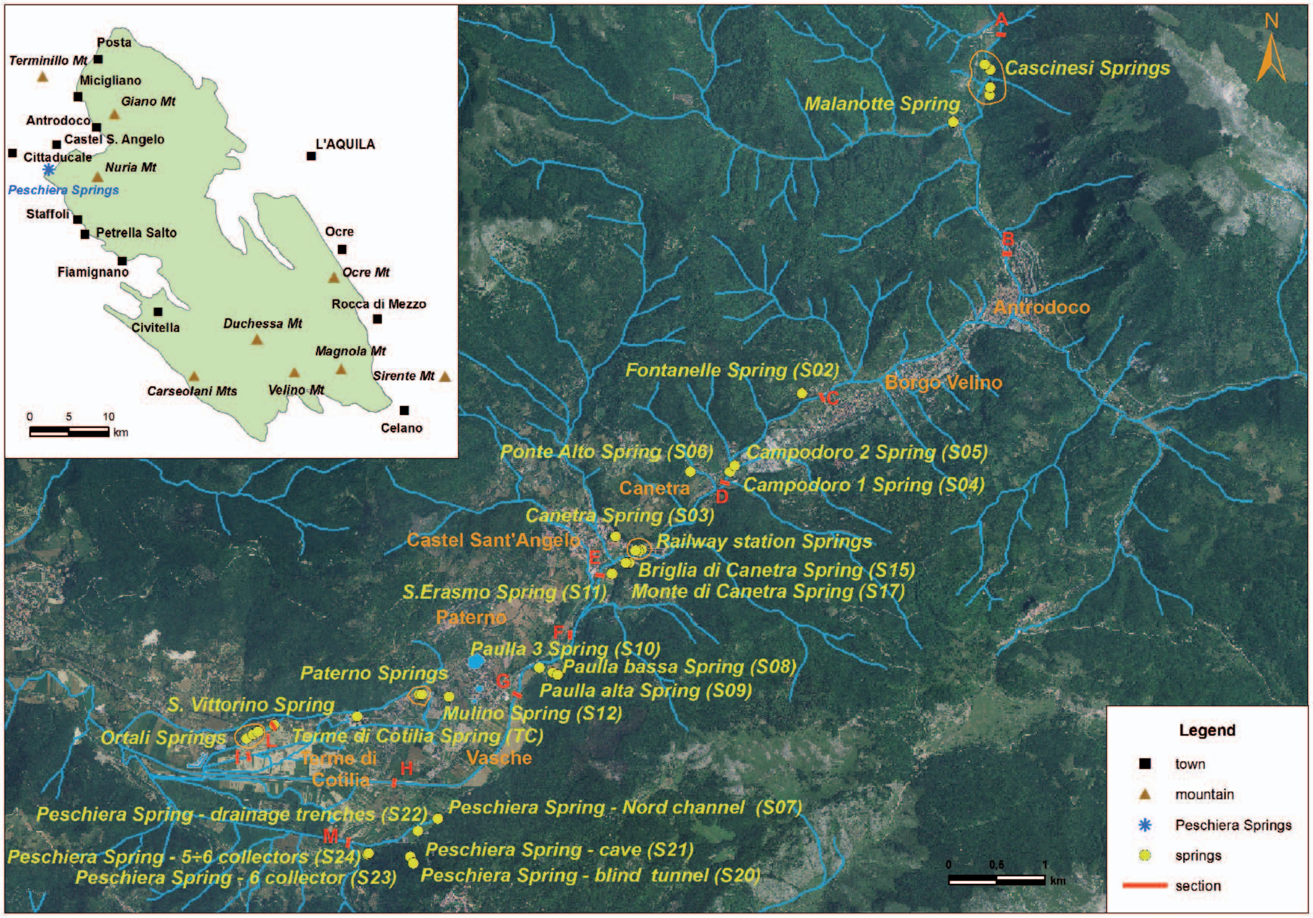

Fig. 2: *Location of the springs feeding the River Velino between Posta and the Spa of Cotilia.*

Spring geochemistry

The hydrochemical data for the study area concern the groundwater from the more important of the censused springs and the surface waters of the River Velino and Lake Paterno. The chemical analyses were conducted at the Hydrogeological Research Laboratory of Turin Polytechnic belonging to the Disaster Planning Laboratory (DiPLab). Samples of the waters from the River Velino upstream and downstream of the study area, from Lake Paterno and from 19 springs (Fig. 3), as reported in Tables 2 and 3, were taken in Spring 2010 and immediately analysed.

On the whole, the waters were fairly mineralised except for the sulphureous Cotilia spa (TC), Paulla bassa (S08) and Paulla 3 (S10) which were highly mineral. In all cases, the waters analysed were of the type $Ca^{2+} > Mg^{2+} > (Na^{+} + K^{+}) – HCO_3^{-} > SO_4^{2-} > Cl^{-}$. The waters were substantially of a calcium bicarbonate facies, wholly compatible with the rocks in the study area. However, within such general uniformity there are differences, albeit slight, which allow chemically similar groups of springs to be identified.

The first group consists of sulphur springs which, as stated above, are appreciably more mineralised than all the others. These are point sources, two of which (Paulla bassa and Paulla 3) were situated close to each other on the left bank of the Velino, upstream of the Peschiera springs, close to the mountains, while the third (Cotilia spa) is on the right bank, close to the mountain ridge and W of the previous two. The chemistry of Paulla bassa and Paulla 3 is substantially identical, both in terms of quantity and quality, as shown by the Schoeller Diagram in Figure 4. Together with their spatial proximity, this indicates that the two springs are sources from the same aquifer. Also the sulphur content of the two springs is substantially identical. By contrast, the waters of the Cotilia spa are appreciable more mineralised and have lower characteristic HCO_3^{-}/SO_4^{2-} and $(Ca^{2+} + Mg^{2+})/(Na^{+} + K^{+})$ ratios than the previous springs. Granted the same origin of the sulphur waters, the differences observed may be reasonably explained by mixing with less mineralised water from the active recharge. This would be confirmed by the temperature data, given that the more mineralised waters of the Cotilia spa are warmer than those of Paulla 3 and Paulla bassa (respectively 14.18; 12.16 and 11.81 °C) as well as by metal contents, appreciably higher at the Cotilia spa than the other two.

The remaining 16 sampled springs may be distinguished into three groups, on the basis of their sulphate ion content and, more generally, the HCO_3^{-}/SO_4^{2-} ratio (Fig. 5). The first group comprises springs with high sulphate contents and a ratio of $HCO_3^{-}/SO_4^{2-} < 10$. These are the springs Campodoro 1 (S04), Campodoro 2 (S05), Monte Canetra (S17), on the left bank of the Velino, and Mulino di Vasche (S12) on the right (Fig. 3). Campodoro 1, Campodoro 2 and Monte Canetra are situated almost in the channel of the Velino. In the Campodoro there is a higher presence of sulphates than in the other. The Mulino di Vasche spring is situated on the alignment with the sulphur springs.

The second group of springs has a mean sulphate content and a characteristic HCO_3^{-}/SO_4^{2-} ratio between 11.866 and 13.359. To this group, upstream of the Peschiera springs, belong Fontanelle (S02),

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Tab. 1: *Discharge (m^3/s) of springs and sections of the River Velino upstream of Cittaducale.*

Code	Measuring point	Q_{av}	Q_{Max}	Q_{min}	I_M
A	River Velino downstream of Posta	0.36			
	Cascinesi springs	0.49			
	Malanotte spring	0.37			
B	River Velino at Antrodoco	1.28	3.11	0.34	
C	River Velino at Borgo Velino	1.61	2.92	0.37	
S02	Fontanelle spring	0.35			
S04 – S05	Campodoro 1 and Campodoro 2 springs	0.12			
D	River Velino at Ponte Alto	1.85	2.87	1.34	
	Railway station springs	0.69			
S03	Canetra spring	1.38			
E	River Velino at Canetra	5.71			
S08	Paulla bassa spring				
S10	Paulla 3 spring	0.04			
S09	Paulla alta spring	0.08			
S11	Sant'Erasmo spring	0.115			
F	ENEL diversion channel	5.25			
G	River Velino at Vasche	1.46			
H	River Velino channel	1.38			
	Paterno springs	0.41	0.43	0.40	0.07
S12	Mulino spring	0.085			
I	Cotilia spa	0.83	0.88	0.58	0.36
L	San Vittorino spring	0.18	0.211	0.145	0.37
	Ortali springs	0.10	0.12	0.10	0.20
	Peschiera springs (total)	17.87	21.30	14.70	0.37
M	River Peschiera	7.74			

Canetra (S03) and Ponte Alto (S06), on the right bank of the Velino and Briglia di Canetra (S15) and Sant'Erasmo (S11), on the left. The third group of springs, characterised by a lower sulphate content, contains Paulla alta (S09) and the various extractions of the Peschiera springs. The Paulla alta spring is situated upstream of the Peschiera springs on the same mountain-side.

Among the springs with low sulphate contents two subgroups may be distinguished: one consists of the Paulla spring and the sources called Canale Nord (S07) and Collettore 6 (S23) of the Peschiera springs, with a higher sulphate content than the others. Interestingly, the Paulla alta spring wells up, as already stated, upstream of the Peschiera springs, while S07 and S23 lie at the ends of the phreatic line of the Peschiera (Fig. 3).

The chemistry of the surface waters sampled at the River Velino, upstream (VM) and downstream (VV) of the study area, as well as Lake Paterno (L4), lies between those described for the first and second group of non-sulphur springs. This should be related to the presumed link between the surface waters and the springs of the two groups that are largely situated in the channel of the River Velino and hence potentially fed by the losses upstream of the same springs. Examination of the chemical data shows a substantial difference between the waters of the Peschiera springs and those of other springs, which may be related to the different catchment areas. That said, the difference in water chemistry cannot be considerable since the chemistry depends on water-rock reactions. In the study area substantially uniform carbonatic rocks outcrop, as evidenced by the main hydrochemical facies common to all the waters (calcium bicarbonate).

