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Outline of the hydrogeology of the Cimino and Vico volcanic area and of the interaction between groundwater and Lake Vico (Lazio Region, Central Italy)

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ABSTRACT

The study area covers the Cimini and Vico volcanic complexes in the province of Viterbo (Northern Lazio Region, Italy), where a large-scale exploitation of the water resources co-exists with fragile environmental conditions. The Vico caldera and the lake of the same name form the central nucleus of a Nature Reserve and are an important source of drinkable water for a number of municipalities. The main aim of the study was to improve our knowledge of the hydrogeological setting of the system in order to quantify the groundwater resource and to examine the interaction between the groundwater and Lake Vico in their specific geological framework.

The hydrogeological investigations included: i) reconstruction of local hydrostratigraphy; ii) collection of data from wells and springs; iii) flow measurement of streams; iv) development of some pumping tests; v) analysis of climatic data.

The volcanic aquifer consists primarily of Pleistocene pyroclastic deposits (tuffs, ignimbrites, ashes, pumice and scoriae) and various lava flows and domes. Its base and part of its SW and NE boundaries are well defined by low-permeability rocks, including sandy-clayey deposits (Pliocene-Pleistocene) and marly-calcareous flysch (Upper Cretaceous-Oligocene). The remaining boundaries are formed by highly permeable Quaternary alluvial and sandy-conglomeratic deposits.

The groundwater flow occurs mainly through the unconfined basal volcanic aquifer and to a lesser extent through various perched aquifers. The basal volcanic aquifer has a centrifugal radial flow network; the groundwater discharges primarily into streams (not less than 1.4 m^3/s) and in part into small springs (less than 0.5 m^3/s). The volcanic aquifer also feeds the aquifer of the surrounding plain, especially where the Quaternary sandy-conglomeratic deposits flank the volcanic hills (about 2 m^3/s).

The pumping test data were correlated with the equipotential surface of the unconfined basal aquifer to define diverse transmissivity zones. The resulting wide range of transmissivity values obtained (between 10^{-6} and 10^{-2} m^2/s) are in agreement with the heterogeneity of the volcanic products and with the variability of the saturated thickness.

An average annual evaluation of groundwater resources points to a volume between 162 and 227 × 10^6 m^3/year. Taking the area of the volcanic system into account, the mean yield of the aquifer amounts to between 5.7 and 8.0 l/s per km^2, consistent with other Tyrrhenian volcanic areas. The analysis of the historical hydro-meteorological data set indicates that precipitation follows a negative trend, i.e. there is a progressive decline of groundwater resources.

In this hydrogeological environment, Lake Vico is closely conditioned by the groundwater, being fed by the basal aquifer on its northern side (about 6% of the total inflow) and drained from the other sides (between 26 and 37% of the total outflow). According to the mean water budget of the lake, in addition to the amounts of water taken from the lake, the surface-groundwater exchange has a considerable effect on the reservoir resources. These factors can influence heavily the level of the lake, artificially regulated by a gated outlet which is not always managed according to a rational strategy of conjunctive use of water resources.

Key words: *Hydrogeology of volcanics, Roman magmatic province, groundwater-lake interaction, Cimini Mountains, Lake Vico.*

RIASSUNTO

Lineamenti idrogeologici dell'area vulcanica Cimino-Vicana e rapporti tra acque sotterranee e Lago di Vico.

L'area di indagine coincide con i complessi vulcanici cimino e vicano e misura circa 900 km^2 (fig. 1). I prodotti dell'attività vulcanica pleistocenica danno luogo ad un acquifero complesso per la varietà delle rocce presenti e le vicissitudini vulcano-tettoniche della regione (Ambrosi *et alii*, 1984; Boni *et alii*, 1986; Capelli *et alii*, 2005). Da questo acquifero traggono alimentazione numerose opere di captazione adibite ad uso potabile ed irriguo; l'area, inoltre, è caratterizzata da importanti valenze ambientali, tra le quali spicca il bacino del Lago di Vico, riserva naturale e nello stesso tempo fonte di approvvigionamento idrico locale.

Nell'ambito del presente lavoro, nell'area sono state condotte nuove indagini idrogeologiche comprendenti (fig. 3): la caratterizzazione idrogeologica dei litotipi affioranti (fig. 2); il censimento dei principali punti d'acqua dell'area (circa 700 pozzi e 41 sorgenti); misure piezometriche su un significativo numero di pozzi (90 punti d'acqua); misure della portata dei torrenti in periodo non influenzato dalle precipitazioni (25 sezioni d'alveo); elaborazione ed esecuzione di prove di pompaggio (circa 300 determinazioni della portata specifica e 19 della trasmissività); elaborazione dei dati meteo-climatici (esame delle serie storiche 1951-1999 di 27 stazioni del S.I.M.N.).

Le indagini condotte, inquadrate nell'ambito del contesto geologico di riferimento (Locardi, 1965; Bertini *et alii*, 1971a; 1971b; Baldi *et alii*, 1974; Borghetti *et alii*, 1981; La Torre *et alii*, 1981; Sollevanti, 1983; Bertagnini & Sbrana, 1986), hanno permesso di delineare lo schema idrogeologico del sistema, stimare l'entità delle risorse idriche sotterranee ed esaminare i rapporti idrogeologici tra acque sotterranee e Lago di Vico.

È risultato che i complessi vulcanici cimino e vicano costituiscono un sistema avente una propria individualità idrogeologica, riconducibile a motivi stratigrafici, vulcano-tettonici e morfologici. Il sistema, costituito da rocce permeabili per porosità e fessurazione, contiene un esteso acquifero di base, spesso da alcuni metri a molte decine di metri, e più falde sospese di limitata continuità e spessore. La falda di base ha un deflusso radiale centrifugo (fig. 9) con recapiti principali verso i torrenti, soprattutto a sud-est, ad ovest e a nord, e travasi verso gli acquiferi adiacenti, soprattutto nel settore orientale verso i depositi alluvionali del fiume Tevere, dove peraltro si hanno le quote piezometriche più basse dell'acquifero vulcanico. La zonazione della trasmissività delle vulcaniti (fig. 11) evidenzia aree caratterizzate da valori compresi in un ampio intervallo (da 10^{-6} a 10^{-2} m^2/s), indice della notevole eterogeneità del mezzo, determinata dal complicato assetto giaciturale dei diversi prodotti emessi, dal diverso grado di fratturazione e dall'assetto vulcano-tettonico.

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Una prima stima della produzione media complessiva di acque sotterranee del sistema idrogeologico ha evidenziato una portata complessiva compresa tra 5 e 7 m^3/s, equivalente ad un rendimento medio in acque sotterranee del sistema compreso tra 6 e 8 l/s per km^2 (tab. 3), valori questi ultimi coerenti con le stime di altre aree vulcaniche della fascia tirrenica (Celico, 1983; Boni *et alii*, 1986; Piscopo *et alii*, 2000; Capelli *et alii*, 2005). Le uscite di acque sotterranee dal sistema sono rappresentate principalmente da incrementi di portata in alveo, da travasi idrici sotterranei verso acquiferi limitrofi, da efflussi dalle sorgenti e da prelievi mediante pozzi, questi principalmente al servizio del fabbisogno irriguo e potabile. La precisione di questa stima soffre, come le altre valutazioni relative allo stesso ambiente idrogeologico, delle gravi carenze di dati di base precisi e continui nel tempo.

Nel quadro idrogeologico generale, il Lago di Vico rappresenta l'affioramento alto della falda di base dell'acquifero vulcanico (figg. 9 e 10). La piezometria mostra che il lago è alimentato a nord dalla porzione di acquifero a bassa trasmissività, corrispondente con l'alto morfologico dei Monti Cimini; ad ovest, a sud e, specialmente, ad est del Lago di Vico, è quest'ultimo che alimenta la falda, e ciò ha una non trascurabile influenza sul bilancio medio annuo del corpo idrico. Infatti dalla valutazione effettuata risulta che, oltre all'evaporazione corrispondente all'incirca al 50% delle perdite totali del lago, il flusso sotterraneo dal lago verso la falda incide tra il 26 ed il 37% sulle perdite totali. Appare invece modesto, sulle entrate generali del lago, l'apporto di acque sotterranee provenienti da zone esterne al bacino imbrifero (circa il 6% delle entrate totali) rispetto alle precipitazioni dirette sullo specchio lacustre ed agli apporti provenienti dal bacino calderico. Dalla valutazione scaturisce anche che il livello del lago risente in maniera assolutamente rilevante delle modalità di regolazione dell'efflusso dall'emissario, non sempre riconducibili a quelle di un razionale uso congiunto delle risorse idriche, come richiederebbero i problemi ambientali del lago stesso.

L'indagine condotta non ha evidenziato alterazioni gravi degli equilibri idrogeologici alla scala dell'intero sistema (circa 900 km^2), ma è necessaria una razionalizzazione degli attuali schemi dei prelievi idrici ed una particolare cautela nell'aumentare i prelievi dal Lago di Vico, anche in considerazione della tendenza alla diminuizione della piovosità media annua, da ricondursi al più generale problema delle variazioni climatiche (Dragoni, 1998; Milly *et alii*, 2005). Tale razionalizzazione non può che scaturire da un approfondito monitoraggio delle principali grandezze idrogeologiche. In particolare, senza un sistema di misura continuo delle portate dei principali torrenti e dei prelievi idrici dall'acquifero e dalle acque superficiali, non sarà mai possibile redigere piani di gestione adeguati alle attuali possibilità di analisi ed ai problemi presenti.

Termini chiave: *Idrogeologia delle rocce vulcaniche, Provincia magmatica romana, interazione lago-acque sotterranee, Monti Cimini, Lago di Vico.*

INTRODUCTION

The area investigated comprises the Cimino and Vico volcanic complexes (fig. 1) and covers a surface area of some 900 km^2. The products of the volcanic activity, which have involved the Tyrrhenian side of the Peninsula since the Pleistocene, have given rise to a complex aquifer controlled by the variety of rocks present and by the volcano-tectonic characteristics of the region. The groundwater supplies several water systems used for drinking water (about 130,000 inhabitants are served by them) and irrigation (for a total irrigated area of some 180 km^2). The area is also characterized by environmental diversities, among which the natural reserve of the Vico Lake catchment, used also as a source of the local water supply, stands out.

