Karst aquifers of the Central Apennines

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Les aquifères karstiques de l'Apennin central

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Mots-clés: Hydrologie karst, Débit, Source, Ressource eau, Eau souterraine, Apennins Centre

Abstract

Karst aquifers of the Central Apennines (Umbria, Marche, Lazio, Abruzzo and Molise) occur in Mesozoic carbonate rocks extending over an area of about 15,000 km² from sea level to an altitude of 2900 m. Geological conditions are not homogeneous throughout this area: a large Triassic basin, constituting the regional basement, was filled with evaporites, dolomite and calcareous sediments. Mesozoic deposition in this large basin occurred in two sedimentological environments separated by a large transitional belt: a carbonate platform in the southeastern sector and a typical carbonate-series basin in the northwest. Orogenesis affected the region during the Miocene-Pliocene.

In the carbonate-platform domain several distinct hydrogeological structures have been recognized over an area of about 9,000 km², karst aquifers supplying a mean discharge of about 230 m³/s from around 140 springs with a regular and predictable discharge regime. Mean annual rainfall ranges from 950 to 1500 mm, whereas mean annual effective infiltration is 750 to 1000 mm. In the transitional belt, effective infiltration ranges from 600 to 900 mm. Overland runoff is negligible.

Three main aquifers, separated by impervious complexes, are found in the carbonate-basin domain. A characteristic of the basin domain is an extensive network of perennial rivers, acting as base level with respect to the main karst aquifers. Rivers and streams fed by groundwater show a regular discharge regime; springs along part of a river have been called "linear springs", in contrast with traditional springs that discharge in one point or in a very localized area. Carbonate structures of the pelagic domain extend over an area of about 5,000 km² and feed 80 major springs with a mean discharge of 75 m³/s. Mean annual effective infiltration is 500 mm, about 50% of total precipitation.

Résumé étendu

Dans cette synthèse, sont pris en considération les aquifères karstiques de l'Apennin central en Ombrie, dans les Marches, dans le Latium, dans les Abruzzes et dans le Molise. Les affleurements de roches carbonatées s'étendent sur une surface de 15 000 km², depuis le niveau de la mer jusqu'à 2 900 m d'altitude.

Les conditions géologiques ne sont pas uniformes. Le substratum dolomitique du Trias s'étend dans toute la région ; le bassin original a évolué, au cours du Lias, en deux domaines différents : une plate-forme carbonatée subsidente, au sud-est, et un bassin pélagique au nord-ouest, séparés par une large zone de transition (fig. 1). L'orogenèse a affecté toute la région au cours du Mio-Pliocène.

Dans le domaine de la plate-forme carbonatée, couvrant une surface de 9 000 km², plusieurs structures hydrogéologiques indépendantes ont été reconnues. Les aquifères karstiques alimentent 140 sources importantes dont le débit moyen total est 230 m³/s. Les précipitations moyennes annuelles varient entre 950 et 1500 mm. L'infiltration efficace moyenne annuelle varie entre 750 et 1000 mm. Dans la zone de transition, l'infiltration efficace est comprise entre 600 et 900 mm. Le ruissellement de surface est négligeable. Le régime des principales sources est particulièrement régulier (fig. 4, 5, 6, 7).

Dans le domaine pélagique, trois aquifères karstiques séparés ont été reconnus. Une caractéristique de ce domaine est l'existence d'un réseau de fleuves et de rivières pérennes qui jouent le rôle de niveau de base des aquifères karstiques. Les fleuves alimentés par des eaux souterraines sont caractérisés par des régimes réguliers (fig. 8). Les sources localisées dans le lit des rivières, sur des longueurs allant de quelques centaines de mètres à plusieurs kilomètres, ont été appelées « sources linéaires » pour les différencier des sources traditionnelles, dont les exutoires sont localisés ponctuellement.

Les structures carbonatées du domaine pélagique, étendues sur 5000 km², alimentent 80 sources dont le débit moyen total est de 75 m³/s. L'infiltration efficace

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annuelle est, en moyenne, de 500 mm, correspondant à 50 % des précipitations.

Les structures hydrogéologiques et la position des exutoires sont représentées dans les figures 2 et 3.

Introduction

The hydrogeology of Central Italy was assessed in the 1970s and 80s by several workers including Zuppi *et al.* (1974), Boni (1975), Boni *et al.* (1980, 1986, 1988), Celico (1983), Capelli *et al.* (1987), and Governa *et al.* (1989). More recent studies have served to better determine groundwater resources and flow paths as well as recharge, storage and discharge characteristics (Boni, 1992; Boni and Mastrorillo, 1993, 1995; Boni *et al.*, 1993, 1995; Boni and Petitta, 1994; Boni and Preziosi, 1994; Carrara, 1995; Checcucci *et al.*, 1999). Mathematical models have been constructed for some fractured and karst aquifers (Boni and Preziosi, 1993; Boni *et al.*, 1994; Angelini and Dragoni, 1997; Preziosi *et al.*, 1995), while for others the modelling is in progress.

Hydrogeological setting

Introduction

The Central Italian regions of Umbria, Marche, Lazio, Abruzzo and Molise extend from 41°N to 43°N latitude. The total area of karst outcrops is about 15,000 km^2.

Folding and faulting have deformed the Mesozoic carbonates into subparallel ridges separated by valleys and tectonic depressions filled by terrigenous sediments. Altitude ranges from sea level to a maximum of 2,900 m.

Cultivated areas and shrub land extend from sea level up to 750 m, deciduous and coniferous forests from 750 to 1,800 m, and meadows above 1,800 m. "Terra rossa" is the typical soil all over.

Climate

The mean annual temperature is 16 °C at sea level; 14 °C at 300 m; 10 °C at 1,000 m; 8 °C at 1,400 m; 5.5 °C at 1,800 m; and 3.2 °C at 2,200 m.

A rain-gage network of about 300 stations collects rainfall data over an area of 15,000 km^2. Mean annual precipitation ranges from 700 mm at sea level to 2,000 mm along the central ridge. Mean annual precipitation in the southeastern region is about 1,300 mm, dropping to about 1,100 mm in the northwest. The average precipitation regime is the following:

Autumn:	35% in 25 rainy days
Winter:	30% in 30 rainy days
Spring:	30% in 30 rainy days
Summer:	10% in 10 rainy days

Snowfalls at altitudes below 500 m are unusual and ephemeral; above 500 m they are as follows:

Elevation (metres):

a) 500-1000
b) 1000-1500
c) 1500-2000

Percentage of total precipitation:

a) 5-10
b) 10-15
c) 15-20

Snow-cover period (days):

a) 10-60
b) 60-90
c) More than 90

Geology

Geological conditions are quite diverse over the area (Fig. 1). After the Paleozoic, more than 1,000 m of evaporitic, dolomitic and calcareous sediments were initially deposited on a metamorphic basement. This original large basin split into two sedimentological environments during the Early Jurassic: a subsiding carbonate shelf, composed of a thick and rigid sequence of limestone and dolomite without terrigenous intercalations, developed in the southeastern sector, while a typical carbonate-series basin filled with biomicrite and associated marl and chert formed in the northwest during the remainder of the Mesozoic. A large transitional belt lies between them. Orogenesis affected the region during the Miocene-Pliocene.

Karst morphology

Surface karst features include karren fields, dolines, dry valleys, karst plains and depressions, and closed basins. Such features are distributed almost uniformly over the region, but they are rarely spectacular. Surface karst features are more marked in the platform domain than in the basin domain, but a drainage network is better developed in the basin domain with typical deep canyons. In the platform domain, the evolutionary stage of surface drainage is still young and immature. The morphology everywhere has a young aspect, even near major springs. Subsurface karst features include sub-vertical conduits, natural wells, and potholes, and some sub-horizontal conduits and natural caves.