Further confirmation of the particular chemistry of the Peschiera spring waters may be evinced from the contents of rubidium and strontium. On the basis of such values, the sulphureous waters and those of the Peschiera springs are quite different from the others (Fig. 6). In particular, in the area of the diagram containing the points of the Peschiera spring waters, there is a slight shift in samples S07 and S23 which come from the ends of the source zone. Subdivision of the waters on the basis of sulphate content, also confirmed by the analysis of Sr and Rb contents, is a further indication that it is precisely the sulphate ion which is the most discriminating parameter. As regards the sulphurous waters, the data reported in the Sr vs Rb diagram confirm the similarity between springs Paulla bassa (S08) and Paulla 3 (S10) as well as the hypothesis already proposed on the basis of their chemistry and their temperature which viewed them as the product of mixing between the sulphureous waters such as those of the spring at the spa Terme di Cotilia (TC) with waters from active recharge. The diagram in figure 6 shows the close alignment between the sulphur springs and Paulla alta (S09) situated close to S08 and S10, confirming the hypothesis of mixing.

As regards the waters of some sources at the Peschiera springs, the rainwater collected by a local pluviometer and the Canetra spring,

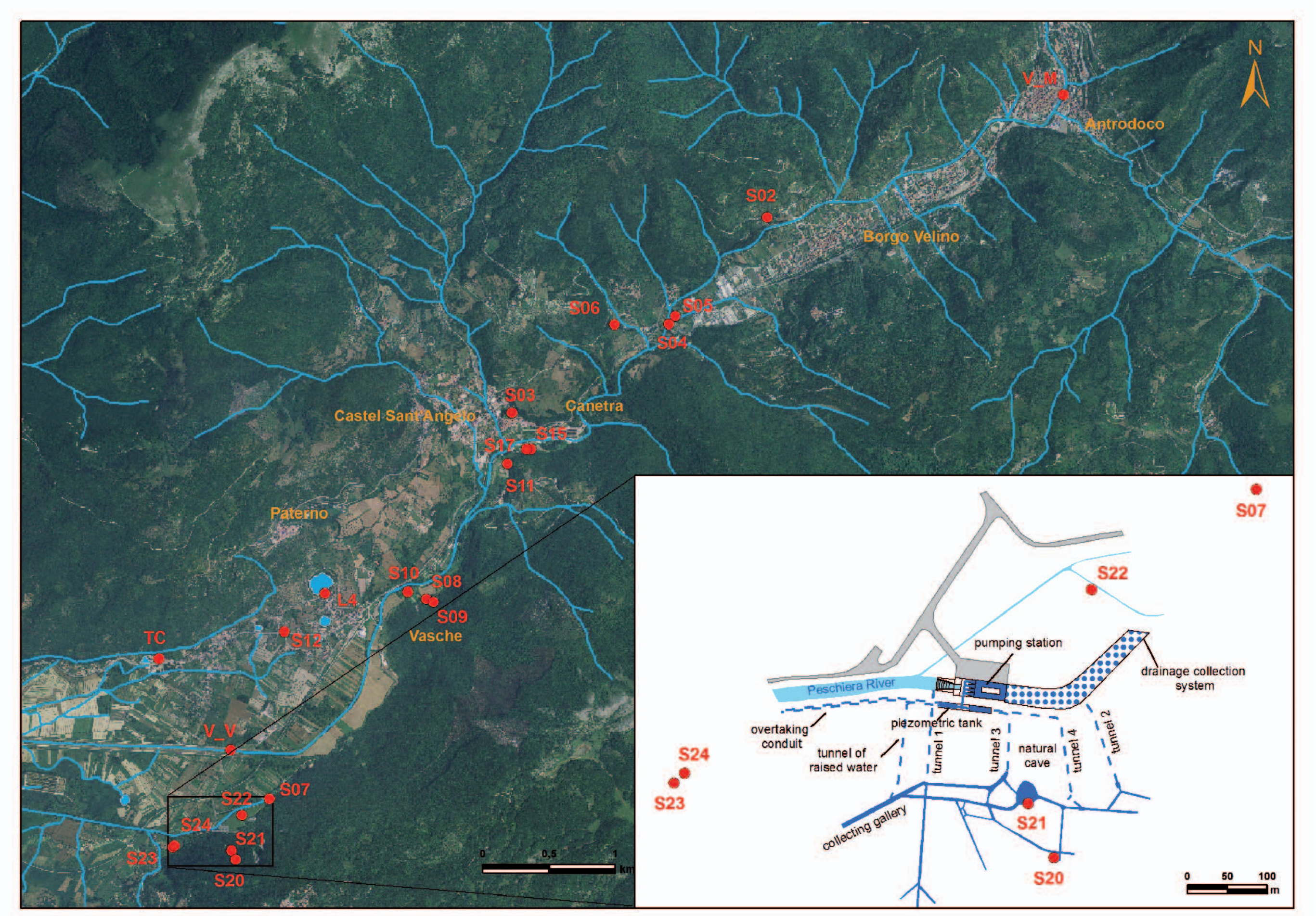

Fig. 3: *Location of the water samples.*

in 1994 ACEA carried out isotope analyses concerning ^{18}O, ^{3}H, ^{13}C and ^{14}C, summarised in Table 4. As for the ^{18}O isotope data, with the extreme values obtained and with reference to the variation of the $\delta^{18}O$ curve with height on the Tyrrhenian and Adriatic coast (Zuppi et al., 1974), the following recharge altitudes are respectively obtained: 1209 and 1060 m a.s.l. and 1329 and 1152 m a.s.l. Considering the averages in the two cases, there are recharge heights of 1134 m a.s.l. and 1240 m a.s.l. absolutely consistent with the orographic features of the area. However, the highest value of $\delta^{18}O$, corresponding to lower recharge heights, belongs to the Peschiera springs while higher amounts are found at the Canetra spring. In each case, the uncertainty of the measured data (estimated at 0.1%) and their non-substantial differences do not allow the infiltration heights of the water from the two springs to be clearly distinguished.

As regards the tritium (^{3}H) data, in the spring waters there are concentrations between 12.0 and 16.5 UT to be referred to rainwater, introduced into the aquifer contaminated by tritium from the fallout of thermonuclear explosions, a particularly evident effect in the 1955-1965 ten-year period (IAEA, 1968; Craig & Lal, 1961). Two hypotheses may be formulated to explain the significance of the tritium values obtained:

Hypothesis A: there is only one aquifer feeding the Peschiera springs. Thus, on the basis of the tritium content, water infiltrating prior to 1955 and after 1980 must be ruled out: the former because it should be tritium-free, after the residence time in question, the latter because it should have a lower tritium content than that measured. Hence, given the tritium concentration in the rainfall between the late 1940s and the 1990s, it must be admitted that the spring waters of the Peschiera are compatible with the water infiltrating in the 1970s. Thus the aquifer in question would have a recharge time of about 20 years.

Hypothesis B: the aquifer feeding the Peschiera springs is complex. It is the result of two overlying water bodies whose waters mix when reaching the springs. One of these water bodies should thus have a much higher tritium content than that measured, while it will show appreciably lower tritium contents or it will be even absent. Bearing in mind the tritium concentration in the rainfall between the late 1940s and the 1990s, the water of the hypothetical body with high tritium content must have infiltrated in the period 1955-1965, corresponding to the peak tritium air concentration. The water in the other body must therefore have infiltrated prior to 1955 (hence tritium-poor) or after 1980 (obtaining water with less tritium than the measured value). However, this second hypothesis cannot be sustained in hydrogeological terms. Thus, as regards a tritium content in the infiltration water in the period 1955-1965 (equivalent to 900 UT), a value of about 150 UT is obtained for the waters belonging to the first body, while the second does not have the radioisotope in question. Thus we hypothesise a 1:10 mixing ratio between the two aquifers. According to the tritium values alone, hypotheses A and B are both valid.

As regards the contents of the radioisotope ^{14}C, measured only at some sources of the Peschiera springs, the values supply an age

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Tab. 2: *Chemical data for groundwater and surface water.*