The amount of literature on the geological, volcanological and petrographic characteristics of the study area is considerable (e.g. Locardi, 1965; Mattias & Ventriglia, 1970; Bertini *et alii*, 1971a; 1971b; Baldi *et alii*, 1974; Ambrosetti *et alii*, 1978; Borghetti *et alii*, 1981; La Torre *et alii*, 1981; Sollevanti, 1983; Bertagnini & Sbrana, 1986; Lardini & Nappi, 1987; De Rita, 1993; Chiocchini & Madonna, 2003). The available hydrogeological information is, however, not so detailed and is provided by regional-scale investigations (Ambrosi *et alii*, 1984; Boni *et alii*, 1986; Capelli *et alii*, 1999), comprising the definitions of hydrogeological patterns on scales of 1:200,000 and 1:500,000, and the overall evaluation of the potential yield of all the volcanic hydrological structures of the Upper Lazio Region, or the analysis of individual surface basins (Capelli *et alii*, 2003). The number of investigations of single hydrostructures, useful for implementing numerical simulations of groundwater flow and for the evaluation of water budgets, is limited.

This study fits into the latter context, having as its objectives the reconstruction of the hydrogeological layout of the Cimino-Vico area and a first estimate of the water resources of the volcanic aquifer. It is also intended as a first step towards the correct understanding of the relationship between groundwater and Lake Vico.

A large monograph on the volcanic aquifers of the Lazio Region (Capelli *et alii*, 2005) was published while this paper was being revised and its results were taken into consideration here.

GEOLOGICAL OUTLINE

The characteristic morphologies of the Cimino-Vico region include the depression which harbours Lake Vico and the domes of the Cimini Mountains, both generated by volcanic activity during the Pleistocene. Although they are situated in the same volcanic region (fig. 1), the Cimino and Vico complexes belong to separate magmatic series. The former includes the acidic rhyolitic and rhyodacitic volcanoes of the Cimini Mountains, the Tolfa Mountains and the Ceriti Mountains; the latter includes the Vulsini Mountains, Vico and the Sabatini and Alban Hills and exhibit an alkaline-potassic petrography.

The Cimini complex was active between 1.35 and 0.8 My ago, an interval during which magmatic upwelling along regional fractures, oriented predominantly in a NW-SE direction, resulted in the formation of over 50 domes and stagnation cupolas of acidic composition, from rhyolitic to trachydacitic. The result of this activity was the emplacement of a vast ignimbritic plateau (quartzolatitic ignimbrite) and the subsequent emission of latitic and olivine latitic lavas (Lardini & Nappi, 1987).

The Vico complex is situated immediately to the south of the Cimini volcanic complex and consists of a strato-volcano with a collapsed central caldera in the northern sector of which there later developed the secondary cone of Mount Venere (838 m asl). The start of the volcanic activity of Vico coincided with the end of Cimini, between 0.8 and 0.09 My, giving rise to products that covered over much of those of Cimini. They include air-fall pyroclastics with compositions varying from latitic to trachylatitic, separated by paleosols and emissions of lava flows, lavas ranging from trachytic to tephrytic-phonolitic, several ignimbritic formations of trachytic, tephrytic and phonolitic composition constituting the most widespread and thick products and pyroclastic products associated with phreatomagmatic activity (Locardi, 1965).

The volcanic and volcanoclastic strata are covered locally by mainly Holocene continental sediments consisting of fairly thin layers of alluvial sandy-silty deposits, as well as travertine deposits to the west of Viterbo and to the east, close to the Tiber valley.

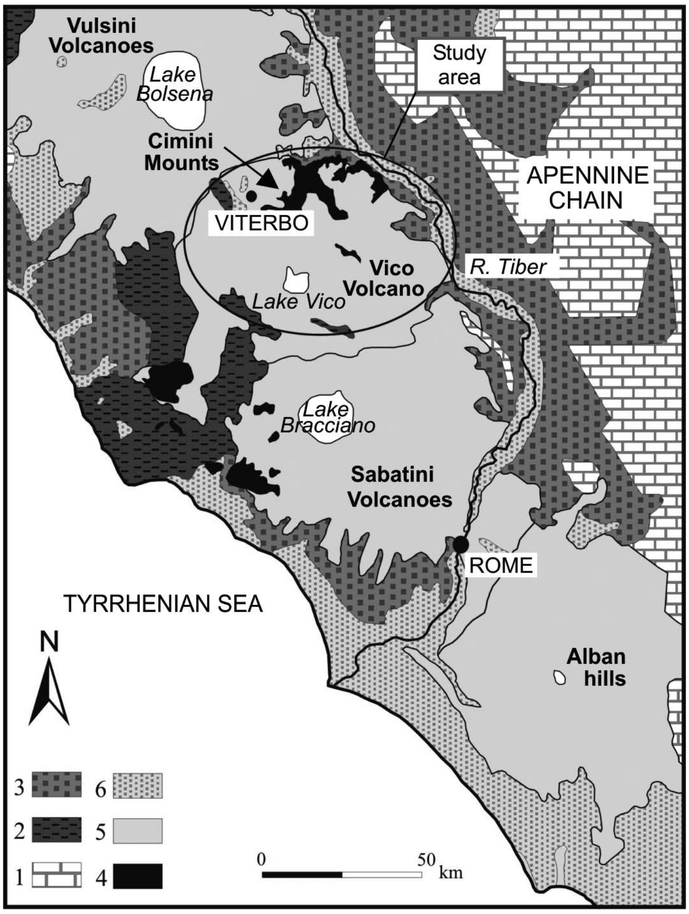

Fig. 1 - Location of the study area. 1) Mesozoic-Paleogene sedimentary rocks (mainly carbonate); 2) allochthonous complexes (Upper Cretaceous-Oligocene); 3) Pliocene-Pleistocene marine sediments; 4) acidic volcanics (Pliocene-Pleistocene); 5) alkaline-potassic volcanics (Pleistocene-Holocene); 6) travertine, alluvial and coastal sediments (Pleistocene-Recent).
– Inquadramento dell'area di studio. 1) Rocce sedimentarie mesozoiche-paleogeniche prevalentemente carbonatiche; 2) complessi alloctoni (Cretaceo Sup.-Oligocene); 3) sedimenti marini plio-pleistocenici; 4) vulcaniti acide (Plio-Pleistocene); 5) vulcaniti alcalino-potassiche (Pleistocene-Olocene); 6) depositi di travertini, alluvionali e costieri (Pleistocene-Attuale).

The basement of the volcanics is sedimentary rock, consisting mainly of the *basal carbonate succession* (not outcropping in the study area) of the Meso-Cenozoic formations of the Tuscan and Umbrian facies, of the *allochthonous complex (Ligurian Unit)* of marls, argillites, marly limestones, calcarenites and sandstones ranging in age from the Upper Cretaceous to the Oligocene, and of the *neoautochthonous cycle* made up in the study area of Plio-Pleistocene sandy, clayey, gravely and conglomeratic marine deposits (BALDI *et alii*, 1974).

From a structural point of view, the study area is subject primarily to Plio-Pleistocene extensional tectonics and to volcano-tectonic effects resulting initially from the upwelling of anatectic magmas and, subsequently, from the emplacement of the Vico volcanics. The main consequences in hydrogeological terms are the considerable structuring of the basement of the volcanics and the presence of fractures and faults mainly in the NW-SE, NE-SW, N-S and E-W directions (BORGHETTI *et alii*, 1981; LA TORRE *et alii*, 1981).

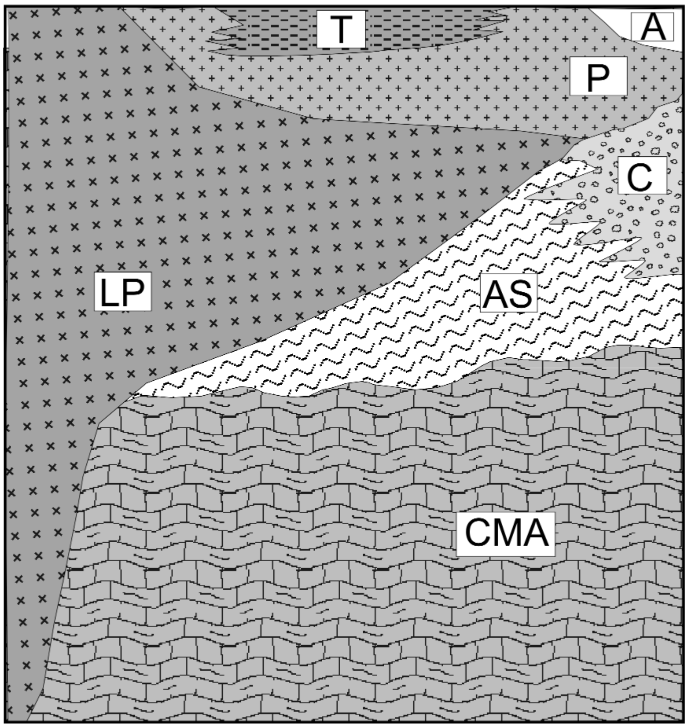

Fig. 2 - Stratigraphic scheme. A = alluvial complex; T = travertine complex; P = pyroclastic complex; LP = lava and pyroclastic complex; C = sandy-conglomeratic complex; AS = sandy-clayey complex; CMA = clayey-marly-calcareous complex.
– Rapporti stratigrafici tra i complessi idrogeologici. A = complesso alluvionale; T = complesso dei travertini; P = complesso piroclastico; LP = complesso lavico-piroclastico; C = complesso sabbioso-conglomeratico; AS = complesso argilloso-sabbioso; CMA = complesso calcareo-marnoso-argilloso.

HYDROGEOLOGICAL COMPLEXES

In order to characterise the rocks outcropping in the Cimino-Vico area from a hydrogeological point of view, they were grouped together into hydrogeological complexes on the basis of the type and relative degree of permeability of the different rocks, the stratigraphic relationships among the complexes (fig. 2) and the structural layout of the area.

Allochthonous flysch units were included in the *clayey-marly-calcareous complex* represented in the area by marls, argillites, marly limestones and calcarenites belonging to the Upper Cretaceous-Oligocene. Considering the frequent occurrence of clayey and marly lithotypes, the complex is characterised by an overall low relative permeability due to primary and secondary porosity. The thickness of the complex is difficult to determine and could well be more than a few hundred metres.