Paleokarst

The morphological history of the region is quite complex and has not yet been fully elucidated. Orogenesis in the Central Apennines developed since the Middle Miocene through alternating tectonic phases of stress and strain, which produced remarkable morphological changes and, in particular, a discontinuous migration of karst base levels. Recent sea-level fluctuations further influenced karst processes in coastal areas, where a paleokarst network in some places occurs 150 m below the present sea level. Karst ridges emerged gradually during the main orogenic phase between the Middle Miocene and Early Pliocene. This process was interrupted by Pliocene-Pleistocene rifting that caused intense volcanic activity along the Tyrrhenian coast and produced broad tectonic depressions inside the ridge. Remarkable changes in the position of the karst base level occurred at this stage of morphological evolution. Most probably, a deep karst network, fostered by favourable climatic conditions, developed during the Quaternary at lower altitudes than those of today's main discharge points. Subsequent filling of tectonic depressions by lacustrine and alluvial deposits obstructed the springs of the paleokarst network and produced an upward migration to their present position. This hypothesis is suggested by such evidence as:

1) most of the major springs occur at the margin of tectonic depressions filled by Pleistocene lacustrine sediments;

2) the morphology around the main springs is still young, since karst water does not emerge from a single conduit but

seeps through several small springs spread over several square kilometres;

3) major karst springs that discharge several m^3/s have a regular and predictable discharge regime with maximum and minimum fluctuations not exceeding 50% of the mean discharge;

4) the age of the karst water, based on tritium isotopes, ranges from 10 to >40 years. Small springs (3 to 5 m^3/s) have younger water, while that in large springs (10 to 20 m^3/s) is older. The chemical composition does not change significantly during the year.

Base levels and springs

In the platform domain, base levels correspond to springs; they are usually localized along the outer boundaries of hydrogeological structures where the impervious belt drops below the groundwater level.

In the basin domain, base levels commonly correspond to part of a river, deeply eroded below the groundwater level, where groundwater feeds the river flow as "linear springs". Here, the groundwater contribution to river flow is not easily observed and discharge measurements are difficult, which is why linear springs are generally overlooked.

Hydrogeology of the carbonate-basin domain

Stratigraphy

In the northwestern part of the region, carbonates were deposited in a typical pelagic basin with discontinuous influx of continental sediments, which split off from the platform domain during the Early Liassic due to rifting. The pre-existing Triassic dolomite platform was drowned and dislocated into ridges and depression structures, creating a new sedimentological environment. Sediments covered an irregular sea bottom, which made the thickness of the Jurassic sediments extremely variable, from a few metres on the top of the ridges to over 500 m at the bottom of depressions. The overlying Cretaceous sequences have a more homogeneous thickness, ranging from 500 to 700 m.

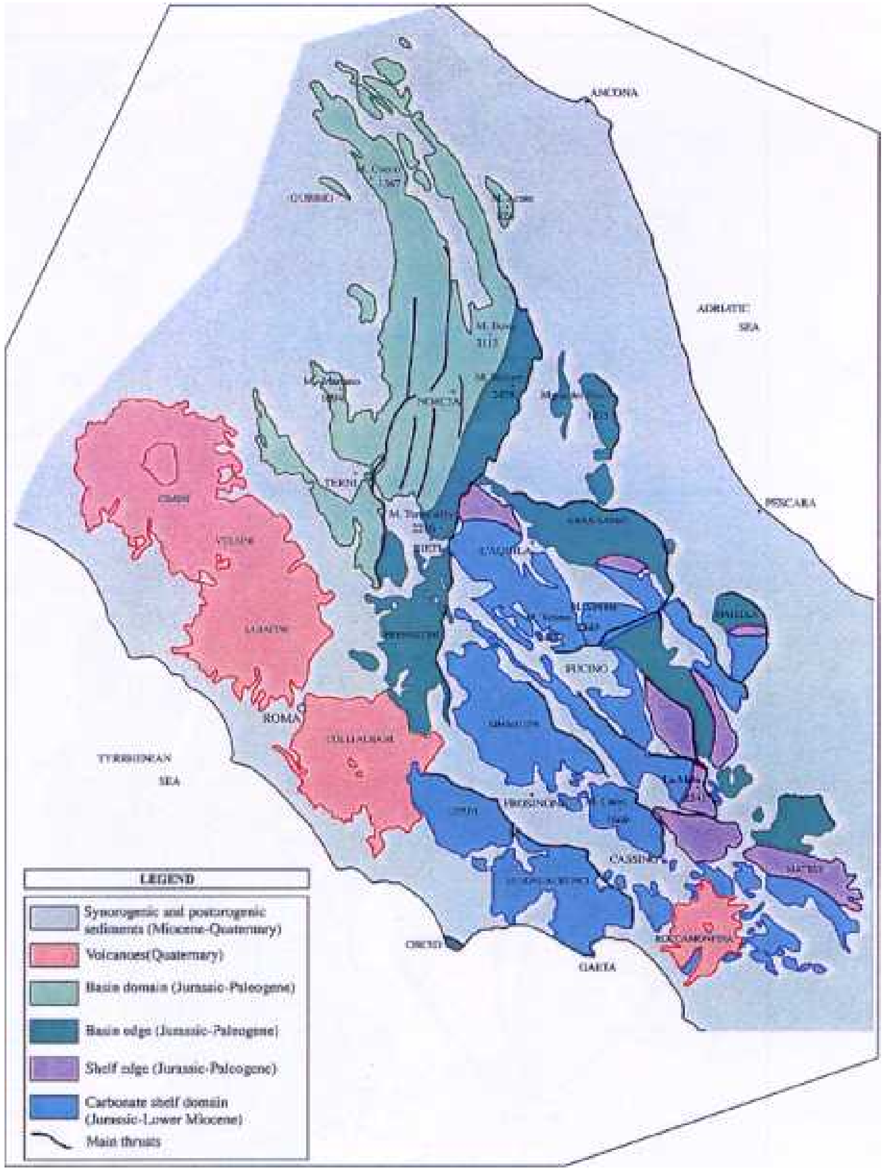

Fig. 1.- Schematic geological map of Central Italy: a subsiding carbonate platform developed in the southeastern sector, while a typical carbonate series basin formed in the northwest: orogenesis affected the region during the Miocene-Pliocene.

Fig. 1.- Carte géologique schématique de l'Italie centrale. Les conditions géologiques ne sont pas uniformes : une plate-forme carbonatée s'est développée au sud-est, un bassin pélagique au nord-ouest. L'orogenèse a intéressé la région dans le Mio-Pliocène.

Unlike platform sediments, the basin series consists of nearly pure limestone interbedded with marl and chert. The limestone is biomicrite with planktonic fossils and a regular thin bedding of 10 to 30 cm, while the marl and chert have even thinner stratification. This thin bedding and the marl intercalations make the pelagic series more plastic compared to the rigid and thick platform series.

Seven main lithological complexes can be distinguished:

1) the "Calcare massiccio" is an Early Liassic complex, a few hundred metres thick and belonging to the platform domain;

2) "Corniola" is a Middle Liassic biomicritic complex, extremely variable in thickness;

3) the "Marly Jurassic complex" consists of marl and chert, variable in thickness from a few metres up to 250 m;

4) "Maiolica" is a 250-m-thick Early Cretaceous biomicritic complex;

5) the "Scisti a fucoidi" is a 75-m-thick Middle Cretaceous marly/cherty formation;

6) "Scaglia" is a 350-m-thick Late Cretaceous biomicritic complex;