Cod	Point	T [°C]	pH	Eh [mV]	EC [mS/cm]	TH [°f]	Na^+ [mg/l]	NH_4^+ [mg/l]	K^+ [mg/l]	Ca^{2+} [mg/l]	Mg^{2+} [mg/l]	F^- [mg/l]	ClO_2^- [mg/l]	BrO_4^- [mg/l]	Cl^- [mg/l]	NO_2^- [mg/l]	Br^- [mg/l]	NO_3^- [mg/l]	PO_4^{2-} [mg/l]	SO_4^{2-} [mg/l]	HCO_3^- [mg/l]	SiO_2 [mg/l]
S04	Campodoro 1	12.62	7.33	177	737	39.61	6.52	< 0.01	1.81	121.56	22.49	0.33	< 0.01	< 0.01	8.93	0.02	< 0.01	6.16	0.01	70.22	394.41	7.47
S05	Campodoro 2	12.53	7.25	190	722	39.02	6.41	< 0.01	1.47	123.24	20.05	0.27	< 0.01	< 0.01	8.38	0.01	< 0.01	6.22	0.01	58.31	402.95	6.43
S17	Monte di Canetra	10.68	7.66	188	769	42.11	4.84	< 0.01	1.31	134.25	20.86	0.22	< 0.01	< 0.01	6.38	0.06	< 0.01	1.80	< 0.01	44.85	461.10	5.20
S12	Mulino	10.99	7.16	178	953	53.53	4.84	< 0.01	1.16	172.66	25.31	0.26	< 0.01	< 0.01	6.45	0.06	0.01	1.69	< 0.01	48.29	596.68	5.14
S02	Fontanelle	11.55	7.83	126	631	34.45	3.58	< 0.01	0.35	113.88	14.61	0.23	< 0.01	< 0.01	4.03	0.02	< 0.01	0.08	< 0.01	25.98	391.54	10.00
S15	Briglia di Canetra	10.62	7.40	165	794	46.66	3.58	< 0.01	1.17	151.37	21.55	0.16	< 0.01	< 0.01	5.08	0.04	0.01	1.55	< 0.01	33.58	531.51	4.81
S03	Canetra	10.87	6.92	172	869	48.64	3.68	< 0.01	1.02	158.57	21.97	0.14	< 0.01	< 0.01	4.80	0.08	< 0.01	1.67	< 0.01	34.65	549.75	5.31
S06	Ponte Alto	10.75	6.92	186	837	46.27	4.28	< 0.01	1.07	150.54	21.10	0.15	< 0.01	< 0.01	5.21	0.08	0.02	1.70	< 0.01	32.24	527.48	5.88
S11	Sant'Erasmo	11.25	6.92	196	898	50.81	3.58	< 0.01	1.18	164.68	23.54	0.16	< 0.01	< 0.01	4.56	0.08	0.01	1.26	0.01	34.07	578.19	4.99
S23	Peschiera channel 6	10.76	7.10	238	738	41.39	2.87	< 0.01	0.79	126.04	24.10	0.15	< 0.01	< 0.01	4.50	0.07	< 0.01	1.81	< 0.01	16.14	485.69	4.36
S09	Paulla alta	10.89	6.82	69	904	51.99	3.36	< 0.01	0.98	169.81	23.28	0.14	< 0.01	< 0.01	4.71	0.22	0.05	1.48	< 0.01	17.59	613.88	4.29
S22	Peschiera drainage trenches	10.23	7.17	222	714	39.63	2.64	< 0.01	0.77	123.71	21.23	0.11	< 0.01	< 0.01	4.04	0.00	< 0.01	1.82	< 0.01	12.54	469.34	4.16
S24	Peschiera between channels 5 and 6	10.83	7.15	231	691	38.28	2.70	< 0.01	0.77	116.78	22.15	0.13	< 0.01	< 0.01	4.35	0.06	< 0.01	1.88	< 0.01	11.86	449.99	3.81
S21	Peschiera Caverna	10.41	7.18	224	749	36.55	2.26	< 0.01	0.72	112.21	20.72	0.12	< 0.01	< 0.01	4.02	0.05	< 0.01	1.85	< 0.01	10.67	430.59	4.10
S07	Peschiera North Channel	11.80	6.85	226	943	54.21	2.79	< 0.01	0.75	175.96	24.96	0.12	< 0.01	< 0.01	4.20	0.10	0.03	1.66	< 0.01	15.64	640.55	4.76
S20	Peschiera blind tunnel	10.58	7.18	240	653	35.44	2.66	< 0.01	0.68	108.98	19.99	0.12	< 0.01	< 0.01	4.00	0.00	0.01	1.88	< 0.01	9.81	421.68	3.75
TC	Terme di Cotilia spa	14.18	6.17	-195	3385	179.98	26.01	0.34	2.77	574.36	88.84	0.64	< 0.01	< 0.01	36.39	1.19	0.17	1.08	< 0.01	196.08	1955.56	8.77
S10	Paulla 3	12.16	6.16	-235	1591	104.81	7.56	< 0.01	1.22	342.34	46.96	0.34	< 0.01	< 0.01	9.18	0.00	0.05	0.10	< 0.01	87.37	1165.10	4.93
S08	Paulla bassa	11.81	6.21	-234	1806	109.43	7.54	0.02	1.18	368.36	42.40	0.48	< 0.01	< 0.01	9.08	0.00	0.11	0.00	< 0.01	88.17	1246.13	5.33
VM	Mt. Velino	10.79	7.82	72	641	34.69	4.73	< 0.01	1.21	109.97	17.58	0.25	< 0.01	< 0.01	6.34	0.05	< 0.01	0.67	< 0.01	38.56	374.03	5.72
L4	Lake Paterno	9.26	7.60	208	690	37.93	4.62	< 0.01	1.47	114.18	22.88	0.19	< 0.01	< 0.01	6.35	0.02	< 0.01	0.00	< 0.01	34.86	421.93	3.24
VV	Velino Valley	11.17	7.58	106	918	51.72	4.19	< 0.01	1.23	167.83	23.85	0.19	< 0.01	< 0.01	5.62	0.18	0.01	1.23	< 0.01	37.07	586.55	4.33

Cod	Point	TDS [mg/l]	S^{2-} [mg/l]	Li [µg/l]	Al [µg/l]	V [µg/l]	Cr [µg/l]	Mn [µg/l]	Fe [µg/l]	Co [µg/l]	Ni [µg/l]	Cu [µg/l]	Zn [µg/l]	As [µg/l]	Se [µg/l]	Rb [µg/l]	Sr [µg/l]	Cs [µg/l]	Ba [µg/l]	Pb [µg/l]	U [µg/l]	SI calcite	SI gypsum
S04	Campodoro 1	633.400		4.50	< 0.01	0.74	0.79	1.30	0.65	0.15	0.42	0.77	3.15	0.53	0.87	1.00	1625.00	0.07	55.13	< 0.01	0.51	0.563	-1.445
S05	Campodoro 2	627.337		4.26	< 0.01	0.77	4.80	0.30	1.16	0.15	0.55	0.76	4.65	0.46	1.34	0.95	1146.00	0.04	55.56	< 0.01	0.51	0.501	-1.516
S17	Monte di Canetra	676.027		4.42	< 0.01	0.92	0.68	1.65	0.29	0.16	1.34	0.98	4.96	0.55	1.02	1.69	1245.00	0.07	40.37	< 0.01	0.52	1.001	-1.601
S12	Mulino	857.713		10.19	< 0.01	0.92	6.79	0.57	2.44	0.19	0.97	0.66	2.80	2.50	1.78	2.80	1114.00	0.90	44.71	< 0.01	0.62	0.698	-1.500
S02	Fontanelle	560.710		2.37	< 0.01	0.42	4.45	0.91	< 0.01	0.14	0.26	0.69	2.19	0.10	0.53	1.96	799.04	0.01	20.42	< 0.01	1.38	1.049	-1.876
S15	Briglia di Canetra	750.817		4.54	< 0.01	1.08	1.13	0.11	< 0.01	0.16	0.59	0.51	2.38	1.37	1.50	2.28	932.00	0.36	32.91	< 0.01	0.51	0.846	-1.690
S03	Canetra	777.971		4.74	< 0.01	1.12	6.78	0.12	< 0.01	0.17	0.48	0.34	1.58	1.12	0.65	2.09	838.50	0.17	32.56	< 0.01	0.52	0.397	-1.662
S06	Ponte Alto	745.466		4.11	< 0.01	1.21	0.63	0.09	< 0.01	0.17	0.39	0.38	1.21	1.01	1.43	2.04	809.50	0.17	34.08	< 0.01	0.59	0.361	-1.708
S11	Sant'Erasmo	812.720		4.85	< 0.01	1.25	1.21	0.49	2.42	0.18	0.66	0.71	2.74	1.06	2.04	2.31	936.30	0.17	33.83	< 0.01	0.55	0.431	-1.661
S23	Peschiera channel 6	663.651		2.73	< 0.01	1.18	1.94	0.07	< 0.01	0.14	0.68	0.34	1.40	0.92	0.42	1.71	517.20	0.12	15.79	< 0.01	0.69	0.441	-2.065
S09	Paulla alta	836.440		5.54	< 0.01	1.09	8.95	2.27	7.40	0.21	0.58	0.45	1.56	1.43	2.24	2.36	539.60	0.48	19.02	< 0.01	0.65	0.369	-1.936
S22	Peschiera drainage trenches	637.706		1.94	< 0.01	1.09	2.04	0.04	< 0.01	0.14	0.61	0.94	2.63	0.59	0.86	1.69	394.90	0.06	15.67	< 0.01	0.57	0.492	-2.175
S24	Peschiera between channels 5 and 6	611.772		2.08	< 0.01	1.07	1.88	0.08	< 0.01	0.13	0.52	0.46	1.86	0.78	0.47	1.67	388.30	0.08	13.48	< 0.01	0.62	0.432	-2.219
S21	Peschiera Caverna	585.053		1.67	< 0.01	1.04	1.20	0.08	< 0.01	0.12	1.88	0.37	6.32	0.70	0.86	1.61	346.60	0.05	14.35	< 0.01	0.54	0.430	-2.274
S07	Peschiera North Channel	868.728		2.21	< 0.01	1.32	3.06	0.13	2.15	0.20	0.86	0.34	1.93	0.79	1.82	1.86	543.80	0.08	16.05	< 0.01	0.70	0.429	-1.979
S20	Peschiera blind tunnel	570.892		1.58	< 0.01	1.08	4.60	0.07	< 0.01	0.12	0.69	0.53	2.65	0.76	0.99	1.64	337.60	0.05	14.20	< 0.01	0.57	0.411	-2.319
TC	Terme di Cotilia spa	2866.161	3.4	200.70	22.35	2.55	28.11	53.51	124.60	0.64	0.58	1.08	0.91	8.45	1.00	15.77	5497.00	7.77	38.22	< 0.01	0.48	0.589	-0.635
S10	Paulla 3	1657.592	4.7	39.63	12.65	1.29	21.18	14.18	65.84	0.38	0.65	1.13	1.91	5.58	1.77	6.42	1617.00	5.40	28.09	< 0.01	0.47	0.207	-1.078
S08	Paulla bassa	1761.245	4.1	44.05	5.93	0.49	3.50	18.04	3.97	0.43	0.63	0.57	0.66	1.15	1.90	6.94	1607.00	6.52	16.89	< 0.01	0.04	0.312	-1.053
VM	Mt. Velino	554.374		4.01	< 0.01	0.50	0.43	2.07	< 0.01	0.14	0.67	1.42	2.54	0.34	0.30	1.11	1212.00	0.04	64.48	< 0.01	0.42	1.002	-1.723
L4	Lake Paterno	605.120		6.82	1.44	0.36	2.98	3.19	0.57	0.14	0.46	1.38	2.62	1.72	0.15	2.87	740.10	0.20	34.43	0.09	0.52	0.843	-1.763
VV	Velino Valley	828.084		7.40	< 0.01	1.00	4.05	13.64	11.80	0.25	0.56	0.46	1.75	1.36	0.25	2.21	873.90	0.47	32.52	< 0.01	0.52	1.103	-1.619

Tab. 3: *Characteristic ratios for groundwater and surface water.*

Point	$\frac{Mg^{2+}}{Ca^{2+}}$	$\frac{HCO_3^-}{SO_4^{2-}}$	$\frac{Na^+ + K^+}{Cl^-}$	$\frac{Ca^{2+} + Mg^{2+}}{Na^+ + K^+}$	$\frac{SO_4^{2-}}{Cl^-}$
Campodoro 1 spring	0.305	4.422	1.308	24.021	5.801
Campodoro 2 spring	0.268	5.440	1.339	24.649	5.137
Monte di Canetra spring	0.256	8.094	1.357	34.464	5.189
Mulino spring	0.242	9.726	1.319	44.569	5.526
Fontanelle spring	0.212	11.866	1.447	41.863	4.760
Briglia di Canetra spring	0.235	12.460	1.296	50.230	4.881
Canetra spring	0.228	12.488	1.376	52.225	5.332
Ponte Alto spring	0.231	12.879	1.455	43.281	4.570
Sant'Erasmo spring	0.236	13.359	1.447	54.633	5.521
Peschiera channel 6	0.315	23.691	1.140	57.146	2.647
Paulla alta spring	0.226	27.469	1.288	60.722	2.756
Peschiera draining ditches	0.283	29.467	1.180	58.908	2.291
Peschiera between channels 5 and 6	0.313	29.870	1.117	55.857	2.015
Peschiera Caverna	0.304	31.755	1.028	62.642	1.959
Peschiera north channel	0.234	32.244	1.188	76.982	2.748
Peschiera blind tunnel	0.302	33.844	1.178	53.269	1.809
Cotilia spring	0.255	7.851	1.172	29.916	3.978
Paulla 3 spring	0.226	10.497	1.390	58.209	7.025
Paulla bassa spring	0.190	11.126	1.399	61.031	7.168
River Velino: mountain	0.264	7.635	1.322	29.320	4.488
Lake Paterno	0.330	9.527	1.330	31.818	4.053
River Velino: valley	0.234	12.454	1.347	48.439	4.872

of about 12,700 years (S18), 11,700 years (S21bis) and 13,700 years (S23), assuming an initial activity A_0 of 85% of the reference standard used. There is an evident contradiction between the ages obtained from the tritium contents (tens of years) and those obtained from ^{14}C, to be estimated overall in over 10,000 years. This difference allows us to reject hypothesis A (single aquifer) proposed to explain the tritium activity measured at the springs, given the activity peak recorded for ^{14}C in the 1960s following the fallout from the thermonuclear explosions and possible dilution of the primitive ^{14}C with the inactive carbon from the CO_2 of water-dissolved carbonates (Bogomil et al., 1992).