The *sandy-clayey complex* includes the Plio-Pleistocene clayey sands of the neoautochthonous cycle. The predominantly clayey matrix reduces considerably the permeability of the whole complex, so much so that this complex is part of the aquiclude defining the volcanic aquifer. It is quite thick, even reaching several hundred of metres. Together, these two complexes define the lower and peripheral limits of the volcanic aquifer in the north-eastern, north-western and south-western sectors (see figs. 2 and 9).

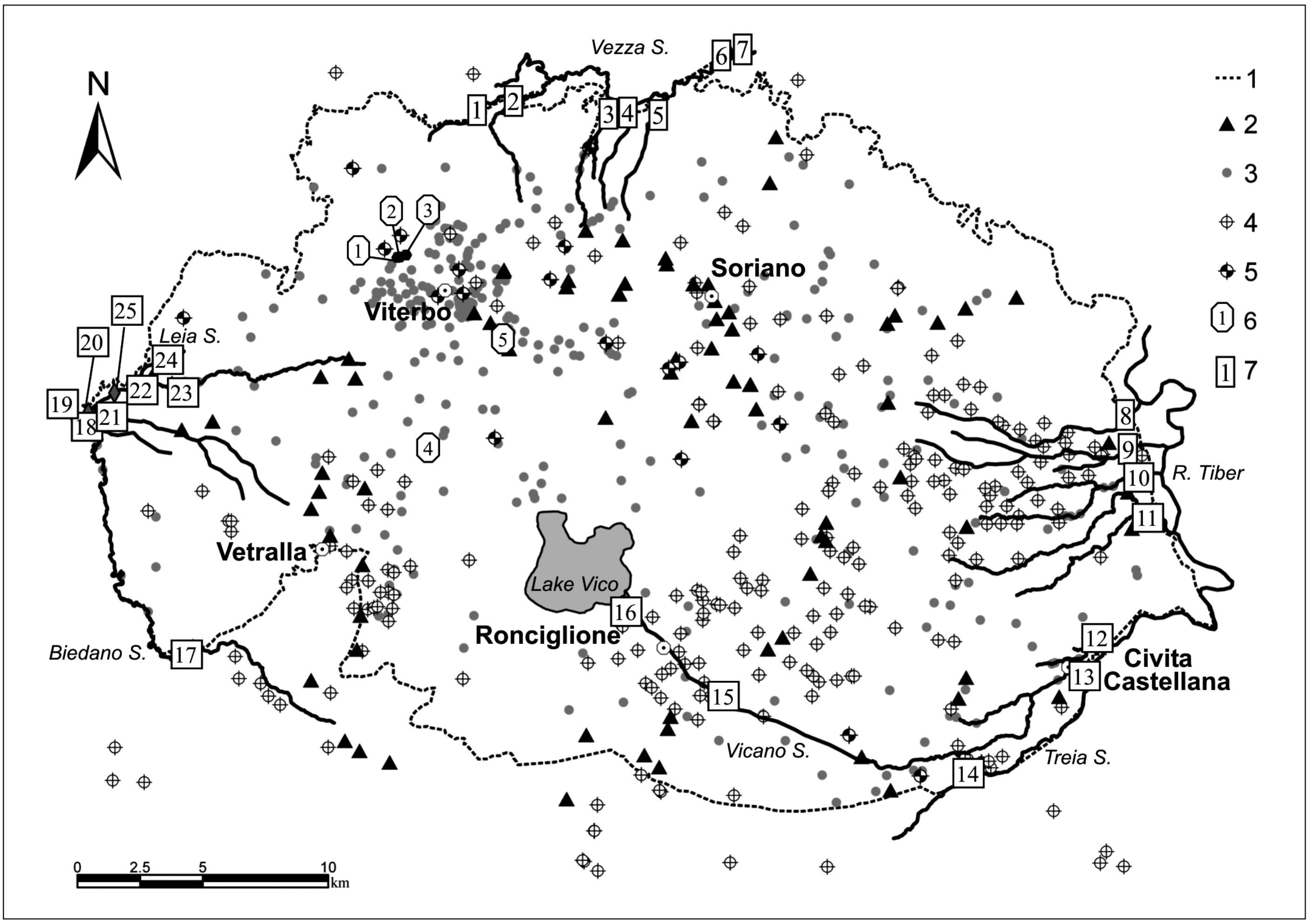

Fig. 3 - Hydrogeological investigations and location. 1) Boundaries of the studied aquifer; 2) investigated springs; 3) investigated wells; 4) specific capacity values; 5) transmissivity values; 6) wells with level fluctuation data (cf. fig. 5); 7) stream flow measurements.
– Distribuzione e tipo di indagini idrogeologiche. 1) Limiti dell'acquifero studiato; 2) sorgenti censite; 3) pozzi censiti; 4) pozzi con determinazione della portata specifica; 5) pozzi con determinazione della trasmissività; 6) pozzi con misura dell'escursione piezometrica (cfr. fig. 5); 7) sezioni di misura della portata dei torrenti.

The *sandy-conglomeratic complex* outcrops primarily on the eastern edge of the area under consideration and is made up of loose or poorly consolidated Pleistocene sand, gravel and conglomerates of the neoautochthonous cycle. Its thickness varies a great deal: limited in the north-east, it becomes considerable towards the south-east (see figs. 2 and 9). Taking the grain size of the deposits, the degree of consolidation of the units and the reduced clayey fraction into consideration, the permeability of this complex can be classed as relatively high, due mainly to its primary porosity.

The *lava and pyroclastic complex* occupies primarily the central part of the study area (approximately 140 km^2). It includes all the Cimini and Vico lavas and Cimini's quartzolatitic ignimbrite, which lithotypes are permeable primarily as result of fissuring, interfingered with other horizons permeable through primary porosity. The degree of fissuring encountered both in the outcrops and in soundings is very variable. It is higher where the complex is affected by faults and, in general, lower in proximity of the central parts of the domes. Generally speaking, this complex is characterised by medium to high relative permeability due mainly to secondary porosity.

The *pyroclastic complex* is responsible for the most extensive outcrop (over 700 km^2). Major components include both the Cimini and Vico pyroclastic formations, sharing a mixed type of permeability due to primary and secondary porosity. The higher matrix porosity distinguishes these rock types from those included in the lava and pyroclastic complex. Furthermore, the different ages and nature of the products, the facies variations and the presence of pumice layers, including a well-developed network of fissured and scoriaceous horizons, in lithic terms, enable the relative permeability of this complex to be classed as variable from high to medium. This complex, together with the lava and pyroclastic complex described above, constitutes the main reservoir rock in the area, heavily influencing the rate of infiltration.

The *travertine complex* outcrops in limited areas to the north and north-west of Viterbo and in the eastern part of the study area. It includes all the travertine formations in the age range from the Pleistocene to the Holocene. Its permeability is due to primary and secondary porosity and varies from medium to low, depending on age.

In the study area, the *alluvial complex* outcrops in small thin patches. It includes Holocene detrital and alluvial deposits characterized by very heterogeneous grain size and its permeability, for the purpose of this study, can therefore be classed as medium to low due to primary porosity.

HYDROGEOLOGICAL INVESTIGATIONS

Our hydrogeological investigations included the acquisition and re-interpretation of all available data relating to the area in question, as well as new measurements and specific surveys. Fig. 3 summarises the distribution and types of investigation undertaken.

A census was carried out of the main water sources of the area (wells and springs), and appropriate measurements were undertaken at these sites.

The data concerning the wells were obtained from public bodies (mainly APAT, ATO 1 for Lazio Region, the Province of Viterbo and the various municipalities) and private organisations operating locally, as well as through direct measurements. Information was obtained on some 700 wells, varying in depth from a few metres to several hundred metres, with maximum yields around a few tens of litres per second (fig. 4). The information acquired, carefully screened in terms of quality, was then processed, enabling detailed listings of technical drilling data, local stratigraphy and hydrostratigraphy, elevations and locations, static piezometric levels (referred to measurements carried out between 1970 and 2000), discharge rates and, in some cases, the specific capacities of the wells and/or the aquifer's transmissivity.

Specifically, groundwater level measurements were carried out between 2001 and 2003 on about 90 private wells.

Using the piezometric data measured and acquired from a total of 220 wells, limited to the period between 1999 and 2003, it was possible to reconstruct the aquifer's overall potentiometric surface. In order to take the fact that the piezometric data did not always refer to the same period into account, the variation in the water level occurring in some of the wells over the period in question were considered. As shown in fig. 5, the variations in level are limited to a few metres, so that it can be assumed that the maximum uncertainty of the piezometric contour lines drawn is also limited to a few metres. It therefore has no great effect on the resulting potentiometric surface considering the scale of the maps (1:100,000) and the contour level separation used (50 m).

In principle, a piezometric map ought to be drafted using data referred to the shortest possible period of time, no more than a few weeks, together with control measurements to take any variation into account. Unfortunately, the lack of a suitable monitoring network made it impossible to work according to a theoretically correct methodology. To determine the extent to which the chosen time interval influenced the potentiometric surface, a comparison was made between the morphology resulting from the 1999 groundwater levels and those for the period 2000-2003, for those areas where measurements were sufficiently concentrated. The results showed that the differences between the two reconstructions were minor, and that gradients and flow lines were fairly similar, on the whole. This suggests that the overall potentiometric surface reported here (see fig. 9) is an acceptable representation of groundwater flow at the scale chosen. From another point of view, it is clear that in a system such as that considered here, with a radial groundwater flow (see fig. 9), the greatest variations in groundwater levels will occur in the central part of the system, coinciding roughly with Lake Vico, which, as demonstrated later, is an outcrop of the basal water-table. The water level of the lake dropped by less than a metre between 1999 and 2003 (fig. 5), indicating the considerable stability of the potentiometric surface during that period.