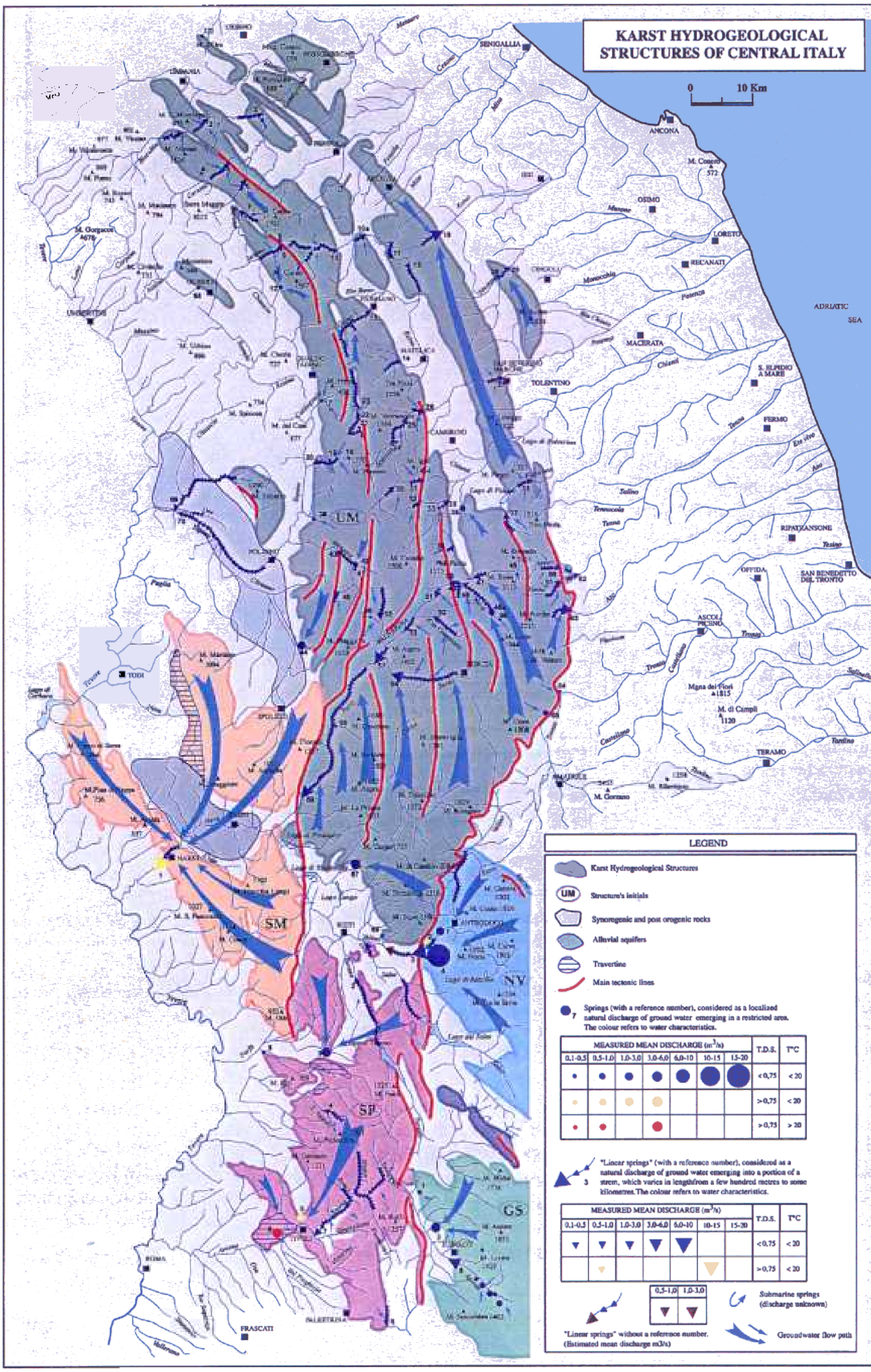

Fig. 2a.- Karst hydrogeological features of Northern Central Italy (see Fig. 2b for legend and the list of the springs).

Fig. 2a.- Carte des principaux grands systèmes hydrogéologiques du karst du Nord de l'Italie centrale. La légende et la liste des sources sont données en figure 2b

(UM) MONTI DELL'ARCO UMBRO-MARCHIGIANO

N	Springs	Altitude m	Disc. m^3/s
1	Linear spring in Biscubio river	405-305	0.16
2	Linear spring in Candigliano river	340-285	0.32
3	Linear spring in Candigliano river	260-190	0.19
4	Pieia spring	600	0.10
5	Linear spring in Bosso river	375-325	0.29
6	Linear spring in Burano river	365-300	0.57
7	Linear spring in Bevano river	475-365	0.13
8	Vena della Gorga spring	575	0.10
9	Linear spring in Sentino river	570-440	0.15
10	Linear spring in Sentino river	440-310	0.35
10a	Linear spring in Sentino river	290-270	0.15
11	Linear spring in Sentino river	230-225	0.13
12	Scirca spring	575	0.19
13	Linear spring in Giano river	575-330	0.43
14	Linear spring in Esino river	575-440	0.25
15	Linear spring in Esino river	230-195	0.22
16	Linear spring in Esino river	173-145	2.00
16a	Gorgovivo spring	145	1.20
17	Boschetto spring	540	0.17
18	Bagnara spring	632	0.12
19	San Giovenale well field	480	0.28
20	Linear spring in Topino river	475-400	0.80
21	Fonte di Brescia spring	650	0.18
22	Linear spring in Potenza river	600-495	0.31
23	Linear spring in Campodonico river	665-480	0.37
24	San Giovanni spring	550	0.21
25	Linear spring in Scarsito river	575-490	0.71
26	Linear spring in Potenza river	440-335	0.83
27	Linear spring in Potenza river	235-215	0.25
28	Crevalcore spring	325	0.11
29	Linear spring in Musone river	300-210	0.28
30	Linear spring in Chienti river	745-640	0.12
31	Linear spring in Chienti river	590-540	0.33
32	Linear spring in Sant'Angelo river	710-625	0.14
33	La Peschiera spring	515	0.23
34	Linear spring in Val di Tazza river	650-660	0.15
35	Linear spring in Chienti of Pieve Torina river	510-475	0.30
36	Pieveboviglíana spring	455	0.98
37	Linear spring in Fiastrone river	1150-650	0.59
38	Linear spring in Fiastrone river	560-482	0.33
39	Capodacqua di Foligno spring	380	0.22
40	Linear spring in Fauvella river	850-800	0.10
41	Alzabove spring	648	0.15
42	Rasiglia spring	650	0.72
43	Linear spring in Menotre river	620-600	0.10
44	Fonti del Clitunno spring	220	1.20
45	Panico spring	1283	0.31
46	Nera (Castel Sant'Angelo) spring	840	0.10
46a	San Chiodo spring	760	0.74
47	Linear spring in Ussita creek	605	0.78
48	Linear spring in Nera river	605	1.54
49	Linear spring in Visso creek	670-610	0.27
50	Linear spring in Nera river	600	0.32
51	Linear spring in Nera river	525-500	0.66
52	Linear spring in Campiano creek	660-475	0.70
53	Linear spring in Nera river	445-425	0.53
54	Linear spring in Corno-Sordo rivers	560-461	4.74
55	Linear spring in Vigi river	562-360	0.87
56	Argentina spring	562	0.24
57	Linear spring in Nera river	400-345	3.56
58	Scheggino spring	276	0.19
59	Linear spring in Nera river	293-242	3.08
60	Linear spring in Ambro river	720-685	0.50
61	Linear spring in Tenna river	710-685	0.90
62	Linear spring in Tenna and Ambro rivers	685-450	0.20
63	Linear spring in Aso river	850-790	2.20
64	Pescara di Arquata spring	750	0.20
65	Capodacqua del Tronto and Pescara di Accumoli springs	840	0.80
66	Cantaro spring	418	0.30
67	Santa Susanna spring	390	5.50
68	Raggio spring	450	0.20
69	Linear spring in Chiascio river	196-174	0.40
70	Linear spring in Topino river	250-174	0.40

Total mean discharge 47.44 m^3/s
Area 3460 km^2

(SP) MONTI SABATINI, PRENESTINI E CORNICOLANI

N	Springs	Altitude m	Disc. m^3/s
1	Linear spring in Salto river	420-390	1.00
2	Linear spring in Turano river	450-376	0.80
3	Capore spring	246	5.00
4	Linear spring in Sant'Angelo creek	500-300	0.25
5	Acquoria and Rivellese springs	70	0.80
6	Acque Albule spring	80-35	4.00
7	Linear spring in Aniene river	320-260	2.50
8	Linear spring in Rio creek	250	0.15
9	Farfa spring	100	0.13

Total mean discharge 14.63 m^3/s
Area 830 km^2

(SM) STIFONE - MONTORO

N	Springs	Altitude m	Disc. m^3/s
1	Linear spring in Nera river	90-75	13.50

Total mean discharge 13.50 m^3/s
Area 740 km^2

Fig. 2b.

7) the thick "Synorogenic marly complex" consists of marl, sandstone and claystone, deposited during the Alpine orogeny from the end of the Cretaceous to the Pleistocene.

This lithologic succession consists of three main permeable carbonate complexes, separated by three relatively impervious complexes.

Structural features

Though the deep structural setting of the region is still a matter of geological debate, the structural features of the exposed Mesozoic karstified terrains are more easily interpreted. During the Late Miocene, a compressive tectonic phase resulted in anticlines and syncline, associated with a close network of reverse faults and compressive fractures. The anticlines, with rigid cores of Lower Liassic limestone, generally occur where the pelagic succession is thinner, while synclines occur where the series is thicker. This Miocene compressive phase was followed by a Pliocene-Pleistocene strain phase that resulted in an extensive system of normal faults with remarkable offsets. This network of normal faults cuts the impervious marly rocks, bringing carbonate formations of different ages into contact. Separate geological structures are not easily detectable because synclines and anticlines are commonly continuous. In the basin domain, impervious synorogenic flysch was deposited on the carbonate series in synclinal depressions, but not between the carbonate ridges already produced by rifting, as occurred in the platform domain. This is one of the main geological features differentiating the platform domain from the basin domain.

Hydrogeological setting

In the basin domain, anticlines and synclines are hydrologically connected over wide areas. The result is that only three major, separate, hydrogeological structures (UM, SM and SP: Fig. 2) have been identified over an area of about 5,000 km^2 of carbonate outcrops.