The hypothesised presence of two overlying water bodies (B), already discussed to explain the measured tritium activity, is better suited to solving the seeming contrast on the radiometric age of the Peschiera spring waters. In this sense, the high tritium content body with water infiltrating in the period 1955-1965 will also have a high ^{14}C content of about 140 pMC. The mean radiocarbon activity measured in the sampled spring waters is about 13 pMC, compatible with a 1:10 mixing ratio in favour of the water body poor in ^3H and ^{14}C, or with much longer residence times, in thousands of years.

Thus the radiometric data show that the Peschiera spring waters are to be attributed to the mixing of water from two bodies with considerably different recharge times: one with residence times of 25-30 years and another, with more complex circulation, with residence times of thousands of years, which cannot be better defined since the starting ^{14}C value cannot be hypothesised. The mixing ratio between the two aquifers may thus be reasonably estimated at 1/10 in favour of the older aquifer.

Given the above radiometric data and introducing them into the

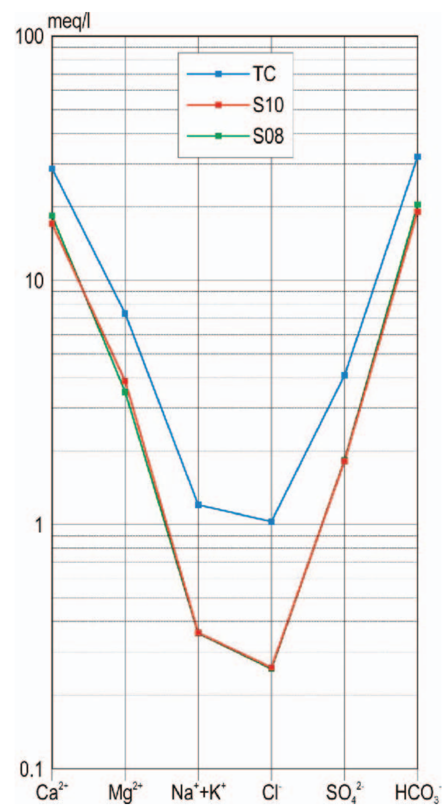

Fig. 4: *Schoeller Diagram of the sulphur springs.*

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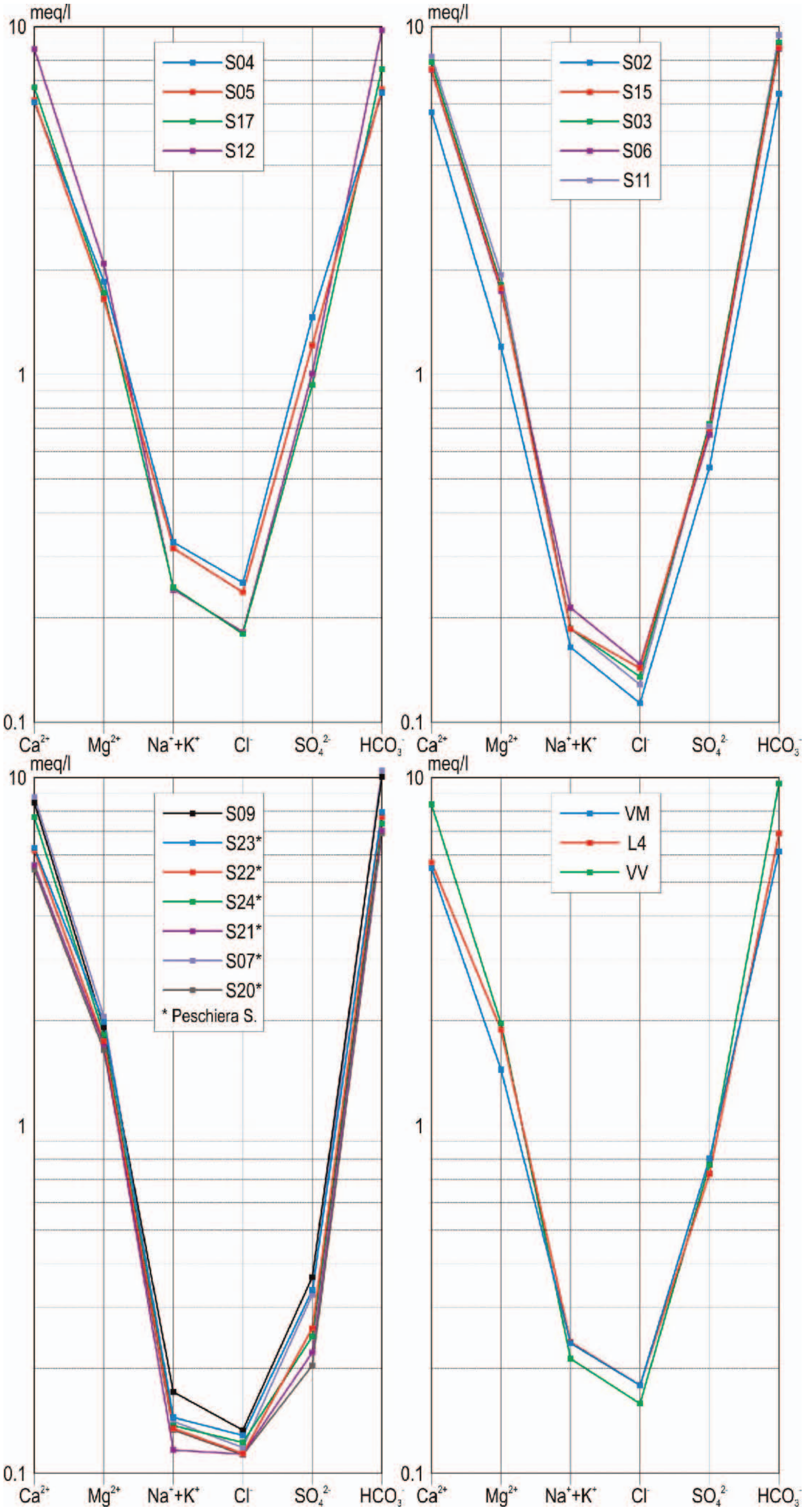

Fig. 5: *Schoeller Diagram of the non sulphur springs.*

physical and hydrodynamic model of the aquifer feeding the Peschiera, we obtain a completely valid interpretation when the two overlying water bodies (**hypothesis B**) become:

the mean annual regulating reserve in the panel with a minimum equal to that of the tunnel extraction, with less chemistry and radiometric contents, and residence times compatible with the aquifer's large area and its division into SERSEM; the other, corresponding to geological reserves, with residence times of thousands of years and waters partly forced to exit at springs due to drag and accumulation of piezometric pressure behind.

Figure 7 explains diagrammatically what was stated above.

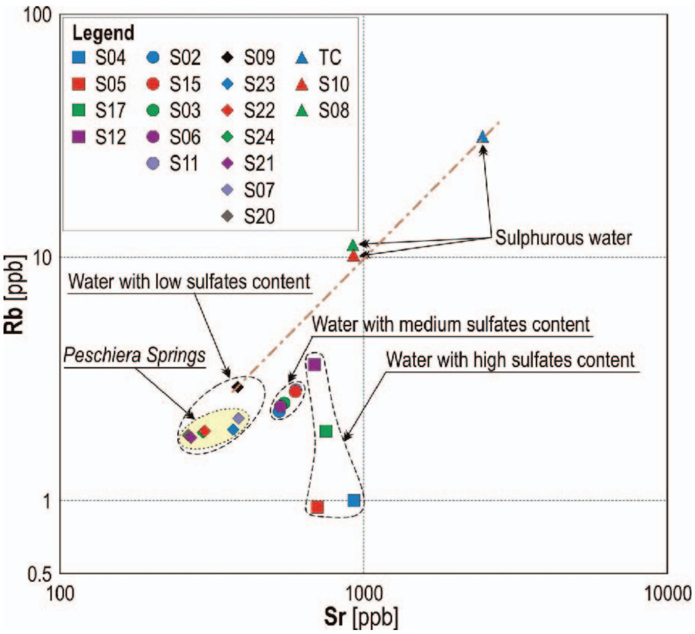

Fig. 6: *Sr vs Rb Diagram.*

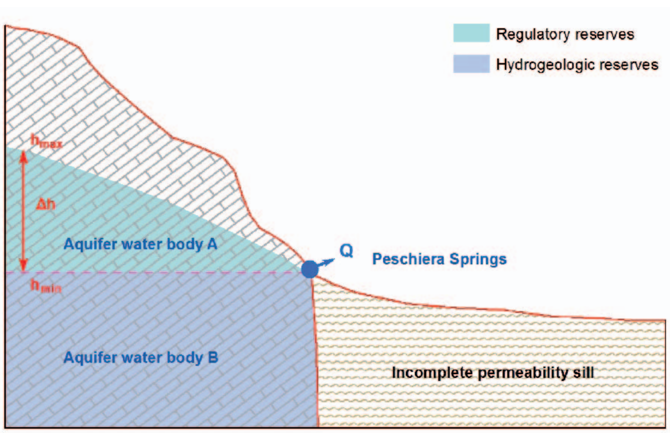

Fig. 7: *Schematic model of the aquifer feeding the Peschiera springs.*

The intake area of Peschiera springs

In the context of this study, determination of the catchment area of the Peschiera springs is one of the main objectives. It is possible to establish first of all that the catchment area is identified with the montane zone on the left of the Velino.