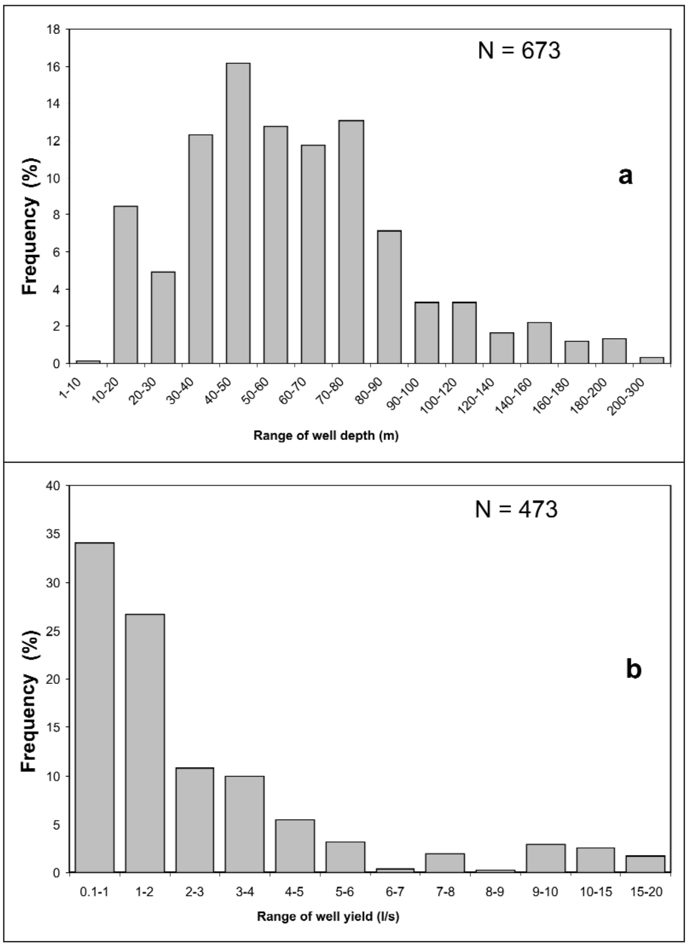

Fig. 4 - Frequency distribution of depth (*a*) and yield (*b*) of the wells. – *Distribuzione di frequenza della profondità* (a) *e della portata di esercizio dei pozzi* (b).

Information on springs was obtained from published and unpublished data and by direct measurements. The graphs on fig. 6 summarise the information concerning elevations and discharge rates of the springs investigated. Relatively complete data is available for only 6 of the 41 springs studied, even though there are a number of other smaller springs (discharge generally less than 1 l/s) in the area. The discharge data obtained for those springs that were examined in detail referred to 1956 onwards, supplemented by data referred to 2002, including the elevation, the type of spring and, when possible, the discharge variation indices (Meinzer's index). Springs controlled primarily by a contrast of relative permeability among the volcanic deposits and by the intersection between the water table and the ground surface were found. Meinzer indices between 33 and 100% were found.

The hydrographic network of the area was examined so as to reconstruct the relationships between surface

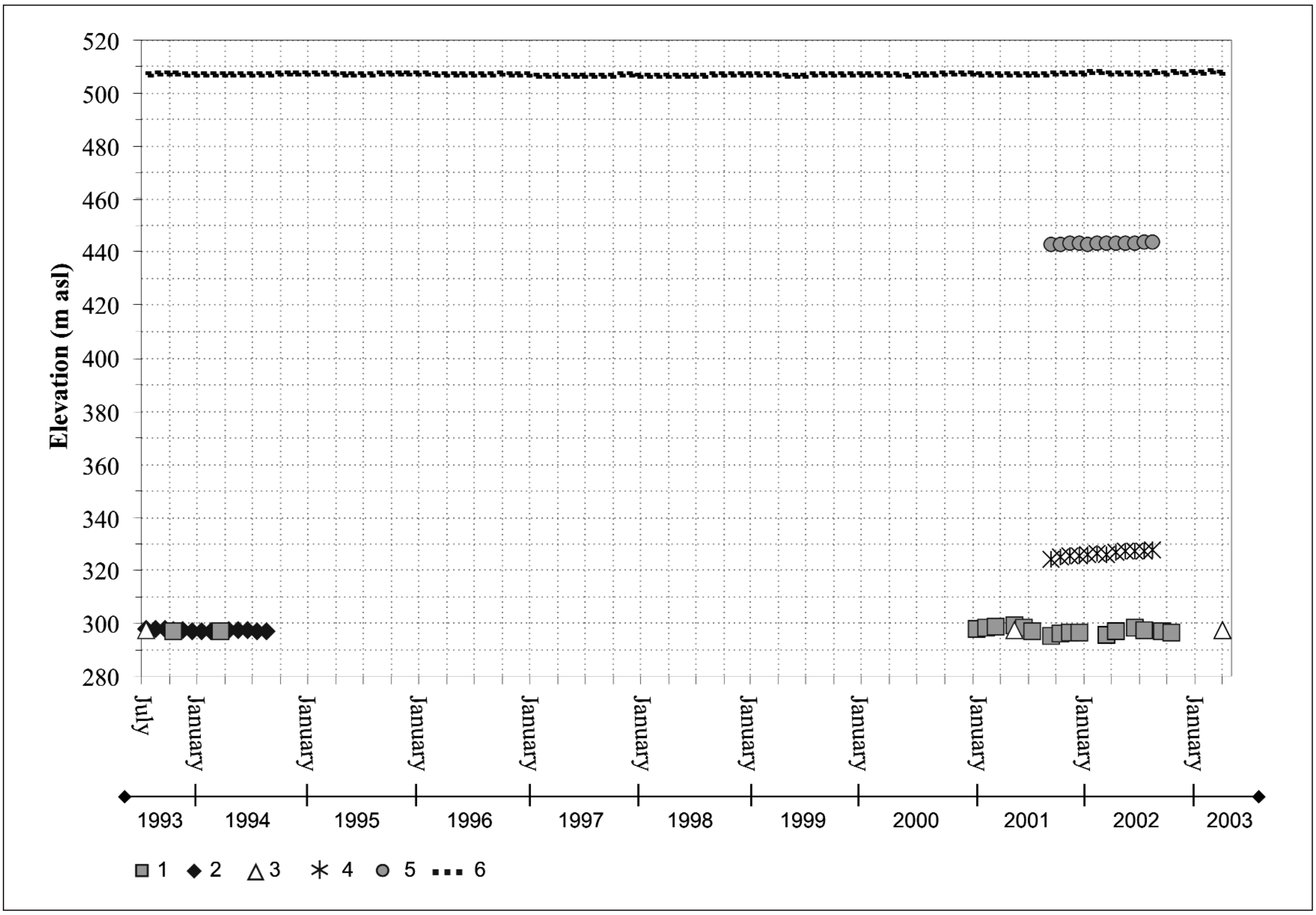

Fig. 5 - Level fluctuation of some wells and of Lake Vico (1993-2003): 1-5 wells, 6 lake.
– *Escursioni piezometriche in alcuni pozzi e variazioni del livello idrico del Lago di Vico (1993-2003): 1-5 pozzi, 6 lago.*

water and groundwater. To this end, flow rate measurements reported in the literature were used, in addition to base flow measurements carried out in summer-dry periods, presumably not influenced by the surface flow produced by 2003-2004 rainfalls. Measurements were carried out on 25 stream bed segments (fig. 3) chosen taking the boundaries of the study area, the waste water discharges into the streams, the water returned from springs, and any tapping works involving surface and ground waters into consideration. Tab. 1 summarises the discharge increments measured in the control streams in July 2003, excluding the contributions of the flows from previously estimated springs.

Overall, 300 pumping tests were considered. These were not evenly distributed throughout the area (fig. 3) and were performed using different methods. Some of them were performed directly, others refer to the processing of unpublished data. For the majority of these tests, the calculations were limited to the specific capacities of the wells (fig. 7), however 19 of the tests acquired and/or performed were found to be significant for determining of the transmissivity of the aquifer, calculated using the Cooper-Jacob's semilog method. The relationship obtained correlating the specific capacity and the transmissivity values, based on these latter tests, is shown in fig. 8. This correlation, similar to those reported in the literature (e.g. RAZACK & HUNTLEY, 1991; CIVITA, 2005), together with the numerous available specific capacity data, were used to draft a first zonation of the volcanic aquifer.

TABELLA 1

Increments of stream flow (summer 2003).
– *Valori degli incrementi di portata in alveo (estate 2003).*

Slope	Streams	N. of measured sections (fig. 3)	Increments of stream flow (m^3/s)
Northern	Right-tributaries of Vezza	*1-2-3-4-5-6-7*	0.206
Eastern	Rustica, Fratta, Salerco	*8-9-10-11*	0.299
South-eastern	Maggiore, Filetto, Vicano, Castello	*12-13-14-15 -16*	0.467
Western	Biedano, Rigomero, left-tributaries of Leia	*17-18-19-20-21-22-23-24-25*	0.480
Total			**1.452**

HYDROGEOLOGICAL LAYOUT

The data acquired were processed and, together with the results of the investigations undertaken, interpreted in the light of the hydrogeological characteristics of the outcropping lithotypes, enabled the overall hydrogeological layout of the volcanic aquifer to be defined. In the first place, the boundaries of the hydrogeological system were defined, in relation to the objectives, to the data and to the available estimates (fig. 9). A first type of boundary corresponds to the outcropping of complexes with relatively low permeability, such as the sandy-clayey complex on the north-eastern edge of the volcanic aquifer and the clayey-marly-calcareous complex on the north-western, western and south-western edges. These limits have been assumed as no-flow boundary, having a relatively negligible flow, considering the difference in relative permeability between the above hydrogeological complexes and the lava and pyroclastic and pyroclastic ones.

Another type of boundary corresponds to the terminal segments of those streams that cut through the volcanic relief, where they appear to drain the basal water-table, as observed from the increases in stream flow encountered both during previous surveys (AMBROSI *et alii*, 1984; BONI *et alii*, 1986; CAPELLI *et alii*, 2005) and during our own measurements.

A third boundary type coincides with the sandy-conglomeratic complex which closes the volcanic aquifer to the south-east. This boundary, being highly permeable, enables the volcanic aquifer to flow towards the aquifer of the Tiber alluvial plain, along a belt where the lowest elevations of the whole perimeter of the hydrogeological system are encountered.

The system is limited to the north-west by the piezometric mound of the basal water-table, located next to the outcrops of the thermal springs of Viterbo (fig. 9). Proceeding to the south-west from this area the rise of the weakly permeable clayey-marly-calcareous substrate is encountered, at first in the Monte Razzano area and then next to a more restricted outcrop which occurs at the confluence of the right and left tributaries of the Leia Stream. The local structural situation seems to indicate the existence of a groundwater divide in this area, whereas the more northerly piezometric mound of the volcanic aquifer can be interpreted basically as being due to the deep groundwater rise which feeds partly the thermal springs of Viterbo and partly the system investigated in this study (PISCOPO *et alii*, 2005).