Western structure (SM)

In the western structure, the occurrence of impervious units between carbonate complexes does not significantly affect deep infiltration and groundwater flow, because the normal-fault offsets are generally greater than the thickness of the impervious units. This structure has a single basal aquifer that feeds only one "linear spring" discharging about 13.5 m^3/s into the Nera River. Mean annual effective infiltration is about 570 mm, over an area of 750 km^2.

Southern structure (SP)

The southern structure covers an area of 830 km^2. In the north, this structure feeds the Capore spring (5.0 m^3/s), fully exploited for the water supply of Rome. In the south, this structure feeds several springs along the Aniene River valley, including the thermal springs near Tivoli. Total discharge is about 15 m^3/s, and mean annual effective infiltration is 570 mm.

Northeastern structure (UM)

In this large structure (3,500 km^2), about seventy relevant springs are fed by three main aquifers that are separated by impervious units:

1) the "basal aquifer" in the Massiccio and Corniola complexes;

2) the "Maiolica aquifer";

3) the "Scaglia aquifer"

Characteristic of this structure is an extensive network of perennial rivers and creeks acting as base levels of the main karst aquifers. More than 80% of the groundwater emerges in deep canyons; rivers, fed by groundwater, maintain a remarkable discharge, even in the dry season, and acquire a regular discharge regime (Fig. 8).

Springs in river sections that range in length from a few hundred metres to several kilometres, have been called "linear springs" to distinguish them from traditional springs that discharge at one point or within a small area.

Mean annual effective infiltration is 500 to 600 mm, and the mean annual runoff over carbonate structures has been evaluated at 150 to 200 mm.

The structural setting strictly controls groundwater flow. In the south, three separate aquifers discharge about 25 m^3/s of karst water into the Nera River and its tributaries, and the flow path is from south to north, parallel to the main thrusts.

In the northern part of the structure, several small linear springs are scattered throughout the region, and a better assessment of the hydrogeological setting in this area is in progress.

Groundwater resource assessment in the pelagic domain

Carbonate structures of the pelagic domain extend over an area of about 5,000 km^2 and feed around 80 springs with a mean discharge of 75 m^3/s (Fig. 2b). Mean annual effective infiltration is 500 mm, about 50% of total precipitation.

Hydrogeology of the carbonate-platform domain

Stratigraphy

Carbonate-platform sediments were deposited in oceanic lagoons, which were interconnected by a network of tidal channels and protected from oceanic energy by coral reefs and bioclastic barriers. In such a sedimentological environment, isolated from continental influence, the biogenic carbonate sedimentation was almost pure. Since the rate of sedimentation was approximately the same as the rate of subsidence, general sedimentological conditions did not change significantly during the Mesozoic. Horizontal and vertical lithological changes are mainly due to migrations of tidal channels and coral reefs, and to the structural evolution of the platform, such as different subsidence rates and different periods of emersion. Carbonate platform sediments consist of dominant biomicrite with benthic fossils associated with intrabiosparite, oosparite, and dolomitic limestone, without significant terrigenous intercalations. Stratification, which is regular and thick, averages 50 cm. Total thickness of the platform ranges from a few hundred metres to a maximum of 3,000 m. The lithological characteristics of carbonate rocks are strictly related to the sedimentological environment.

The carbonate-platform domain includes a large belt of "edge sediments" resulting from the erosion of coral reefs

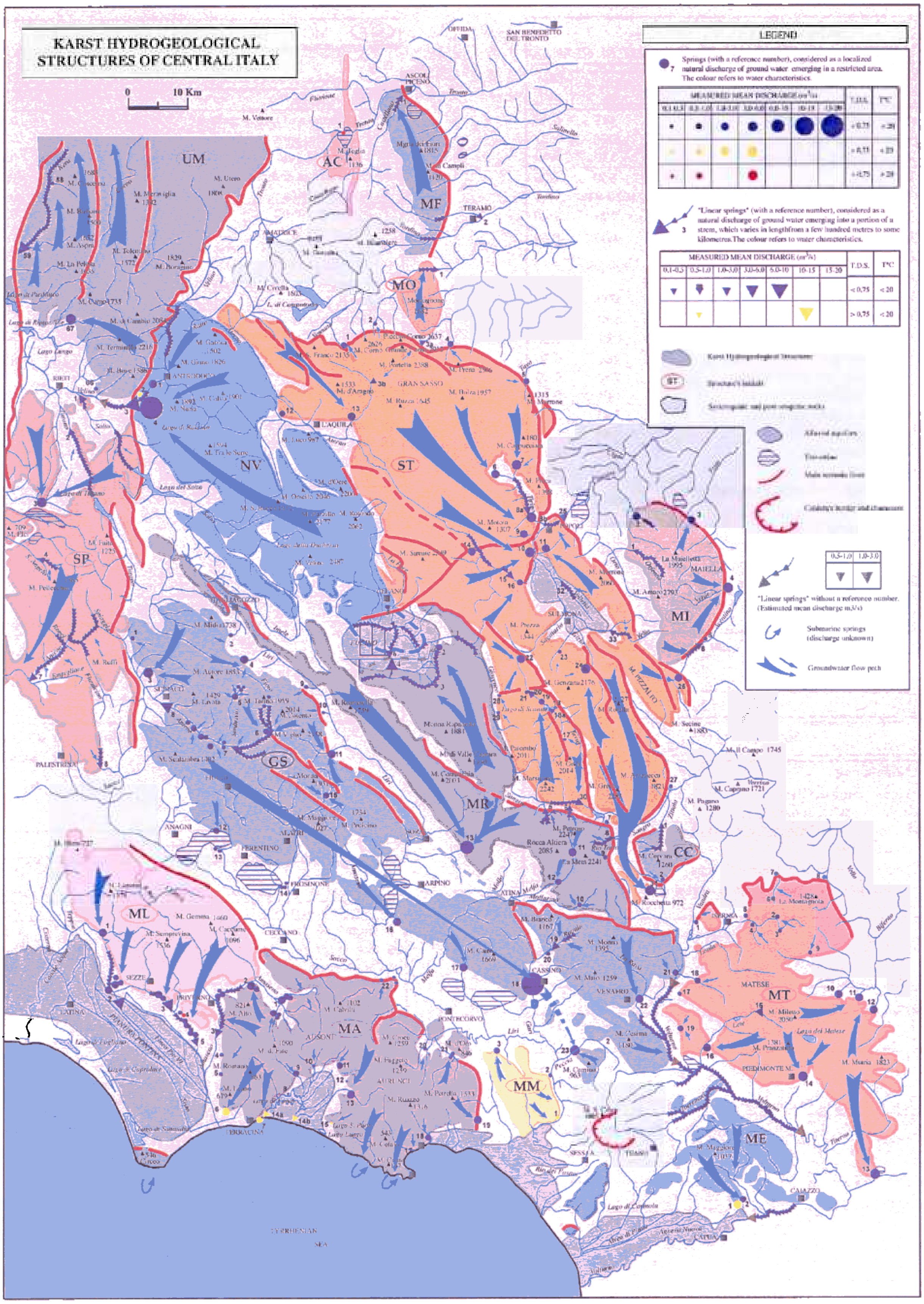

Fig. 3a.- Karst hydrogeological featuresof southern Central Italy (see Fig. 3b for legend and the list of the springs).

Fig. 3a.- Carte des principaux grands systèmes hydrogéologiques du karst du Sud de l'Italie centrale. La légende et la liste des sources sont données en figure 3b.