Geology and lithology

The hydrogeological structure that feeds the above springs is one of the most important in the Apennines. It comprises the entire limestone massif of Mt. Nuria - Mt. Velino, whose structural limits appear to embrace an area of about 1200 km^2. On the basis of previous studies (CasMez, 1983; Boni et al., 1988), it did not seem possible to separate the structure of Mt. Giano from that of Mt. Nuria - Mt. Velino: this problem would clearly be detrimental for the delineation of protection areas of the Peschiera springs. Thus the boundaries first identified on the basis of tectonics comprise only the southern flank of the Mt. Giano massif; they continue SE along the Aterno river valley to beyond l'Aquila; from here they turn southward passing along the Ocre-Rocca di Mezzo-Celano line, terminating on the edge of Fucino. From Avezzano, the boundary runs westward to the River Imele and then NW left of Lake del Salto up to the River Velino east of Cittaducale (Fig. 8). This massif culminates with the peaks of the Velino group, at over 2000 m, and Mt. Nuria, which tops 1800 m.

The hydrostructure consists of Trias – Palaeocene carbonatic rocks (dolomites at the base, then limestones), bounded by fairly impermeable soils in a flysch facies and by a marly limestone complex dating to the Tertiary. In Tab. 5 we summarise the geological and hydrogeological series, and list its particular features.

Tectonic boundaries of the hydrostructure

The hydrogeological structure is typical of carbonatic massifs in the Apennines, so important in the socio-economy of southern Italian regions due to their optimal water resources (Civita, 1975). The structural boundaries (Fig. 8) used to identify the catchment areas of springs follow the main tectonic lines (GruGeo, 1995) separating the Nuria–Velino-Giano group from the adjacent limestone massifs of the Apennines. They are reported briefly below:

- **Olevano - Antrodoco Line:** N-S direction. This overlies the pelagic carbonatic ends of the Umbro-Sabina series on those of the Laziale-Abruzzese platform;
- **Micigliano folding:** N-S direction. This overlays the pelagic ends with the platform limestones (eastern slope of the Terminillo massif);
- **Fiamignano – Petrella – Staffoli Line:** NNW-SSE direction. This joins the platform limestones with Miocene limestones;
- **Fault of Mt. Velino:** NW-SE direction. This joins the platform limestones with Miocene limestones.

Infiltration dynamics

In examining the structure, remote-sensing from an mivis aircraft was used to produce a reflectivity map which enabled identification of the main karstic areas upstream of the springs and provided verification that these areas act as a block to surface runoff, increasing secondary infiltration. This phenomenon is important in the upper part of the Mt. Giano massif and in the central zones of the Nuria–Velino structure. Particularly karstified and rich in tectonic-karst depressions are some parts of the catchment area (Monti della Magnola, Campo Felice, Monti della Duchessa, etc.) occupied by more or less temporary lakes (Lago della Duchessa, Lago di Rascino etc.), sinkholes (e.g. Piana di Cornino) and swallowholes. Such areas have a powerful role in the dynamics of infiltration, considerably increasing the intake capacity of the soilless higher zones, which experience higher effective rainfall and snowmelt. Runoff waters within such endorheic depressions are rapidly absorbed and are sent to the deep groundwater network.

Tectonics, consisting of napping and major folds, prior to very recent repeated disjointed phases, greatly affects both the intake index and that of limestone aquifer transport. This is characterised by fairly recent surface karst phenomena favouring infiltration. By contrast, at greater depth, there predominate conditions of permeability due to intense fracturing, which greatly affect the transit time and hence the self-cleansing effect of the unsaturated zone (Civita, Forti et al., 1991). The flow model is thus one of dispersive circulation (Civita et al., 1991).

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Tab. 4: *Isotope data for groundwater and surface water.*

Cod	Point	$\delta^{18}O$ [%]	^3H [UT]	^{14}C [pMC%]	$\delta^{13}C$ [%]
	Rain gauge	-9.2	10.0 ± 1.6		
S03	Canetra	-9.3	13.7 ± 1.5		
S07	Peschiera North Channel		14.2 ± 1.8		
S18	Peschiera	-9.0	16.5 ± 1.4	17.63 ± 0.33	+ 2.2
S20	Peschiera Blind tunnel		14.5 ± 1.7		
S21bis	Peschiera	-8.9	15.5 ± 1.2	15.71 ± 0.33	- 2.4
S22	Peschiera drainage ditches		13.5 ± 1.6		
S23	Peschiera channel 6	-8.8	12.0 ± 1.3	19.72 ± 0.34	- 1.4

The origin of the springs is linked to a juxtaposition of impermeable materials which, in the Velino river valley, create a permeability threshold. More or less recent floods with both coarser and finer sediment lead to groundwater transfers from the carbonatic structure to the sub-channel of the River Velino.

In agreement with the indications supplied by a geological survey (GruGeo 1995), in the study area we distinguished four substructures (Fig. 9), the largest of which is situated in the central sector of the area in question and comprises the Nuria–Velino massif (no. 2). The other three substructures are those of Mt. Giano (no. 1), Mt. Ocre (no. 4) and Mt. Carseolani (no. 3).

Groundwater balance

The problem of whether the contiguous substructures belonged to the structure strictly connected to the Peschiera springs was solved with the potential groundwater balance, carried out with an appropriate numerical calculation model (for details see Civita & De Maio, 1997). This model allows calculation of mean annual effective infiltration congruent with the system. It constitutes the output that generates the mean annual discharge of the Peschiera springs. This must be considered the only reliable method to validate the hydrostructure and identify the recharge-discharge process of a groundwater system in fractured, karstified rocks (Civita, 2005).

The study area was split into a grid (500 m x 500 m squares) based on the UTM network on 1:25,000 maps comprising the hydrostructure. The maps were used to obtain the altimetric data of each square, recording the heights of the four corners and the geometric centre. The hypsometric study served to assign a weighted average height to each cell in the grid.

To calculate the groundwater balance we considered the rainfall and temperature data from 20 weather stations situated in the study area or in the immediate neighbourhood. The available data cover a multi-year interval, generally between 1975 and 1990. The existing historic series were homogenized, with the reconstruction of some missing data. For each series we calculated the monthly and annual means, starting from daily rainfall (in mm) and temperature (in °C) data. Using data from each weather station we were able to draw the characteristic curves of variation P = f(h) and T = f(h). Having obtained the characteristic curves, it was possible to assign to each square in the grid its value in terms of rainfall, correct temperature and hence real evapotranspiration.

For each element in the grid we calculated the effective mean annual rainfall (Q), determined by the difference between the precipitation (P) and real evapotranspiration Er. The latter parameter is calculated with the method of Turc (1954) for each cell, optimised for rainfall and temperature (Castany, 1967). Subtracting the value of Er from that of rainfall grid by grid, the model calculates the mean available global water resource, which will in turn be split into two parts: effective mean annual infiltration (Iw) and mean annual runoff (R). Effective infiltration is calculated by attributing to each square of the grid a coefficient of potential infiltration (c), variable between 0 and 1, multiplied by the quantity of rainfall. The c values

Tab. 5: *Geologic and hydrogeologic features of the Nuria–Velino-Giano ridge and of the Terminillo massif.*

Age	Lithology	Hydrogeologic complex	Hydrogeologic characters	Hydrostructural role
Quaternary and Upper Pliocene	Alluvium, coarse breccias, Travertine, fluvial-lacustrine fine deposits.	Overburden	Various permeability degree, very low in alluvium and lacustrine layers.	Complete/incomplete permeability sills by fine sediments in the spring discharge area
Upper Miocene	Marls and clay-arenaceous flysch	Aquiclude	Overall very low permeability.	Limits of the hydrostructure NE side
Lower Lias – Paleogene	Calcarenites; oolitic, bioclastic, organic limestone.	Main aquifer	High to medium permeability by karst and fracturing.	Ingestion, transmission and discharge of high rate resources
Lower Lias – Lower Miocene	Pelagic series (limestone, marls, clay and chert); Massive limestone.	Aquifer	Vertical permeability variable from layer to layer.	Feeds some springs in the Velino valley (r), chemically diversified (l)
Upper Trias	Dolomite and dolomite limestone.	Aquitard	Fracture middle-low permeability.	In opposition to the main aquifer, makes a permeability limit.