The overall area defined as above is pseudo-elliptical in shape, covers approximately 900 km^2 and coincides basically with the Cimini and Vico volcanic complexes (fig. 9). The base of the volcanic aquifer is limited by the sandy-clayey complex on its eastern edge and by the clayey-marly-calcareous complex on its western side (fig. 10).

The complex morphology of the low permeability basement results in the variable thickness of the volcanic aquifer (from a few metres to several hundred). It is thicker in its central part in coinciding with the lake and becomes progressively thinner towards the edges. This system includes mainly the lava and pyroclastic and pyroclastic complexes. It should be stressed that when these volcanic complexes are considerably thicker, their permeability decreases gradually with their depth, due to the closure of fissures and a reduction of the primary porosity of the volcanic and volcanoclastic rocks.

Using the piezometric and spring data, it was possible to recognise a continuous basal aquifer as well as several perched aquifers of limited, discontinuous extent.

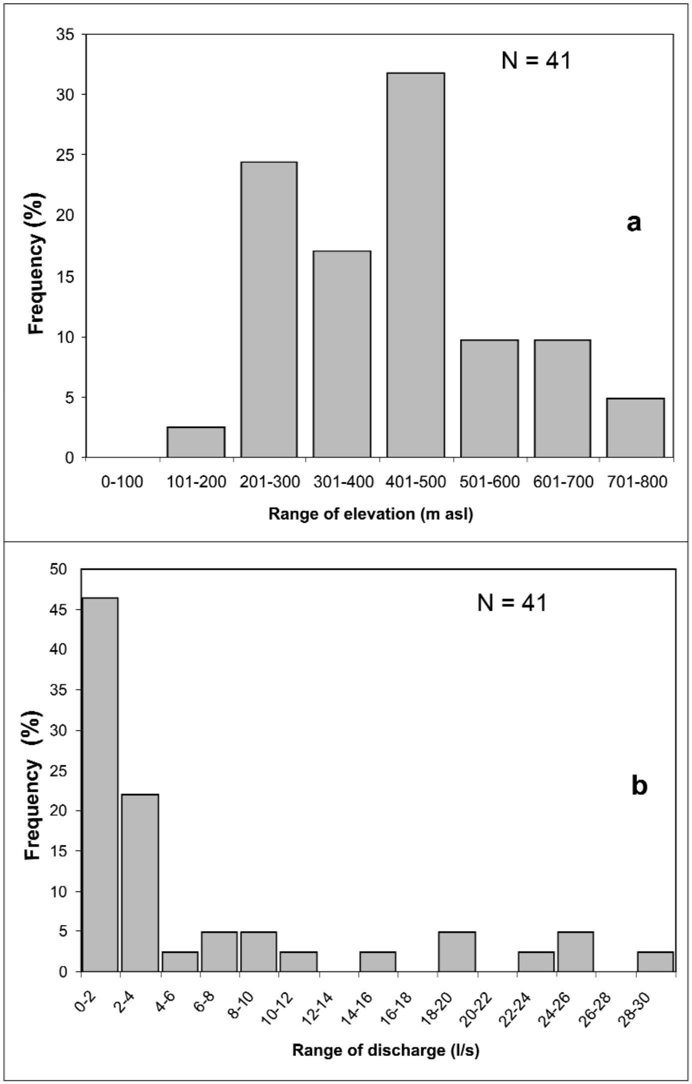

Fig. 6 - Frequency distribution of elevation (*a*) and discharge (*b*) of the springs.
– *Distribuzione di frequenza della quota* (a) *e della portata* (b) *delle sorgenti.*

For the basal aquifer, a radial, divergent flow, controlled by the boundaries of the sandy-clayey complex along the north-eastern margin, and by the clayey-marly-calcareous complex along the south-western and north-western margins could be recognised. The potentiometric surface follows the topography, especially in the central sector which includes the Cimini domes and the Lake Vico caldera, where the morphological high corresponds to the piezometric high (fig. 9). Furthermore, in this area, the effect of the lake on groundwater flow is quite evident. The surface of the lake can be correlated to that of the basal water-table, showing inflow from the aquifer towards the lake basin, in the northern sector, and the flow from the lake towards the aquifer along the eastern, western and southern edges.

The central part of the aquifer is surrounded by a belt with a high hydraulic gradient (from 4% to 7%), beyond which the directions of the flow are controlled mainly by the low-permeability boundaries, by the stream elevations and by the groundwater levels of the adjacent aquifers. Indeed, the directions of the flow are more or less parallel to the low-permeability boundaries. The main groundwater drainage axes run towards the streams and the alluvial

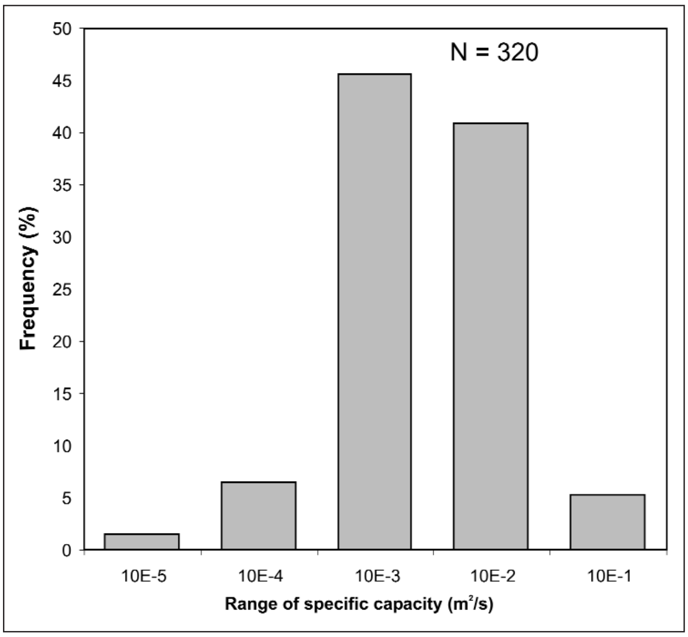

Fig. 7 - Frequency distribution of specific capacity of the wells.
– *Distribuzione di frequenza della portata specifica dei pozzi.*

deposits of the Tiber in the south-eastern sector of the system. The discharge areas of the aquifer are to be found along the water-gaining streams from the eastern, south-eastern, western and northern slopes (fig. 9) and towards the south-east where the sandy-conglomeratic complex enables groundwater to flow towards the alluvial aquifer of the Tiber.

The springs constitute additional groundwater discharge points. Most of those found are, however, discharge points from perched aquifers, considering the elevations of the springs, their limited flow rate (fig. 6) and their high Meinzer's indexes. The few springs that can be associated with the basal aquifer are located on the outer edges of the high gradient belt and are generally characterised by yields of not more than a few tens of litres per second.

In this context, the thermal springs of Viterbo are of special significance. Considering their chemical and physical characteristics, they cannot be due exclusively to the flow taking place in the volcanic aquifer (ARNONE, 1979; CHIOCCHINI *et alii*, 2001), but must instead be due also to groundwater circulation deeper than that studied here. Notwithstanding, based on a comparison of their emergence elevations, ranging from 230 to 319 m asl, with those of the aquifer in the area of the high morphological and piezometric levels of the Cimino-Vico structure, a common recharging area cannot be excluded (PISCOPO *et alii*, 2005).

It was possible to determine the flow characteristics within the aquifer primarily by comparing the potentiometric surface (fig. 9) with the transmissivity map drafted using the numerous specific capacity data for the wells (fig. 11). It was found that the central portion of the system, inclusive of the Cimini domes and the Vico Lake caldera, is characterised by the lowest transmissivity values (this parameter is in the order of magnitude between 10^{-6} and 10^{-4} m^2/s), in keeping with the high hydraulic gradients encountered. Towards the marginal zones to the W and SE, where the main discharge areas are situated, the aquifer transmissivity values are higher, with relatively gentle piezometric slopes. The highest transmissivity zone by far is that corresponding to the sandy-conglomeratic complex (up to 10^{-2} m^2/s), where the existence of substantial groundwater flows towards the alluvial aquifer of the Tiber valley could be inferred.

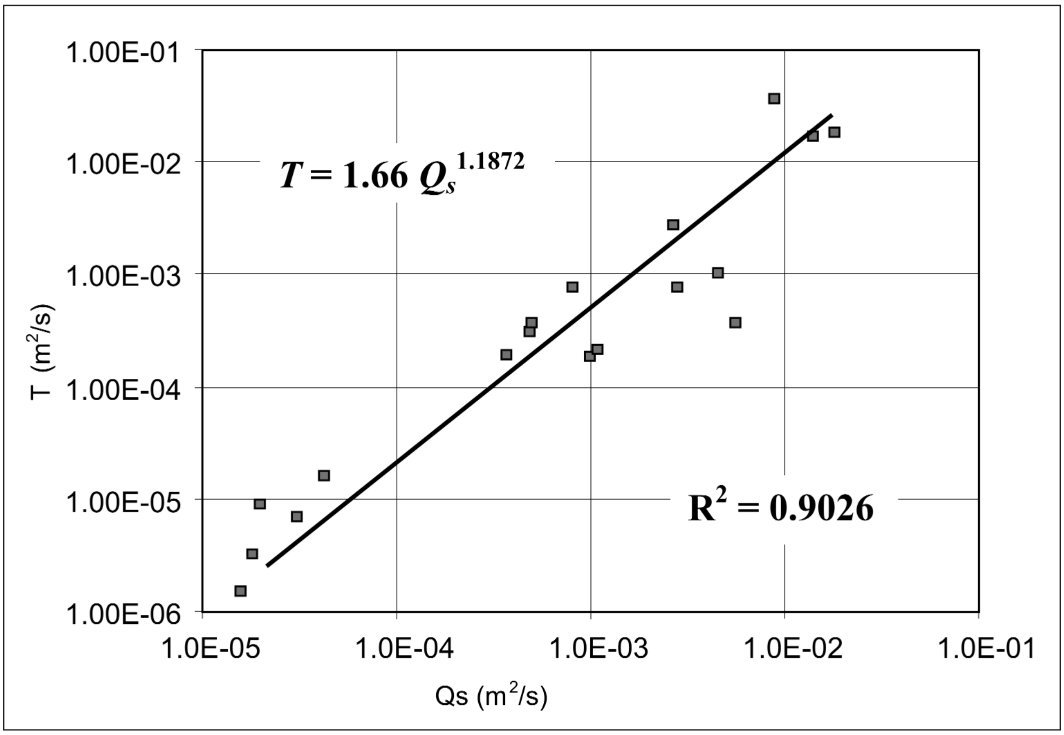

Fig. 8 - Plot of specific capacity (Q_s) vs transmissivity (T).
– *Relazione tra portata specifica (Q_s) e trasmissività (T).*