(GS) MONTI SIMBRUINI, ERNICI, M. CAIRO, M. CAMINO, M. DI VENAFRO, M. CESIMA

N	Springs	Altitude m	Disc. m^3/s
1	Arsoli and minor springs	345	0.40
2	Verrecchie spring	1020	0.20
3	Agosta and minor springs	330	5.40
4	Liri spring	950	1.00
5	Valle del Simbrivio and minor springs	1070-940	0.60
6	Pertuso spring	700	1.60
7	Ceraso spring	600	0.60
8	Linear spring in Aniene river and minor springs	900-360	3.70
9	Rio Sonno spring	900	0.15
10	Sponga spring	830	0.40
11	Pantanecce and minor springs	780	1.60
12	Tufano spring	284	0.70
13	Le Monache and minor springs	230	0.30
14	Laghetto and minor springs	140	0.20
15	Alto Cosa and minor springs	700	0.90
16	Bucone spring	140	1.80
17	Capodacqua spring	112	1.20
18	Gari spring	40-35	18.00
19	Linear spring in Rapido river, including minor springs	300-100	1.50
20	Salauca spring	75	0.20
21	Capodacqua Santa Maria Uliveto spring	215	0.50
22	San Bartolomeo and minor springs	175	1.30
23	Peccia river and minor springs	27	5.50
-	Linear spring in Volturno river (estimated discharge)	250-200	3.00

Total mean discharge 50.75 m^3/s
Area 1800 km^2

(ML) MONTI LEPINI

N	Springs	Altitude m	Disc. m^3/s
1	Ninfa spring	29	2.50
2	Linear spring in Cavata and Cavatella creeks including minor springs	10-6	6.00
3	Linear spring in Uffente river, including minor springs	6-3	4.30
4	Laghi del Vescovo and minor springs	3	0.20
5	Linear spring in Uffente channel including minor springs	5-3	2.00

Total mean discharge 15.00 m^3/s
Area 530 km^2

(ME) MONTE MAGGIORE

N	Springs	Altitude m	Disc. m^3/s
1	Triflisco and minor springs	30	2.80
2	Pila spring	30	0.80
-	Linear spring in Volturno river (estimated)	27-25	1.00

Total mean discharge 4.60 m^3/s
Area 170 km^2

(MM) MONTE MAIO

N	Springs	Altitude m	Disc. m^3/s
1	Suio and minor springs	16	0.40
2	Mola Salomone spring	12	0.40
3	San Giorgio a Liri spring	39	0.70
-	Linear spring in Garigliano river (estimated)		1.00

Total mean discharge 2.50 m^3/s
Area 90 km^2

(MT) MONTI DEL MATESE E MONTE TOTILA

N	Springs	Altitude m	Disc. m^3/s
1	Dei Natali spring	280	0.20
2	Carpinone and minor springs	640	0.20
3	Pantaniello spring	510	0.20
4	Lucito and minor springs	400-350	0.25
5	Capodacqua and minor springs	460-450	0.15
6	Sessano spring	700	0.20
7	Sorgenza spring	800	0.20
8	Pincio spring	800	0.30
9	Santa Maria e San Giacomo springs	610	0.30
10	Maiella and minor springs	485	1.20
11	Pietrecadute and minor springs	490	1.80
12	Rio Freddo and minor spings	510	1.70
13	Grassano and minor springs	60	5.50
14	Piedimonte d'Alife and minor springs	200-175	4.30
15	Linear spring in Lete river, and minor springs	1030	0.60
16	Pratella and minor springs	160-150	1.40
17	Caprinero spring	400	0.30
18	San Nazzaro spring	250	0.70
19	Sant'Agata spring	170	0.50
-	Linear spring in Volturno river (estimated discharge)		3.00

Total mean discharge 23.00 m^3/s
Area 810 km^2

(CC) COLLI CAMPANARI

N	Springs	Altitude m	Disc. m^3/s
1	Linear spring in Zittola river, including minor springs	825-800	0.30
2	Acquarulo springs	575-550	0.15

(MA) MONTI AUSONI E AURUNCI

N	Springs	Altitude m	Disc. m^3/s
1	Capodacqua di Amaseno and minor springs	98	0.60
2	Fiumicello spring	44	1.20
3	Linear spring in Amaseno river	150-10	0.20
4	Marutte spring	4	0.15
5	Ponticelli-Strada Consolare and minor springs	98	0.35
6	Linea and minor springs	2	2.60
7	Mola Bisletti and minor springs	1	0.90
8	Portella-Pezzenti and minor springs	8-11	0.25
9	Villa San Vito spring	40-20	0.75
10	San Magno spring	25	0.30
11	Capodacqua di Fondi and minor springs	12-10	0.70
12	Gegni and minor springs	21-5	0.15
13	Vetere and minor springs	14-8	1.20
14	Springs in Fondi lake (estimated discharge)	0	2.00
15	Springs in San Puoto lake	4	0.30
16	Sperlonga and minor springs	0	0.20
17	San Maria di Conca spring	2	0.20
18	Mazzoccolo and minor springs	15	0.50
19	Capodacqua di Spigno spring	52	1.10
20	Caldaia spring	75	0.35
21	Le Bocche spring	70	0.80
22	Obaco spring	170	0.20
-	Submarine springs (estimated discharge)		8.00

Total mean discharge 23.00 m^3/s
Area 910 km^2

Fig. 3b

(ST) MONTI SIRENTE, GRAN SASSO, MORRONE TERRATTA, GRANDE, GRECO, PIZZALTO

N	Springs	Altitude m	Disc. m^3/s
1	Chiarino and minor springs	1320	0.70
2	Rio Arno and minor springs	1500	0.20
3	Drainage in Gran Sasso tunnel	960	1.00
4	Ruzzo and minor springs	1600-925	0.90
5	Vitella d'Oro and minor springs	750-700	0.60
6	Presciano and Capestrano and minor springs	360-330	1.00
7	Capodacqua del Tirino spring	340	4.60
8a	Linear spring in Tirino river including minor springs	330-230	2.00
8b	Bussi spring		
9	San Calisto e Santa Liberata springs		
10	Capo Pescara spring		
11	Giardino spring		
12	Vetoio and Boschetto springs		
13	Tempera and Capovera springs		
14	Molina Aterno springs		
15	Linear spring in Aterno river	440-300	1.00
16	Raiano springs	280	0.70
17	Capodacqua del Tasso spring	1230	0.20
18	La Marca spring	940	0.10
18a	Manona spring	930-924	0.19
19	Fonte Vecchia, Molino e Lagoscuro springs	900	0.70
20	Linear spring in Sagittario river and San Domenico lake	900-805	2.00
21	Sega spring	807	0.30
22	Cauto spring	500	1.50
23	Introdacqua springs	730	0.25
24	Gizio spring	620	2.80
25	Linear spring in Pescara river, including minor springs	230-200	1.00
26	Capo di Fiume dell'Aventino spring	880	1.20
27	Acqua Soriente spring	810	0.20
28	San Sebastiano spring	1030	0.30
29	Ferriera spring	1030	0.30
30	Linear spring in Sangro river, including minor springs	990-975	2.10
31	Capo Volturno spring	570	6.60
32	Linear spring in Velletta river	360-280	0.40
33	Linear spring in Vella river	810	0.20

Total mean discharge 53.84 m^3/s
Area 2160 km^2

(NV) MONTI NURIA E VELINO

N	Springs	Altitude m	Disc. m^3/s
1	Canetra spring	435	2.90
2	San Vittorino spring	410	0.30
3	Linear spring in Velino river, including minor springs	615-410	7.00
4	Peschiera spring	405	18.00
-	Linear spring in Velino river, including minor springs (estimated discharge)	410-395	2.00
5	Santissimi Martiri and minor springs	790	0.20
6	Linear spring in Fucino Plain	650	1.30

Total mean discharge 31.70 m^3/s
Area 1000 km^2

(MR) MONTI DELLA MARSICA OCCIDENTALE

N	Springs	Altitude m	Disc. m^3/s
1	Linear spring in Giovenco river	910-700	0.20
2	Venere and minor springs	670	0.60
3	Ortucchio and minor springs	660	0.40
4	Linear spring in Fucino Plain	650	5.50
5	Linear spring in Fondillo river	1300-1100	0.30
6	Linear spring in Scerto river	1350-1000	0.20
7	Le Donne and minor springs	1150	0.40
8	Linear spring in Rio Torto including minor spring	1300	0.50
9	Le Forme and minor springs	1450	0.10
10	Serrone, Capodacqua and minor springs	800-700	0.30
11	Madonna di Canneto spring	1010	1.20
12	Schioppaturo spring	500	0.30
13	Fibreno Lake and minor springs	295	9.80

Total mean discharge 19.80 m^3/s
Area 840 km^2

(AC) ACQUASANTA

N	Springs	Altitude m	Disc. m^3/s
1	Acquasanta springs	355	0.30

Total mean discharge 0.30 m^3/s
Area 50 km^2

(MF) MONTAGNA DEI FIORI

N	Springs	Altitude m	Disc. m^3/s
1	Linear spring in Castellano creek	320-310	0.80
2	Linear spring in Tordino and Vezzola rivers	320-310	0.80

Total mean discharge 1.60 m^3/s
Area 140 km^2

(MO) MONTAGNONE

N	Springs	Altitude m	Disc. m^3/s
1	Linear spring in Vomano river	470-260	0.50

Total mean discharge 0.50 m^3/s
Area 60 km^2

(MI) MONTI DELLA MAIELLA

N	Springs	Altitude m	Disc. m^3/s
1	Linear spring in Orta and Orfento rivers	500-400	0.30
2	Lavino-De Contra springs	150	1.20
3	Foro spring	420-290	1.00
4	Verde spring	410	3.60
5	Lettopalena-Taranta-Peligna springs	500-450	0.40
6	Linear spring in Aventino river	500-450	1.00