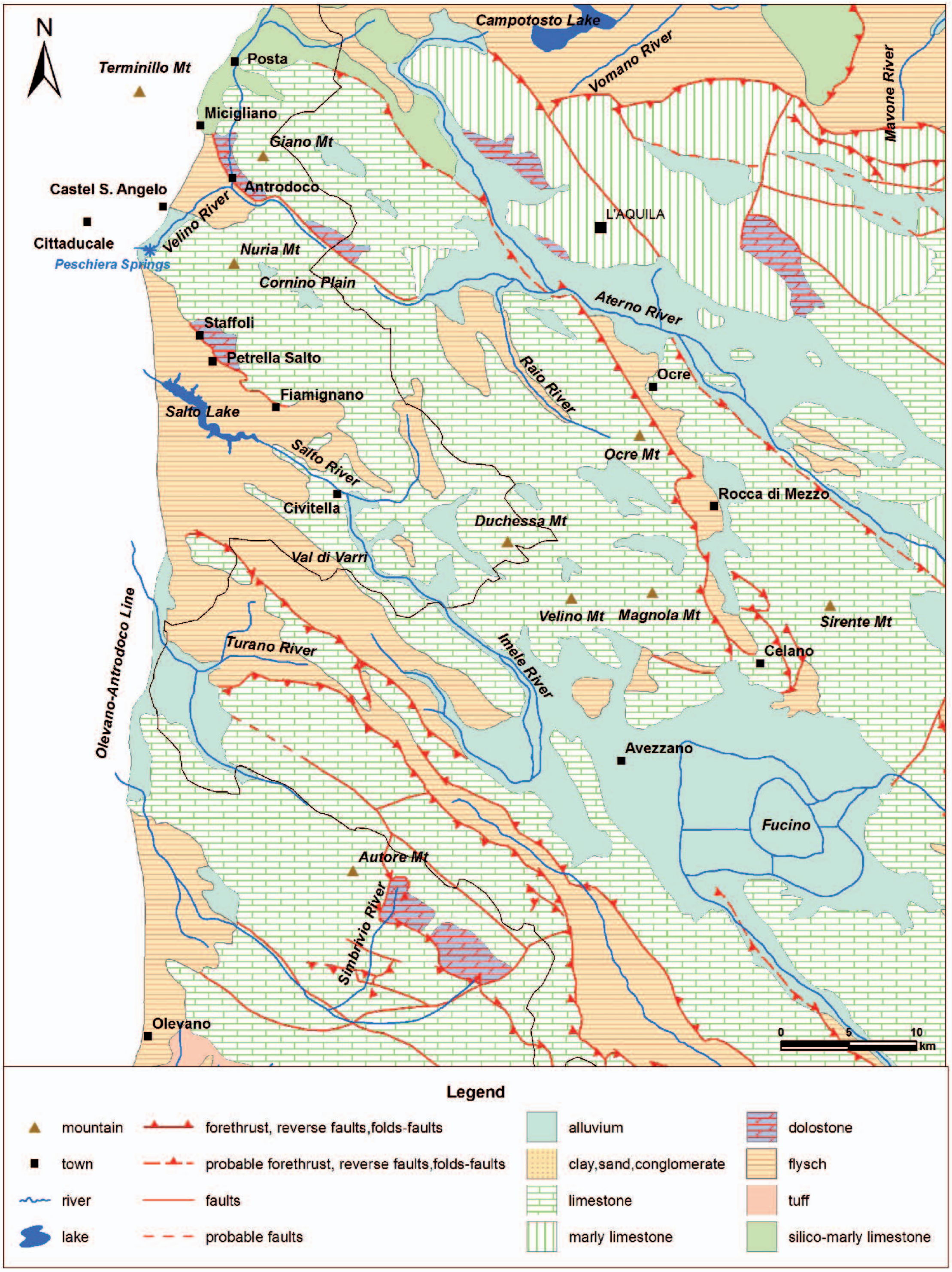

Fig. 8: *Geological map with the structural boundaries of the study area.*

were chosen on the basis of the morphological and hydrogeological properties of the element considered, the type and degree of permeability and the outcropping conditions, exposure and cover. The amount attributed to mean annual runoff is generally low or absent in the limestone massifs of the Apennines.

The final results obtained with the numerical calculation model are presented in Table 6, in which the items of the balance are reported both as the mean annual emptied volume (m^3/y), and as the mean discharge (m^3/s). For the whole hydrostructure in question, mean annual infiltration rate was 618 Mm^3/y, equivalent to 19.594 m^3/s.

The reference data for the balance comprised the mean discharge of the Peschiera springs (Tab. 1). Comparison of such data (17.87 m^3/s, or 563 Mm^3/y) with the effective infiltration supplied by the model shows that the calculated infiltration was 8.8 % higher. The difference, albeit slight, encountered between the impulses (recharge) and the system responses (outlets) must nonetheless be interpreted. First

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Tab. 6: *Results of the hydrogeological balance by single subarea.*

Zone	P		E_r		Q		R		I	
	m^3/y	m^3/s	m^3/y	m^3/s	m^3/y	m^3/s	m^3/y	m^3/s	m^3/y	m^3/s
1	**1.84E+08**	**5.848**	**0.66E+08**	**2.092**	1.18E+08	3.756	0.13E+08	0.4181	1.05E+08	3.3381
2	**7.42E+08**	**23.541**	**2.65E+08**	**8.396**	4.78E+08	15.145	0.49E+08	1.5569	4.29E+08	13.588
3	**0.98E+08**	**3.105**	**0.47E+08**	**1.482**	0.51E+08	1.623	0.07E.08	0.2332	0.44E+08	1.3897
4	**1.06E+08**	**3.348**	**0.48E+08**	**1.516**	0.58E+08	1.832	0.17E+08	0.5542	0.40E+08	1.2777
Total	*1.13E+09*	*35.842*	*4.25E+08*	*13.486*	***7.05E+08***	***22.356***	***87118085***	***2.7625***	***6.18E+08***	***19.594***

of all, it should be pointed out that averages are compared for different periods (1941-1977 for spring discharges and 1975-1991 for inflows), there being no isochronous data available. However, as we are dealing with very broad historic series, the calculated averages may be considered comparable. The results of the global balance thus lead to a review of the boundaries of the catchment area for the Peschiera springs, also on the basis hydrogeological tests carried out in Summer 1994, assessing the contribution of each sub-zone.

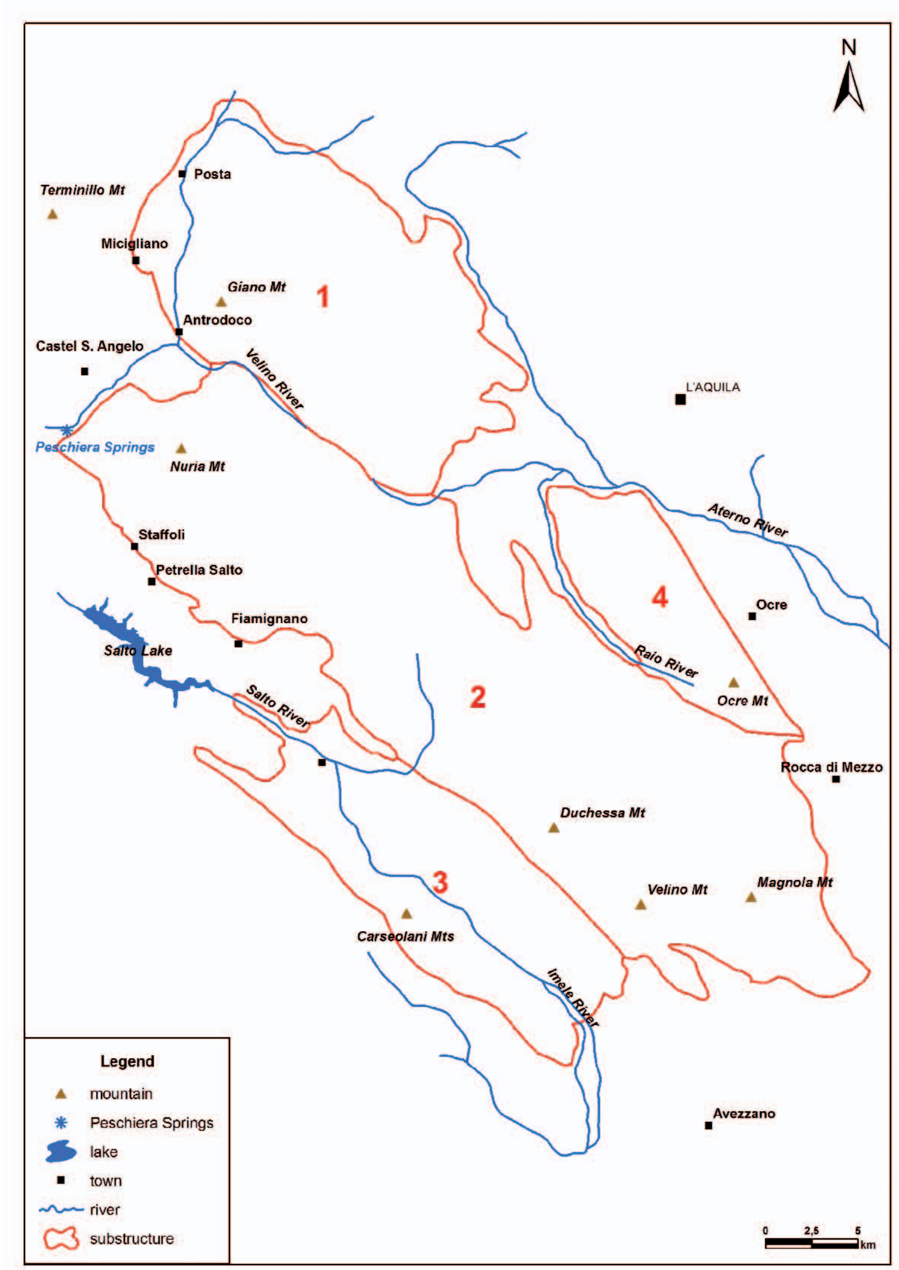

Fig. 9: *The four substructures recognized.*

Tab. 7: *Average monthly discharges from the Peschiera springs from 1941 to 1977 (I_v = Meinzer Index).*