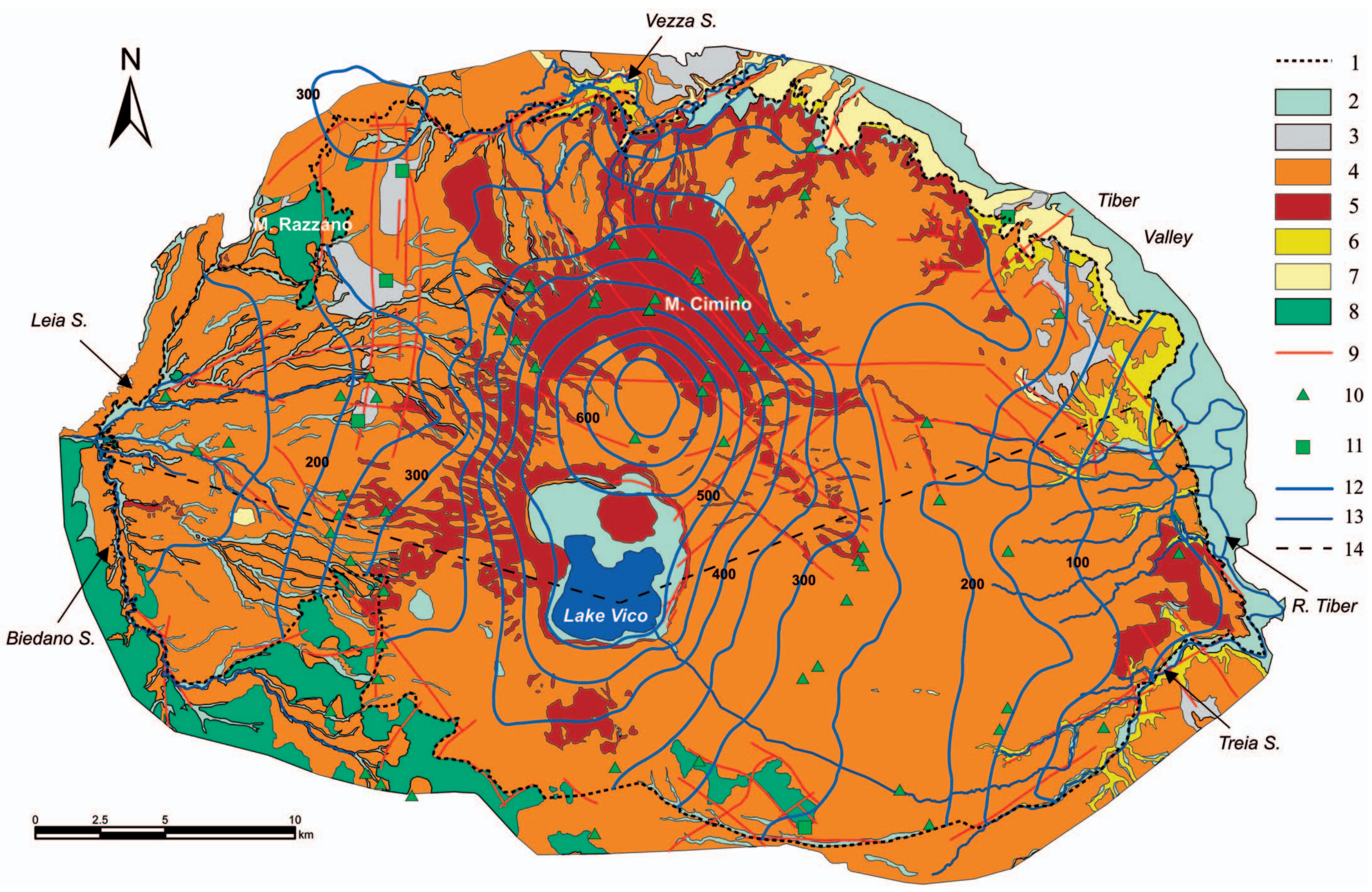

Fig. 9 - Simplified hydrogeological map. 1) Boundaries of study area; 2) alluvial complex; 3) travertine complex; 4) pyroclastic complex; 5) lava and pyroclastic complex; 6) sandy-conglomeratic complex; 7) sandy-clayey complex; 8) clayey-marly-calcareous complex; 9) faults and fractures; 10) springs (discharge > 5 l/s); 11) main mineral and thermal springs; 12) equipotential lines (m asl); 13) gaining streams; 14) trace of cross-section (cf. fig. 10).
– Carta idrogeologica schematica. 1) Limiti dell'area di studio; 2) complesso alluvionale; 3) complesso dei travertini; 4) complesso piroclastico; 5) complesso lavico-piroclastico; 6) complesso sabbioso-conglomeratico; 7) complesso argilloso-sabbioso; 8) complesso calcareo-marnoso-argilloso; 9) faglie e fratture; 10) sorgenti (portata > 5 l/s); 11) principali sorgenti minerali e termali; 12) curve isopiezometriche e relative quote in m s.l.m.; 13) torrenti drenanti; 14) traccia della sezione idrogeologica (cfr. fig. 10).

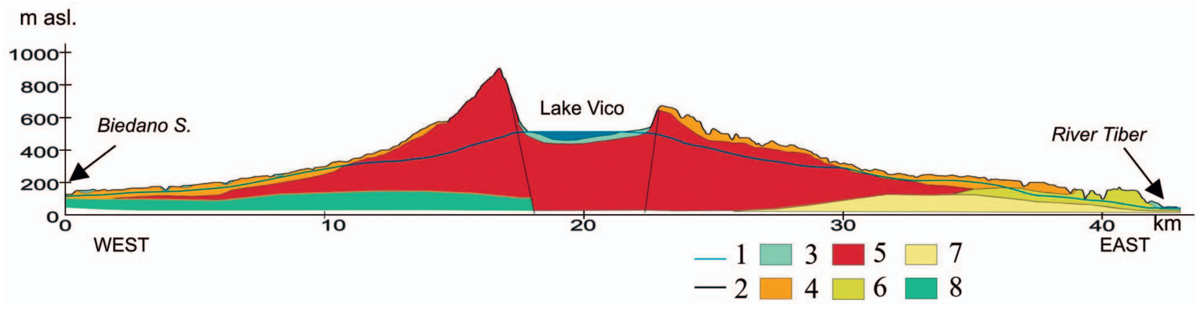

Fig. 10 - Simplified hydrogeological cross-section. 1) Groundwater level; 2) faults and fractures; 3) alluvial complex; 4) pyroclastic complex; 5) lava and pyroclastic complex; 6) sandy-conglomeratic complex; 7) sandy-clayey complex; 8) clayey-marly-calcareous complex.
– Sezione idrogeologica schematica. 1) Livello piezometrico; 2) faglie e fratture; 3) complesso alluvionale; 4) complesso piroclastico; 5) complesso lavico-piroclastico; 6) complesso sabbioso-conglomeratico; 7) complesso argilloso-sabbioso; 8) complesso calcareo-marnoso-argilloso.

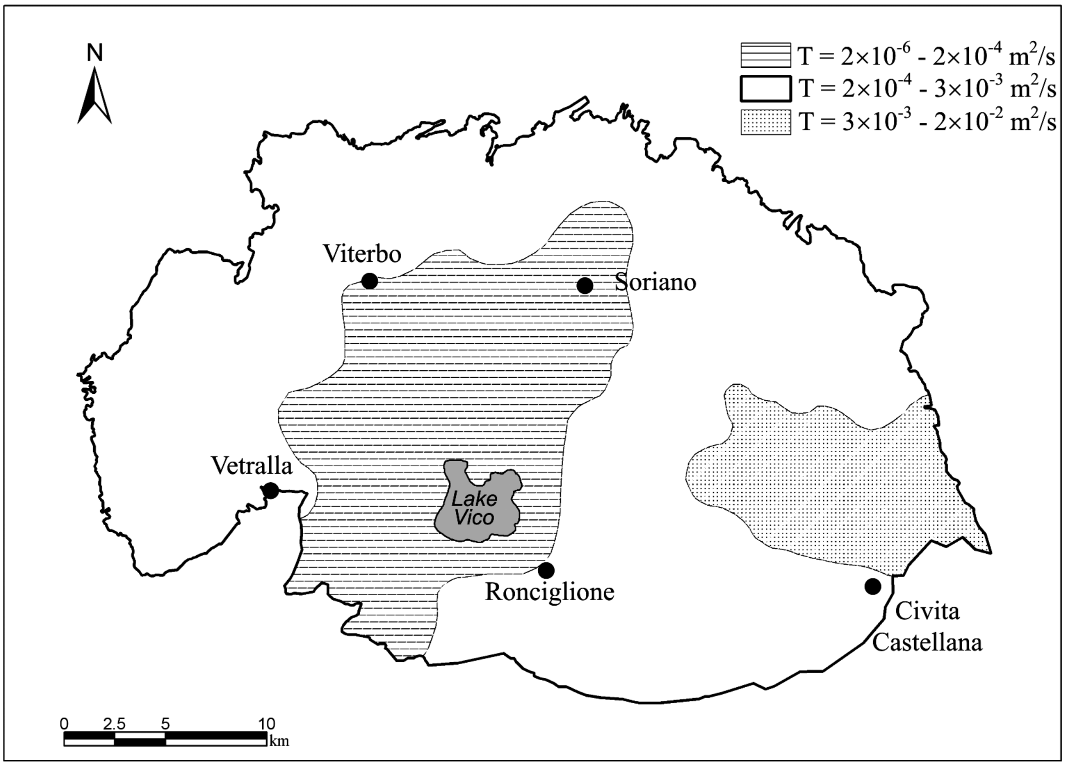

Fig. 11 - Zones of aquifer transmissivity *(T)*.
– *Zonazione della trasmissività dell'acquifero (T).*

In addition to this first general characterisation of the aquifer, the hydrogeological effect of discontinuities and of the volcanic domes had also to be considered. In the marginal western and south-eastern areas, characterised by higher transmissivity, there is also a relatively higher fracture and fault density, in addition to a reduced thickness of the aquifer. In contrast, in the other highly fractured zone, slightly to the north of Lake Vico, transmissivity was relatively low and there is a high concentration of springs. This could be interpreted as the result of considerable splitting of the groundwater circulation which, due to the low permeability, is obstructed centrally by the presence of domes, and is diverted marginally along fractures and faults. These conditions imply an extreme heterogeneity and anisotropy of the volcanic aquifer, with the possible formation of perched aquifers, as demonstrated by the presence of numerous springs with limited and/or temporary flows.