Total mean discharge 7.50 m^3/s
Area 300 km^2

Fig. 3c

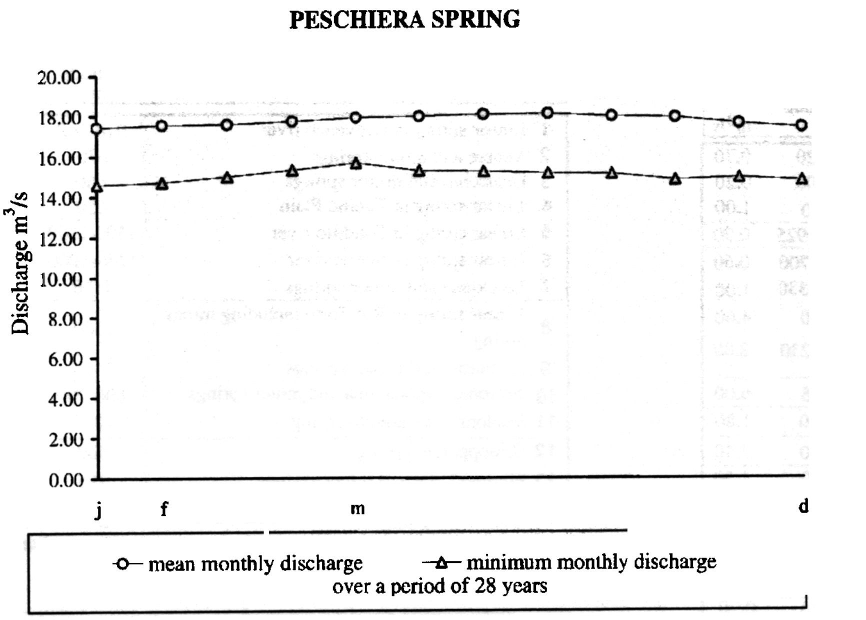

Fig. 4.- Peschiera spring: discharge is extremely regular without any seasonal variation, the regime being affected only by long-term cyclic variations.

Fig. 4.- Évolution du débit de la source du Peschiera. Extrêmement régulier, sans variations saisonnières, il est soumis à des variations cycliques à long terme.

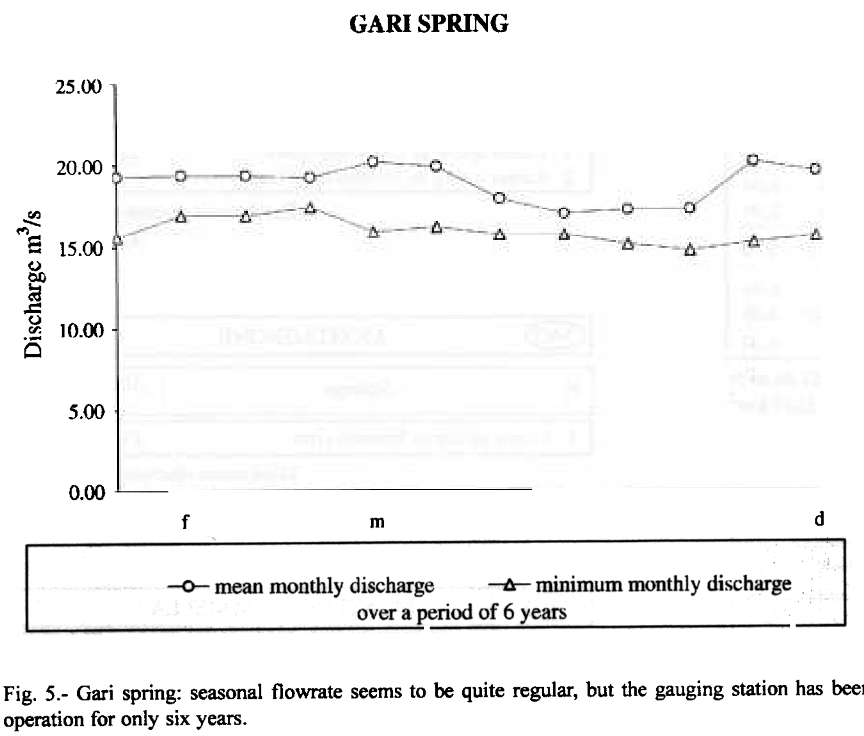

Fig. 5.- Gari spring: seasonal flowrate seems to be quite regular, but the gauging station has been in operation for only six years.

Fig. 5.- Évolution saisonnière du débit de la source du Gari. D'après les données disponibles (6 ans) il semble être régulier ; la station hydrométrique a fonctionné seulement six ans.

surrounding the platform. This transitional facies consists of carbonate breccia and detrital limestone, interbedded with pelagic sediments. The platform domain extends over an area of about 9,000 km^2 and can be considered, on a regional scale, as a single hydrogeological complex due to its lithological homogeneity. Miocene argillaceous flysch was deposited on the platform during orogenesis.

Structural features

Orogenesis began in the Middle Miocene and developed in three main phases up to the Pliocene-Pleistocene:

1) during the first rifting phase, the platform was cut by long regional faults into subparallel ridges, divided by deep trenches that soon filled with terrigenous flysch;

2) during the second phase, the carbonate ridges were uplifted and thrust over the flysch by a general northeast translation;

3) a third phase, characterized by a system of normal faults, produced deep tectonic depressions and gave rise to intense volcanic activity in the western sector. Tectonic depressions were filled by clay and sand from a Pliocene marine transgression in coastal areas, and by fluvial and lacustrine deposits farther inland.

The carbonate platform reacted to orogenic movements as a rigid and brittle mass. Tectonic activity partitioned the platform into several carbonate structures, surrounded by a continuous belt of impervious units. Alternating stress and strain from the tectonic forces created a network of uniformly distributed sub-vertical faults and fractures; the network of significant fractures has a close spacing of one to ten metres.

Hydrogeological setting

The hydrogeological setting reflects the lithological and structural conditions. Each carbonate ridge, surrounded by impervious rocks, acts as an independent hydrogeological structure consisting of a recharge area, a karst body with impervious boundaries, and one or several base levels located on the outer limits of the structure where the impervious belt is more depressed. Since the drainage network is still immature, erosion has not yet cut into the karst aquifers. Streams fed by "linear springs" are therefore an exception in the platform domain. The size of karst structures ranges from 100 to more than 1,000 km^2. Eleven independent hydrogeological structures have been identified in the platform domain: seven consist only of pure platform sediments, while four also include sediments that are transitional to the pelagic domain.

Due to the lack of impervious intercalations and to the extensive fracture network in the platform domain, infiltration is abundant and distributed evenly over the region (60 to 70% of total precipitation). The karst network is extensive, but generally neither spectacular nor penetrable. Deep infiltration feeds large basal aquifers that extend to the bottom of all hydrogeological structures.

Groundwater discharges through large springs that are characterized by a regular and predictable discharge regime. Significant perched aquifers are uncommon in the platform domain. Where present, perched aquifers are related to the uplift of Triassic dolomite that acts as a semi-impervious basement compared to the more permeable, overlying limestone. Unlike other carbonates, Triassic dolomite bears groundwater up to a maximum elevation of 1,000 m and feeds a high-altitude network of perennial streams.

Hydrogeological structure NV (Fig. 3) feeds the Peschiera (18 m³/s) and other springs in the Velino valley, for a total discharge of about 30 m³/s. The Peschiera spring (Fig. 4) is exploited for 9 m³/s by the water supply system of Rome.

Hydrogeological structure GS (Fig. 3) is divided into two parts. The northern part feeds the Aniene and Liri rivers; the main spring near Subiaco has a mean discharge of 6 m³/s, fully exploited for Rome water supply. The southwestern part feeds the Gari (18 m³/s, Fig. 5) and Peccia (5 m³/s) springs near Cassino, and several other minor springs. Total mean discharge of this structure is 50 m³/s.

The hydrogeological structures ML and MA (Fig. 3) feed several springs along the southern margin of the ridges. Base level varies from an altitude of 30 m to sea level. In many places, karst water mixes with perivolcanic gases and thermal waters. The mean discharge of the springs, measured over several years, is about 30 m³/s. Submarine springs discharge into the sea about 8 m³/s of karst water.

Hydrogeological structure ST (Fig. 3) feeds the Pescara River and its tributaries. Main springs are Capo Pescara (7.5 m³/s) and Bussi (6 m³/s). The southeastern sector feeds the Volturno River spring (6 m³/s, Fig. 6). Total discharge of this structure is more than 50 m³/s.