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average	Iv
1941	**18.00**	**18.40**	**19.00**	**19.40**	**20.00**	**21.30**	**20.55**	**20.62**	**20.43**	**20.20**	**20.00**	**20.00**	**19.83**	**0.17**
1942	**20.00**	**19.80**	**19.72**	**20.00**	**20.05**	**20.10**	**20.00**	**19.90**	**19.70**	**19.57**	**19.57**	**19.30**	**19.81**	**0.04**
1943	**19.00**	**18.60**	**18.20**	**18.00**	**18.00**	**18.00**	**17.60**	**17.40**	**17.25**	**17.10**	**17.00**	**16.90**	**17.75**	**0.12**
1946		**16.45**	**16.25**	**15.90**	**15.65**	**15.50**	**15.59**	**15.61**	**15.61**	**15.50**	**15.42**	**15.42**	**15.72**	**0.07**
1947	**15.61**	**16.20**	**16.90**	**17.20**	**17.30**	**17.22**	**17.00**	**16.99**	**16.32**	**16.82**	**16.70**	**16.52**	**16.73**	**0.10**
1948	**16.50**	**16.87**	**17.10**	**17.18**	**17.21**	**17.30**	**17.30**	**17.21**	**17.18**	**17.10**	**17.07**	**17.00**	**17.09**	**0.05**
1949	**16.80**	**16.30**	**16.59**	**16.21**	**16.19**	**16.00**	**15.42**	**15.41**	**15.09**	**14.79**	**14.89**	**14.75**	**15.70**	**0.13**
1950	**14.60**	**14.70**	**14.98**	**15.30**	**15.70**	**16.15**	**16.40**	**16.35**	**16.15**	**15.70**	**15.70**	**16.00**	**15.64**	**0.12**
1951	**16.00**	**16.22**	**16.75**	**17.70**	**18.80**	**19.50**	**20.00**	**20.20**	**20.22**	**20.00**	**19.70**	**18.65**	**18.65**	**0.23**
1952	**18.50**	**18.30**	**18.00**	**17.90**	**17.90**	**17.90**	**18.20**	**18.20**	**17.90**	**17.90**	**17.58**	**17.19**	**17.96**	**0.07**
1953	**17.85**	**17.80**	**16.80**	**17.70**	**19.00**	**19.10**	**18.40**	**18.30**	**18.20**	**17.81**	**17.82**	**17.90**	**18.06**	**0.13**
1954	**17.67**	**17.41**	**17.30**	**17.31**	**17.42**	**17.30**	**17.39**	**17.40**	**17.00**	**16.87**	**16.95**	**16.80**	**17.24**	**0.05**
1955	**16.50**	**16.50**	**16.59**	**16.60**	**16.61**	**16.62**	**16.58**	**16.29**	**16.45**	**16.93**	**16.80**	**16.40**	**16.57**	**0.04**
1956	**16.21**	**16.30**	**16.42**	**16.59**	**17.00**	**17.62**	**17.80**	**17.97**	**18.00**	**18.20**	**17.59**	**17.00**	**17.23**	**0.12**
1957	**17.00**	**17.10**	**17.05**	**17.18**	**17.22**	**17.30**	**17.70**	**18.00**	**18.00**	**17.99**	**17.55**	**16.90**	**17.42**	**0.06**
1958	**16.90**	**17.25**	**17.20**	**16.78**	**17.10**	**17.62**	**17.90**	**17.95**	**17.95**	**17.90**	**17.80**	**17.65**	**17.50**	**0.07**
1959	**17.50**	**17.30**	**16.70**	**16.30**	**16.90**	**17.50**	**17.65**	**17.78**	**17.62**	**17.20**	**17.42**	**17.90**	**17.31**	**0.09**
1960	**18.22**	**18.80**	**19.25**	**20.21**	**20.60**	**20.82**	**20.83**	**20.78**	**20.62**	**20.49**	**20.40**	**20.40**	**20.12**	**0.13**
1961	**20.40**	**20.40**	**20.49**	**20.50**	**20.29**	**19.90**	**19.90**	**20.00**	**20.05**	**20.05**	**19.80**	**19.40**	**20.10**	**0.05**
1962	**19.10**	**18.80**	**18.70**	**18.85**	**19.10**	**19.30**	**19.50**	**19.55**	**19.95**	**19.10**	**18.50**	**18.00**	**19.04**	**0.10**
1963	**18.25**	**18.90**	**19.42**	**19.90**	**20.15**	**20.42**	**20.62**	**20.80**	**20.53**	**20.44**	**19.80**	**19.70**	**19.91**	**0.13**
1964	**19.50**	**19.40**	**19.33**	**19.22**	**19.35**	**19.52**	**19.53**	**19.42**	**19.38**	**19.30**			**19.40**	**0.02**
1973	**18.25**	**19.29**	**18.35**	**18.65**	**16.65**	**16.75**	**18.35**	**19.27**	**17.61**	**19.07**	**16.51**	**15.62**	**17.86**	**0.21**
1974	**15.94**	**16.23**	**16.54**	**16.90**	**17.18**	**17.01**	**17.11**	**16.84**	**16.54**	**17.17**	**16.67**	**16.67**	**16.73**	**0.07**
1975	**16.36**	**16.60**	**16.54**	**16.10**	**16.00**	**15.26**	**15.21**	**15.13**	**15.09**	**15.25**	**15.41**	**15.22**	**15.68**	**0.10**
1976	**15.25**	**15.43**	**15.45**	**15.64**	**15.96**	**15.82**	**16.00**	**16.04**	**16.08**	**16.10**	**16.50**	**17.00**	**15.94**	**0.11**
1977	**17.00**	**17.95**	**18.10**	**18.55**	**19.20**	**18.44**	**18.17**	**18.46**					**18.23**	**0.12**

Structure 2 (Mt. Nuria-Mt. Velino) constitutes the main catchment area for the Peschiera springs, supplying according to the hydrogeological balance a mean infiltrating volume of 429 Mm3/y, equal to a mean discharge of 13.588 m^3/s. To be added to the groundwater structure is the contribution of subzone 1 (Mt. Giano), i.e. an active recharge of 105 Mm^3/y, corresponding to 3.338 m^3/s. This zone has been set apart from the main structure due to the presence of an extensive outcrop of low-permeability dolomites, located close to the town of Antrodoco in correspondence with a major dislocation line.

The dolomites constitute a threshold of permeability with a series of springs (Cascinesi), of very variable discharges between 0 and 1.3 m^3/s. For several years, these springs have completely dried up, even on the occasion of considerable rainfall in the system. This hydrogeological situation is attributed to the particular geometry of the two hydrogeological units (Mt. Giano, Mt. Nuria- Mt. Velino) that are contiguous and hence interact. The Cascinesi springs should constitute the outlet for the substructure, emptying discharges that are even fairly high. During long droughts, the mean piezometric surface is lowered below the threshold, deactivating the springs. This hypothesis is borne out by field observations, which testify to the absence of other springs fed by the Mt. Giano structure, as well as by geochemical data for the water of the sector's various springs (Canetra, etc.), fed instead by the Terminillo system. The infiltrating volume overall in the first two structures is calculated at 534 Mm^3/y, or 16.92 m^3/s.

Tab. 8: *Hydrodynamic parameters of the 1993 depletion curve and dynamic indexes of the regulating groundwater resources (Q_0 = discharge at the start of depletion [for $t = t_0$*; Q_t = Discharge at time $t \neq t_0$; α = depletion coefficient; W_0 = volume of regulating resources stored; W_t = volume of residual regulating reserves; ΔW = reserve volume flowed; TR = average rage of reserve renewal; TMR = average time of renewal; DT = Delay time, time of spring self-maintenance).*

Q_0 (m^3/s)	Q_t (m^3/s)	t (days)	α	W_0 (Gm^3)	W_t (Gm^3)	ΔW (Mm^3)	TR (%)	TMR (years)	DT (days)
19.60	15.55	170	0.00136	1.24	0.99	256.99	20.7	4.8	734

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Structure 4 (Mt. Ocre) supplies an overall value of 403 Mm^3/y, equivalent to a mean annual discharge of 1.27 m^3/s. Hydrogeological measurements made along the edges of this structure showed the absence of springs of a certain importance. Moreover, along the course of the Raio, which represents the local base level, no discharge increases were observed in relation to any sub-channel transfers supplied by the structure. Also note that the height of a possible destination of groundwater, at the lowest point of the substructure in question, is 660 m a.s.l., hence 250 m higher than the Peschiera springs, which represent the lowest point of the whole hydrogeological system. Taken together, these three substructures yield a mean infiltrated volume of 574 Mm^3/y, equivalent to a mean discharge of 18.21 m^3/s. This value is close to the mean recorded at the Peschiera springs (563 Mm^3/y, or 17.87 m^3/s), with a more than acceptable deviation.

Substructure 3 (Mts. Carseolani) does not belong to the system supplying the Peschiera springs, confirming a whole series of structural and hydrogeological data. Information gathered in loco testifies to the presence of a spring (or group of springs) with fairly constant, high discharges (about 1 m^3/s) which, before the creation of the reservoir, supplied several mills that worked even in low-rainfall periods and which currently lies below the level of the reservoir. Moreover, in this substructure there is a secondary karst system consisting of a hydrogeological tunnel which, from the Val di Varri swallowhole, transfers the surface waters of the whole valley towards a spring close to the village of Civitella. A test with artificial tracers showed the existence of a direct connection between the swallowhole and the spring. The hydrogeological characteristics of this system are also shown by the discharges measured at the entrance (swallowhole) and outlet (spring). The spring waters thus flow towards the channel of the River Salto and, after a brief stretch on the surface, are swallowed in a series sub-channel losses.

Calculation of the balance for this area supplies an effective infiltration of 44 Mm^3/y, or 1.39 m^3/s, which may be compared with the historic discharges of Lake Salto. Finally, it is now possible to define and delimit as a precaution the intake area of the Peschiera springs, which corresponds to the sum of substructures 1, 2, 4.

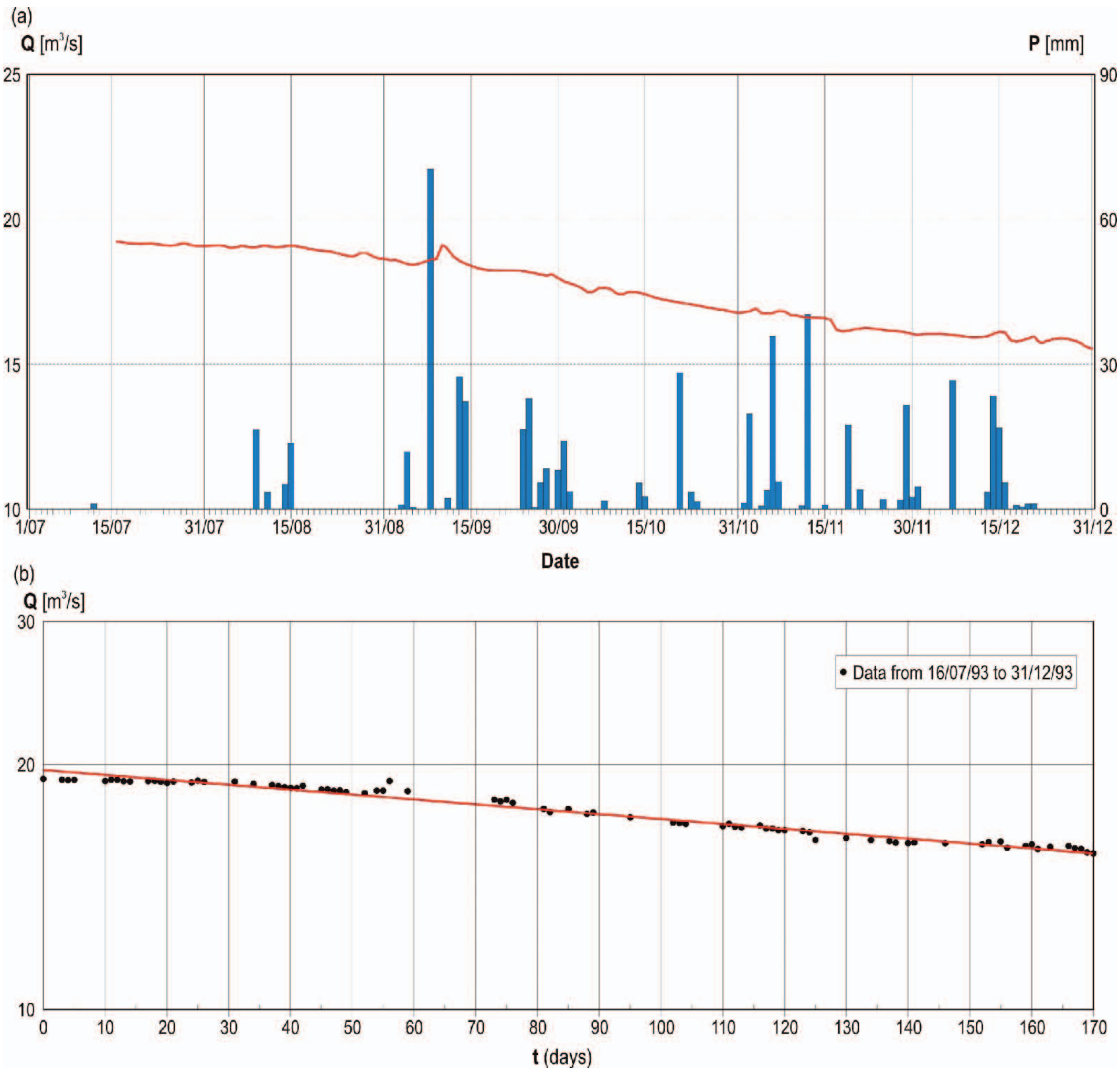

Fig. 10: *(a) Hydrogram of the Peschiera springs, with cumulative daily rainfall for the period, 16/07/1993 – 31/12/1993. (b) Relative linearization of the depletion curve.*