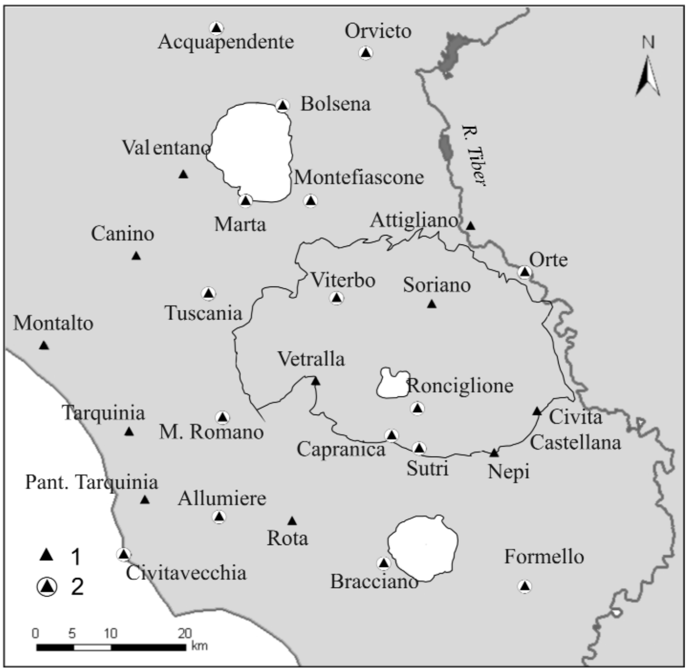

Fig. 12 - Location of meteorological stations. 1) Rain gages; 2) rain gages and thermometers.
– *Localizzazione delle stazioni meteorologiche. 1) Stazioni pluviometriche; 2) stazioni termo-pluviometriche.*

Other factors affecting groundwater circulation are the complex morphology of the basement to the volcanics. An example of this effect is noticeable in the north-western sector, where the geometry of the low-permeability basement along the axis which joins Monte Razzano and the small outcrop of the clayey-marly-calcareous complex near the upper water-course of the Leia Stream (fig. 9) seems to be responsible for the separation between the groundwater flows from the system in question and those from the Vulsini Mountains. This effect of the structural setting on groundwater flow of the area deserves further study. It is necessary to investigate the role of the deep discontinuities in the area of the main Cimini and Vico caldera intrusions. These discontinuities, traversing the basement to the volcanics (fig. 10), could be communication pathways between the latter and the carbonate Meso-Cenozoic basement, underlying the Cretaceous-Oligocene Flysch substrate. In other words, the deep carbonate reservoir, identified in the literature as a low-enthalpy geothermal system (CALAMAI *et alii*, 1976), could be fed through these deep fractures. Given this hypothesis, the recharge areas of Viterbo's thermal springs and the other mineralised showings found around the volcanic aquifer would coincide directly with the morphological and piezometric high, located between the Cimini domes and the Vico caldera (PISCOPO *et alii*, 2005).

The hydrogeological layout described here differs from that reported by CAPELLI *et alii* (2005) in three ways: the role of the north-eastern edge of the system, the groundwater flows towards the Leia Stream and, generally speaking, the rate of streamflow increases along the river beds.

As far as the first point is concerned, in this study we considered the units outcropping along the north-eastern edge of the hydrogeological system, which are part of the sandy-clayey complex (fig. 9) and the corresponding Plio-Pleistocene clays and clayey sands of the neoautochthonous cycle (BERTINI *et alii*, 1971a; MANCINI *et alii*, 2001), responsible for the formation of a no-flow boundary. According to CAPELLI *et alii* (2005), these units drain the volcanic aquifer into that of the Tiber plain. The opinion expressed in this paper is based on survey conducted specifically in the area. In this same area the independently reconstructed potentiometric surface was found to be consistent with a no-flow boundary (fig. 9).

As for the second point, CAPELLI *et alii* (2005) attributed the base flow of the Leia Stream (about 1.4 m^3/s in 2002) as originating entirely from the Cimino-Vico hydrogeological system. According to our study, it originates partly from the volcanic aquifer of the Vulsini Mountains. This opinion is based on the presence, close to the upper section of the water-course, of a groundwater divide affecting the basal aquifer, corresponding to a local elevation of the clayey-marly-calcareous complex (fig. 9).

The third point concerns the flow rate increments along stream beds as reported in this paper by comparison with those described in CAPELLI *et alii* (2005) for the same streams. This difference can be explained by the fact that the comparison was made of spot measurements carried out at different times, i.e., the 2003 dry period considered in this study versus the summer of 2002 considered by CAPELLI *et alii* (2005).

EVALUATION OF GROUNDWATER RESOURCES

A preliminary estimate of the groundwater yield of the hydrogeological system was carried out with respect to the surface area indicated in fig. 9, which is approximately 902 km^2. The mean annual recharge of the aquifer was estimated by processing historical meteorological data and considering the hydrogeological characteristics of the outcropping units.

Rainfall and temperature data were obtained from the former S.I.M.N. (Servizio Idrografico e Mareografico Nazionale, now APAT). These include all the stations present in the area and its surroundings (fig. 12) and cover the period from 1951 to 1999 (SIMN-ANNALI IDROLOGICI, 1951-1999). After reconstructing the missing data by means and multiple regressions between stations (chosen on the basis of their elevations and distances), a mean annual rainfall map was produced using the geostatistic *kriging* technique. While processing the data, a reduction in rainfall was noticed in the last years of the series (fig. 13), consistent with the literature referring to Central Italy (e.g. DRAGONI, 1998; BARAZZUOLI *et alii*, 2003).

To calculate the actual evapotranspiration of the hydrogeological system, the Turc's formula (TURC, 1954) was applied to the individual stations and, subsequently, a map was plotted of the lines of equal magnitude for the parameter. This method was chosen because the lack of data concerning specific meteo-climatic dimensions did not enable physical methods (e.g. those based on the work by PENMAN, 1948) to be used. However, it must be noted that, at least for Central Italy, the Turc method appeared to give rise to good results (cf. for example, in DE FELICE & DRAGONI, 1991; BONO, 1993).

The evaporation of Lake Vico was determined using the equation developed by DRAGONI & VALIGI (1994), again on the basis of thermometric data.

To calculate the aquifer's recharge, first the overall water flow (*DG*), that is to say the sum of effective infiltration and surface runoff, was evaluated. The calculation was carried out using the following expression:

$$DG = (P \times S) - [ETR \times (S - S_l)] - (E_v \times S_l) \qquad [1]$$

where

P = mean rainfall, in m/year;

ETR = mean actual evapotranspiration, in m/year;

E_v = mean evaporation from the lake surface, in m/year;

S = surface area of the hydrogeological system, in m^2 (902.4×10^6 m^2);

S_l = surface area of the lake, in m^2 (12.3×10^6 m^2).

The values determined for *P, ETR* and E_v are shown in tab. 2. In the same table the foregoing quantities are also indicated as mean annual volumes (*V*). It appears that the system has an overall available water flow (*DG),* including both groundwater and surface flow, of some 324×10^6 m^3/year.

TABELLA 2

Overall flow of the hydrogeological system.
– Risultati della valutazione del deflusso globale del sistema idrogeologico.

Term	Computed values (m/year)	*V* (10^6 m^3/year)
P	0.971 (spread on *S*)	876.4
ETR	0.606 (spread on $S - S_l$)	539.4
Ev	1.086 (spread on S_l)	13.3
DG		**323.7**

To differentiate between groundwater recharge (*I*) and runoff (*R*), the so-called potential infiltration coefficients (*CIP* = *I/DG*) reported in the literature (CELICO, 1986; CIVITA, 2005) were used. According to published data, for the rock types outcropping in the area under consideration the *CIP* is between 0.5 and 1. On the basis of the morphology, of land use and of the permeability of the rock types, it seemed reasonable to restrict the field to a *CIP* between 0.5 and 0.7. These coefficients enable a groundwater rate of between 162 and 227 × 10^6 m^3/year (tab. 3), corresponding to a flow of between 5 and 7 m^3/s. Starting out from these values, a specific mean groundwater yield of the surface area (that is to say a groundwa-

TABELLA 3

Aquifer recharge according to the two hypotheses of infiltration coefficient (*CIP*): V_r: recharge volume; Q_{ds}: mean groundwater yield; R_s: specific mean groundwater yield. – *Ricarica dell'acquifero secondo le due ipotesi del coefficiente di infiltrazione potenziale (CIP):* V_r*: volume della ricarica;* Q_{ds}*: portata media del deflusso sotterraneo;* R_s*: rendimento specifico medio in acque sotterranee.*

CIP	V_r (10^6 m^3/year)	Q_{ds} (m^3/s)	R_s (l/s per km^2)
0.5	161.8	5.1	5.7
0.7	226.6	7.2	8.0

ter yield per unit of surface area) of between 5.7 and 8.0 l/s per km^2 can be calculated, which is consistent with the values found in the literature for volcanics along the Tyrrhenian strip (CELICO, 1983; BONI *et alii*, 1986; PISCOPO *et alii*, 2000; CAPELLI *et alii*, 2005).

In order to have a check of the order of magnitude of these estimates, the outflow of groundwater (U) from the area considered was evaluated, using the following expression based on an analysis of the hydrogeological layout, the boundary conditions of the hydrogeological system and the current use of the water resources:

$$U = S + I_a + T_r + P_r \qquad [2]$$

where

S = outflow from springs, in m^3/s;
I_a = streamflow increments, in m^3/s;
T_r = flows towards other aquifers, in m^3/s;
P_r = withdrawals from the aquifer, in m^3/s.