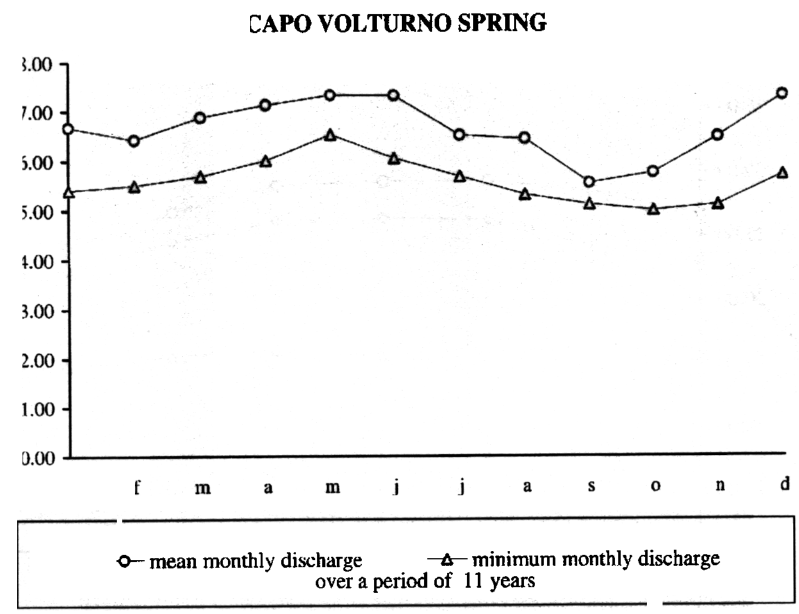

Fig. 6.- Capo Volturno spring: seasonal flowrates show a regular regime affected by minor seasonal variations.

Fig. 6.- Évolution saisonnière du débit de la source de Capo Volturno. Son régime est régulier, soumis à des variations saisonnières assez limitées.

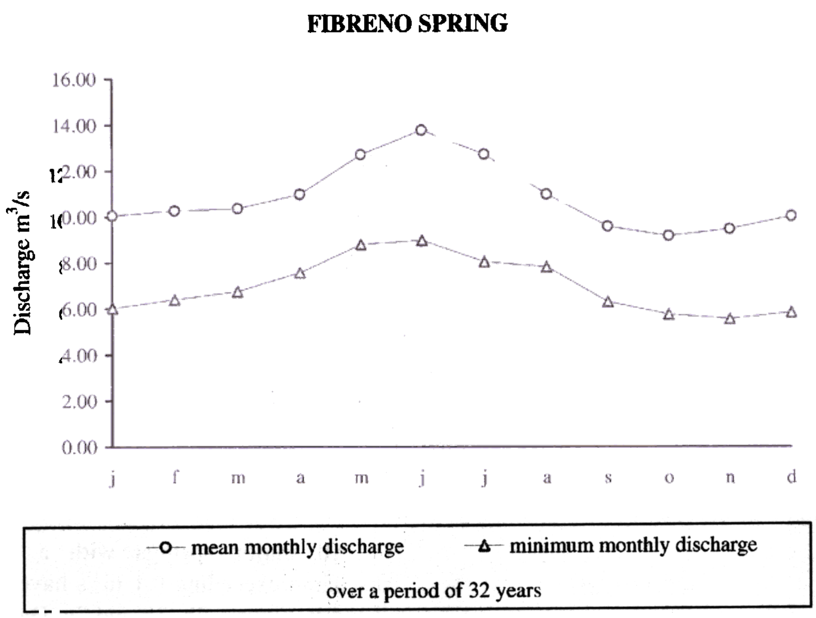

Fig. 7.- Fibreno spring: seasonal flowrates show a regular regime with a characteristic fluctuation in spring time, due to snow melting.

Fig. 7.- Évolution saisonnière du débit de la source du Fibreno. Son régime est régulier, avec une fluctuation nette au printemps, due à la fonte des neiges.

Hydrogeological structure MR (Fig. 3) feeds the Fibreno Lake spring (10 m³/s, Fig. 7) and several springs located in the Fucino Plain (6 m³/s). Minor aquifers, perched on an impervious dolomite substratum, are located on the "La Meta" ridge. Total discharge of this structure is about 20 m³/s.

Groundwater recharge

Groundwater recharge is well distributed over the region and results only from

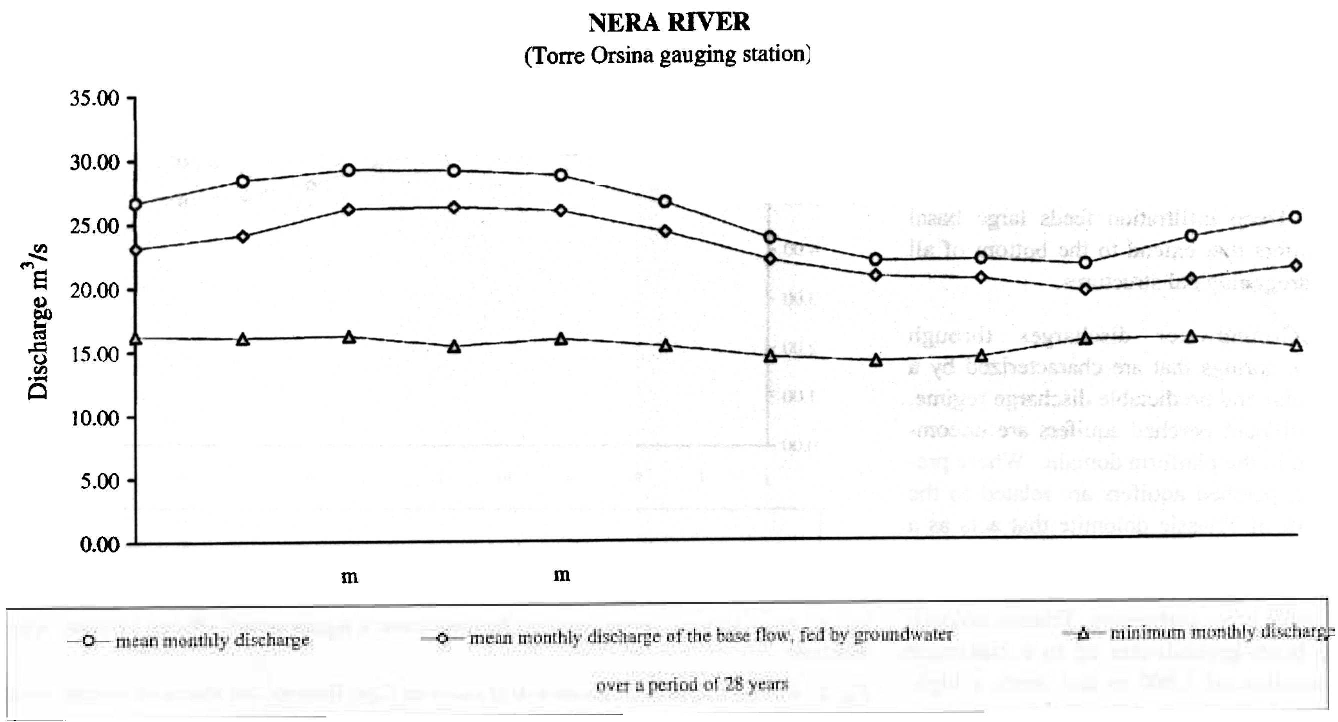

Fig. 8.- Nera river: seasonal flowrate upstream from Torre Orsina show a very regular regime that is mainly fed by groundwater; overland runoff, based on hydrographic analysis, is about 15% of the total discharge.

Fig. 8.- Évolution saisonnière du débit de la Nera. Cette rivière est alimentée par des eaux souterraines. D'après l'analyse des hydrogrammes, le ruissellement de surface est estimé à 15 % du débit total.

local precipitation. Effective infiltration in the platform domain was calculated in 11 independent hydrogeological structures over a total area of about 9,000 km^2, including 4,000 km^2 of transitional belt. In platform sediments, the mean annual effective infiltration is about 900 mm with a minimum of 750 mm and a maximum of about 1,000 mm. In the transitional belt, the mean value is 725 mm (minimum of about 550 mm and maximum of around 900 mm).