Tab. 9: *Hydrodynamic parameters of the depletion curves in the period 1941 - 1975 and dynamic indexes of the regulating groundwater resources (x = average; σ = standard deviation).*

Cycle (years)	Q_0 (m^3/s)	Q_t (m^3/s)	t (days)	α	W_0 (Gm^3)	W_t (Gm^3)	ΔW (Mm^3)	TR (%)	TMR (years)	DT (days)
41-42	20.62	19.72	213	0.00021	8.50	8.13	371.13	4.4	22.9	4772
42-43	20.10	18.00	304	0.00036	4.78	4.28	499.85	10.4	9.6	2755
43	18.00	16.90	184	0.00034	4.54	4.26	277.32	6.1	16.4	2918
47-48	17.30	16.50	245	0.00019	7.73	7.38	357.67	4.6	21.6	5174
48-49	17.30	16.30	214	0.00028	5.37	5.06	310.53	5.8	17.3	3594
49-50	16.59	14.60	306	0.00042	3.43	3.02	411.74	12.0	8.3	2394
50	16.40	15.70	122	0.00036	3.96	3.79	169.15	4.3	23.4	2797
51-52	20.22	17.90	212	0.00057	3.04	2.69	348.68	11.5	8.7	1739
52	18.20	17.19	123	0.00046	3.39	3.20	188.00	5.6	18.0	2154
53	19.10	17.81	121	0.00058	2.86	2.66	192.86	6.8	14.8	1730
54-55	17.40	16.50	184	0.00029	5.21	4.94	269.40	5.2	19.3	3464
55-56	16.93	16.21	92	0.00047	3.10	2.96	131.69	4.3	23.5	2117
56-57	18.20	17.00	92	0.00074	2.12	1.98	139.84	6.6	15.2	1349
57-58	18.00	16.90	122	0.00052	3.01	2.82	183.88	6.1	16.4	1935
58-59	17.95	16.30	212	0.00045	3.41	3.10	313.43	9.2	10.9	2198
59	17.78	17.20	61	0.00054	2.82	2.73	92.7	3.3	30.7	1839
61-62	20.05	18.70	150	0.00046	3.73	3.48	251.00	6.7	14.9	2152
62	19.95	18.00	91	0.00113	1.52	1.38	149.10	9.8	10.2	885
63-64	20.80	19.22	243	0.00033	5.53	5.11	419.87	7.6	13.2	3076
73	19.27	15.62	122	0.00172	0.97	0.78	183.21	18.9	5.3	581
74	17.18	16.54	123	0.00031	4.81	4.63	179.15	3.7	26.8	3240
74-75	17.17	16.36	93	0.00052	2.85	2.72	134.68	4.7	21.2	1924
75	16.50	15.09	184	0.00049	2.94	2.68	250.93	8.5	11.7	2060
x	***18.30***	***16.97***	***166***	***0.00051***	***3.90***	***3.64***	***253.27***	***7.2***	***16.5***	***2472***
σ	***1.41***	***1.25***	***69***	***0.00033***	***1.77***	***1.71***	***109.55***	***3.6***	***6.5***	***1091***

Modelling spring discharge and evaluating groundwater reserves

Spring regime

The regime of the Peschiera springs does not have noticeable peaks or rapid decreases. The variability index (Meinzer, 1927):

$$I_v = \frac{Q_{\max} - Q_{\min}}{Q_{med}} \tag{1}$$

was calculated year by year (for a total of 27 years between 1941 and 1977 - Tab. 7) and the individual data were averaged to obtain: *Iv* = 0.1 (arithmetic mean) and *Iv* = 0.09 (geometric mean). The spring group must thus be classified as constant.

Modelling of the depletion curves

The depletion of a carbonatic system usually consists of two parts: one part, starting from peak capacity, is called the decrease curve and corresponds to the decrease in spring discharge when there persists the phenomenon of short circuit infiltration and the unsaturated zone of the aquifer is still unaffected. The other part is the exhaustion curve and corresponds to the progressive gradual decrease in discharge due to emptying of the saturated zone of the system in an unaffected or scantily affected regime. To analyse the whole depletion curve, the most advanced model is as follows:

$$Q_t = Q_0 \frac{1+\eta' t}{1+\varepsilon t} + Q_{R0} e^{-\alpha t} \tag{2}$$

For the constant springs fed by a permeable aquifer due to fracturing rather than karst phenomena, the conceptual model of reference is that of the hydrodispersive circulation network (Civita et al., 1991). The depletion curves of such aquifers rarely present the decrease curve. In practice, the decrease curve is never observed on large regional systems such as the one feeding the Peschiera. In such cases, the model (2) is simplified into:

$$Q_t = Q_0 e^{-\alpha t} \tag{3}$$

where Q_t is the spring discharge at any moment $t \neq 0$, Q_0 the instantaneous discharge at time $t = 0$ (start of exhaustion), *e* the base of Neperian logarithms and α a coefficient of depletion that describes the hydrodynamics of the groundwater reservoir.

The coefficient of depletion has considerable interpretative power. Its absolute value enables us to determine the geometric characteristics of the aquifer and to obtain global information on the system's discharge process, linked to the type and degree of permeability. Indeed, the coefficient of exhaustion is:

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- directly proportional to the permeability of the saturated zone of the aquifer;
- inversely proportional to the dynamic (useful) porosity of the aquifer;
- inversely proportional to the length of the saturated zone upstream of the springs;
- inversely proportional to the volume of the stored regulating resource.

Low coefficients highlight a slow depletion of a low-porosity groundwater reservoir (cracks and non-karst channels), considerable length of the saturated zone upstream of the springs, considerable width and power of the saturated zone. Integrating (3) between $t = 0$ and $t = \infty$ we obtain the stored volume at the start of depletion:

$$W_0 = \int_0^\infty Q_t dt = \int_0^\infty Q_0 e^{-\alpha t} dt \qquad (4)$$

which is solved, homogenising times (α is expressed in days while discharges are in m³/s):

$$W_0 = Q_0 \frac{86400}{\alpha} \qquad (5)$$

Equations (4) and (5) are suitable for calculating the various indexes and parameters. See Civita (2005, 2008) for the calculation details and expressions. The various indices, calculated for 1993, are presented in Table 8 while Figure 10 reports the hydrogram of the Peschiera springs, with cumulative daily rainfall for the period, 16/07/1993 – 31/12/1993, as well as relative linearization of the depletion curve.

The volume of the total regulating reserve (W_0) is to be considered with attention, both for its absolute value, and as a function of the mean renewal rate (*RR*) and minimum renewal time (*MRT*). On the basis of these data, it could be stated that all the groundwater stored in the aquifer is renewed by active recharge approximately every five years and that the regulating reserve is such as to allow a diversion of over 15 m³/s for more than two years even in the unlikely event of active recharge stopping altogether. The storage index is equal to 1.28 while the depletion index assumes the value of 266 mm/year. These data that reflect the hydrodynamics of the system are considered fairly reliable. However, we should point out that various parameters and hydrodynamics indices for 1993 deviate from the mean calculated on annual cycles from 1941 to 1975 (Tab. 9), especially the MRT which is 16.5 ± 6.5 years. This difference could be ascribed to the fact that 1993 may be an atypical year, but it is also true that the 1941-1975 data come from discontinuous measures of discharges while the 1993 data were acquired daily and extensively validated.

Conclusions

On the basis of ^3H and ^{14}C concentrations, the waters of the Peschiera springs come from an aquifer whose discharge comes partly (10%) from a 25-30 year recharge, with the remainder (90%) from water so poor in the two isotopes that it infiltrated thousands of years ago. The conceptual model of the Peschiera is thus that of a classic spring in terms of permeability threshold.

This threshold leads to an altimetric separation between the geological reserve and the regulating reserve. It might thus be hypothesised that, during drought conditions, the flow would be largely sustained by water from the geological reserve (in theory of low mobility and thus resident for a very long time). Indeed, during droughts the aquifers are often exhausted and old waters pushed forward by the piston-effect of newly infiltrating water. The radiometric age is in contrast with that inferable from the MRT calculated in 1993 (~5 years) and with that obtained from the mean of 23 cycles from 1941 to 1975 (16.5 ± 6.5 years). In effect, in the real case, old waters are unlikely to contribute to final discharge at a proportion of 10 parts to 1 since the permeability threshold is far from limited, and hence the waters of the geological reserve are mobilised, albeit to a lesser extent than those of the regulating reserve, being continually forcibly drained through extraction lower down. Moreover, this ratio is subject to seasonal variations.

Finally, the huge body of hydrodynamic and hydrogeochemical data allowed us to map out a complete scenario as regards the diversity of the spring waters in the study area. We now have a clear picture of the hydrogeological structure feeding the Peschiera springs and their outflow characteristics. Scant correspondence was found with the limited radiometric data. Only a lengthy targeted campaign of radiometric analysis could definitively clarify the relations between geological reserve waters and those from regulatory reserves which, in their mixed state, generate discharges at the Peschiera springs.

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