Base levels

Each independent structure has its own basal aquifer and one or more base levels. In only one case (Structure MA, Fig. 3) the karst structure plunges into the sea, which acts as base level. In all other cases the base level is located at the outer limits of the structure, where the impervious rocks surrounding the carbonate structure drop below the level of the basal aquifer. Each structure has thus one or more discharge points, depending on the shape of the impervious belt. Due to the high infiltration capacity of karst outcrops, runoff over platform rocks is negligible. The process of normal erosion is therefore reduced and the drainage network, still immature, does not reach into basal aquifers. Rivers and streams acting as base levels are an exception in the platform domain. Pumping from karst aquifers is also reduced to negligible values due to the depth of the water level and to the abundance of low-cost spring water.

Water points and discharge regime

All major springs with a mean discharge exceeding 0.1 m^3/s have been listed in Figures 2b, 3b and 3c. Data are available on rivers and streams fed by karst aquifers, but very little is known about the abstraction from wells though the exploited volume is certainly negligible. Springs discharging more than 5 m^3/s are generally monitored and records are available for periods of 20 to 50 years. Springs discharging <5 and >1 m^3/s are periodically monitored. Fig. 3 shows the locations of the main springs of the shelf domain.

The discharge regime of the main springs fed by the karst aquifer is extremely regular and predictable (Figs. 4, 5, 6, 7), unlike many other karst areas. Positive and negative fluctuations generally do not exceed 50% of the mean annual discharge, though the regime of large springs is affected by long-term cyclic variations (10-15 years) due to climatic changes. Regime stability increases with the amount of mean discharge, and this stable discharge regime is associated with a remarkable stability of hydrochemical and isotopic characteristics (see next section) and with a residence time of several years. A few significant springs with variable discharge are typically fed by perched aquifers.

Hydrochemistry and isotope analysis

Hydrochemistry reflects the hydrogeological conditions. Spring waters fed by basal aquifers have almost constant hydrochemical characteristics and do not show significant seasonal variations, according to their regular discharge regime. The concentration of stable ^{18}O and ^{2}H isotopes shows an almost complete mixing of seasonal recharge.

For main springs, the mean residence time – estimated from tritium content – ranges from a minimum of ten years to over forty years. The use of ^{14}C for evaluation of the residence time did not give meaningful results, due to a widespread contamination from hydrothermal gas circulating in the main regional faults. However, minor springs with a more variable discharge regime do show significant variations in hydrochemical characteristics and isotope concentrations.

Special attention must be paid to the influence of hydrothermal waters. Near volcanic areas, hydrothermal waters mix with karst water, leading to anomalous temperatures and chemical compositions. Far from volcanic areas, karst waters still can mix with hydrothermal water and gas along main regional faults. As a rule, the occurrence of thermal water significantly increases sulphate and carbonate concentrations and produces travertine deposits near springs. Any geochemical consideration of karst waters is thus made difficult by hydrothermal contamination.

Water resources assessment in the platform domain

The hydrogeological balance of platform-domain aquifers (including the transitional belt to the basin domain) has been calculated in eleven independent structures over a total area of about 10,000 km^2. Mean annual precipitation ranges from 950 to 1,500 mm.

In platform aquifers, the mean annual effective infiltration ranges from 750 mm to about 1,000 mm; in the transitional belt aquifers, infiltration ranges from 600 to 900 mm.

The mean contribution of karst outcrops to the recharge of basal aquifers is about 25 l/s/km^2. Mean annual evapotranspiration ranges from 400 to 600 mm; overland runoff has a negligible value. Both platform and transitional-belt aquifers supply a mean discharge of about 230 m^3/s from around 140 springs.

References

Angelini P., Dragoni W. (1997) - The problem of modeling limestone springs: the case of Bagnara (North Apennines, Italy). *Groundwater*, **35**, 612-618.

Carrara C. (1995) - Lazio meridionale. Sintesi delle ricerche geologiche multidisciplinari. ENEA Serie Studi e Ricerche, 163-176.

Boni C. (1975) - The relationship between the geology and hydrology of the Latium-Abruzzi Apennines. *In*: Structural Model of Italy. *Quad. Ric. Sci.* 90, 301-311.

Boni C. (1992) - Karst hydrogeology in Central Italy. International Contributions to Hydrogeology, 13, Int. Karst Commission, Verlag Heinze, Hannover.

Boni C., Mastrorillo L. (1993) - Rilevamento idrogeologico dei Monti di Foligno. *In*: Atti del Convegno "Ricerca e protezione delle risorse idriche sotterranee delle aree montuose". Brescia, 24-25 October 1991.

Boni C., Mastrorillo L. (1995) - Valutazione delle risorse idriche sotterranee dei bacini dei fiumi Esino e Potenza (Appennino marchigiano) e considerazioni sul loro uso. *Quad. Tecniche di protezione ambientale*, **1**, 257-266, Pitagora Ed., Bologna.

Boni C., Petitta M. (1994) - Sorgenti Lineari e valutazione dell'infiltrazione efficace in alcuni bacini dell'Italia Centrale. *Quad. Geol. Appl.*, **1**, 99-113, Pitagora Ed, Bologna 1994.

Boni C., Preziosi E. (1993) - Una possibile simulazione numerica dell'acquifero basale di M. Coscerno - M. Aspra (bacino del fiume Nera). *Geol. Appl. Idrogeol.*, **28**, 131-140.

Boni C., Preziosi E. (1994) - Le sorgenti lineari nell'alto bacino del fiume Nera (Appennino Umbro-Marchigiano Italia centrale). *In* Atti dell'International Meeting for Young Researchers in Applied Geology. GEOLEP-DGC/EPFL, 31-35, Lausanne 1994.

Boni C., Bono P., Calderoni G., Lombardi S., Turi B. (1980) - Indagine idrogeologica e geochimica sui rapporti tra ciclo carsico e circuito idrotermale nella Pianura Pontina (Lazio meridionale). *Geologia applicata e idrogeologia*, **15**, 203-247.

Boni C., Bono P., Capelli G. (1986) - Schema idrogeologico dell'Italia centrale - A) Carta idrogeologica (scala 1:500,000); B) Carta idrologica (scala 1:500,000); C) Carta dei bilanci idrogeologici e delle risorse idriche sotterranee (scala 1:1,000,000). *Mem. Soc. Geol. It.*, **35**, 991-1012.

Boni C., Bono P., Capelli G. (1988) - Carta idrogeologica del territorio della regione Lazio (scala 1:250,000). Regione Lazio.

Boni C., Petitta M., Preziosi E., Sereni M. (1993) - Genesi e regime di portata delle acque continentali del Lazio. Coll. Mon. Scientifiche del C.N.R., 78, 40 tab., 1 map.

Boni C., Mastrorillo L., Preziosi E. (1994) - Simulazione numerica di acquiferi carbonatici: l'esempio della struttura M.Maggio - M.Penna (Nocera Umbra). *Geologica Romana*, **30**, 27-36.

Boni C., Mastrorillo L., Petitta M. (1995) - Scomposizione della portata dei corsi d'acqua dell'Appennino Marchigiano con il metodo delle "Portate mensili caratteristiche". *In* Atti del 3° Convegno Nazionale dei Giovani Ricercatori in Geologia Applicata, Potenza, 28-30 October 1993 SAFRA edit.

Capelli G., Cosentino D., Messina P., Raffi R., Ventura G. (1987) - Modalità di ricarica e assetto strutturale dell'acquifero delle sorgenti Capore-S. Angelo (Monti Lucretili-Sabina meridionale). *Geologica Romana*, **26**,

Celico P. (1983) - Idrogeologia dei massicci carbonatici, delle piane quaternarie e delle aree vulcaniche dell'Italia centro-meridionale. Quad. della Cassa per il Mezzogiorno, 4, 225.

Checcucci R., Dragoni W., Marchetti G. (1999) - Le risorse idriche strategiche in Umbria. Conoscenze e prospettive di utilizzo. *Quad. Geol. Appl.*, **2**, 4,133-4,141, Pitagora Bologna.

Governa M.E., Lombardi S., Riba M., Zuppi G.M. (1989) - Karst and geothermal water circulation in the Central Apennines (Italy). Isotope Techniques in the study of the hydrogeology of fractured and fissured rocks. IAEA, Vienna, STI/PUB/790, 173-202.

Preziosi E., Ledoux E., Boni C. (1995) - Évaluation par modèle mathématique de l'infiltration efficace dans un aquifère multicouche de l'Apennin central. *In:* Proc. 2nd International Meeting of Young Researchers in Applied Geology, 367-375, Peveragno, Cuneo, 11-13 October 1995.

Zuppi G.M., Fontes J.Ch., Letolle R. (1974) - Isotopes du milieu et circulations d'eaux sulfurées dans le Latium. *Isotope Techniques in Groundwater Hydrology*, 1, 341-361, IAEA, Vienna.