The outflows from springs (S) were determined by adding up the data of known flows from springs related to the volcanic aquifer and from the thermal and mineral sources in the study area (including those fed by wells). The overall value (in the region of 0.5 m^3/s) refers to a census which was by no means exhaustive, considering that no homogeneous and periodic flow data for springs are available. It is, however, the only possible estimate based on current knowledge.

As pointed out previously, one of the groundwater discharges consists of the hydrographic network. A preliminary estimate of the average increases along stream beds (I_a) was calculated using the 2003 measurements, resulting in an overall value of about 1.4 m^3/s (not including the flows from springs considered previously).

In order to evaluate the discharge from the hydrogeological system under consideration towards the surrounding aquifers (T_r), Darcy's equation was applied to the sectors identified through the hydrogeological system, using the reconstruction of the potentiometric surface and the transmissivity map. The resulting outflows of groundwater amounted to about 2.3 m^3/s, concentrated primarily on the south-eastern edge, where the volcanic aquifer allows groundwater to flow towards the Tiber's alluvial deposits through the sandy-conglomeratic complex (approximately 2.0 m^3/s).

The last component of the outflows from the volcanic aquifer consist of the withdrawals (P_r) for irrigation, drinking water, and to a lesser extent, industrial usage. Data covering these uses are very scarce or inhomogeneous.

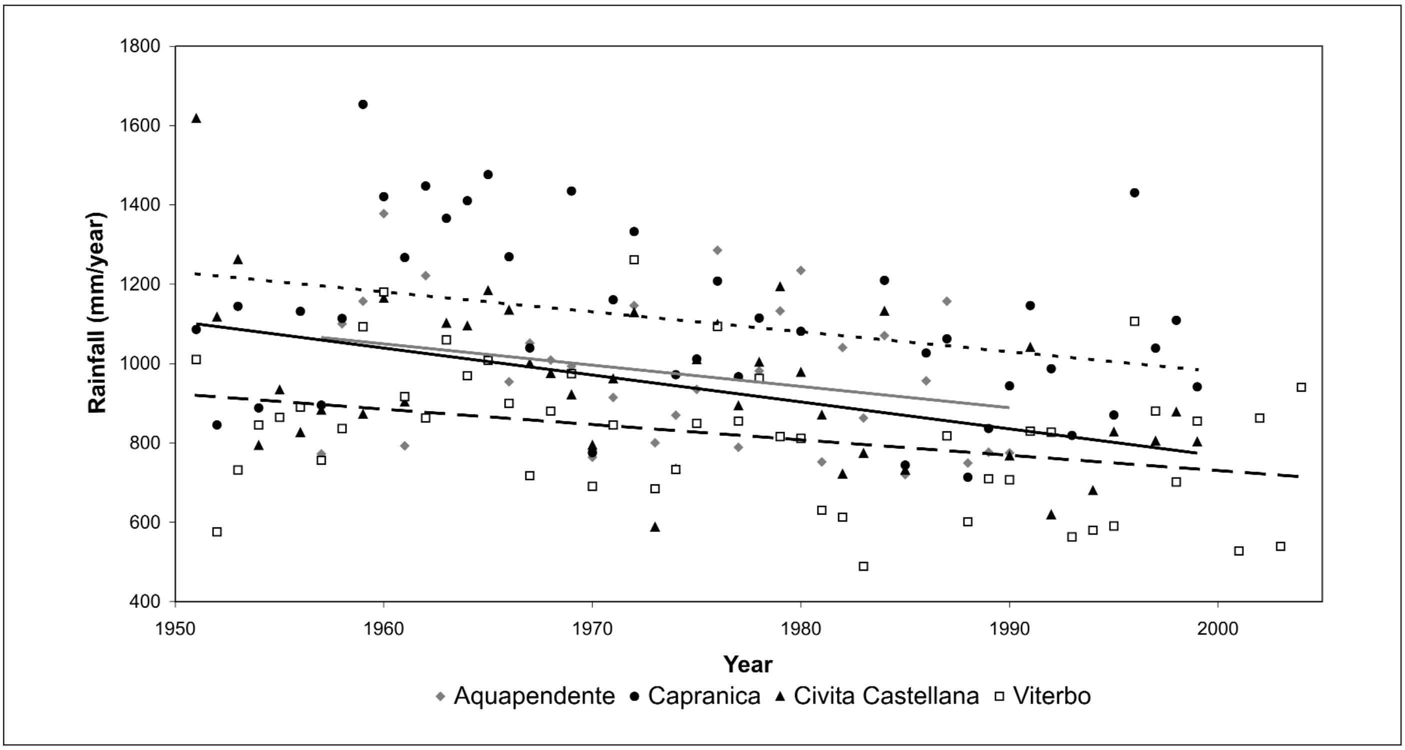

Fig. 13 - Trend of the mean annual rain from 1951 to 2003 for some stations.
– *Andamento della piovosità media annua per alcune stazioni nel periodo 1951-2003.*

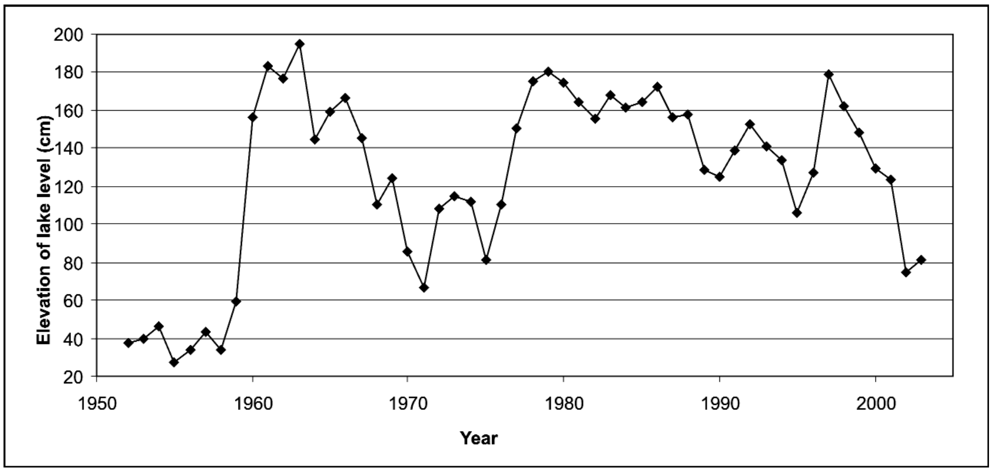

Fig. 14 - Plot of the mean annual level of Lake Vico (referred to 508.89 m asl).
– *Andamento del livello idrico medio annuo del Lago di Vico (riferito a 508,89 m s.l.m.).*

As far as aqueducts are concerned, a mean flow of around 0.4 m^3/s was calculated on the basis of data concerning extractions from wells in the study area (the Lazio Region's ATO 1 census). No reliable data on withdrawals for industrial purposes are available, but considering that the only significant industrial facilities situated to the north of Viterbo and in Civita Castellana, a pumping rate of not more than about 0.2 m^3/s was estimated on the basis of the sizes of these facilities, the working flow rates of the wells and the local transmissivity of the aquifer.

A first evaluation of water losses from the aquifer due to irrigational practices took the difference between potential and actual evapotranspiration into account, considering that any surplus lost into the ground would seep back into the same aquifer. The difference between potential and actual evapotranspiration was calculated by applying the THORNTHWAITE-MATHER (1957) approach to Viterbo's meteorological station for the western sector and to the mean values measured by the Soriano, Corchiano, Ronciglione and Capranica stations for the eastern sector, where irrigational practices are more common. Considering the extent of the irrigated area (about 178 km^2) within the study area (AA.VV., 1995-96), in terms of mean annual flow, water losses from the aquifer were calculated to be around 0.9 m^3/s.

The sum of the estimates calculated for the different parameters in expression [2] gives groundwater outflow (U) from the hydrogeological system of about 5.7 m^3/s. Considering that this estimate includes the streamflow increments (I_a) during the summer of 2003, which was a particularly dry year (the mean annual rainfall in Viterbo for the years 2001 to 2003 was 643 mm versus 830 mm for the period from 1951 to 1999), the result obtained is not inconsistent with the range of values for the estimated recharge (see tab. 3).

LAKE VICO IN THE HYDROGEOLOGICAL CONTEXT OF THE VOLCANIC STRUCTURE

The most important body of surface water of the Cimino-Vico system is that of Lake Vico, in a protected area defined by the Lazio Region in 1982 of significant economic and environmental importance. The potentiometric surface reported in fig. 9 indicates that the lake's hydrogeological basin is larger than the catchment basin, especially in the northern sector, whereas in the remaining sectors the lake's waters feed the aquifer. Based on the piezometric contour lines, it can be seen in particular that the lake basin is fed from groundwater from an area of some 8.0 km^2 (A_{ex}) external to the watershed divide.

Using this scenario, a mean annual hydrological balance for the lake was computed for the 1951-1999 period, for which, in addition to temperature and rainfall, fairly continuous data concerning the level of the lake were available (fig. 14). Considering conventionally water inputs into the lake as positive and the outputs as negative, the balance can be expressed in the following way:

$$(P_i \times S_l) + P_{ef} \times (S_i - S_l) + (E_v \times S_l) + I_{ex} + U_s + Q = \Delta W \qquad [3]$$

In [3] the symbols have the following values:

– P_i = 1.029 m/year is the mean rainfall over the lake's catchment basin, based on the reconstruction of the mean annual rainfall; it was assumed, on the basis of the available data, that the rainfall was the same over the catchment basin as on the lake surface;

– S_l = 12.3 × 10^6 m^2 is the mean surface area of the lake;

– S_i = 41.0 × 10^6 m^2 is the surface area of the lake's catchment basin, inclusive of the lake surface;

– P_{ef} = 0.414 m/year is the effective mean rainfall, understood to be the difference between rainfall and actual evapotranspiration *(ETR_i)* in the catchment basin; the value of ETR_i was calculated to be 0.615 m/year, on the basis of the evapotranspiration map plotted using Turc's formula;

– E_v = –1.086 m/year is the mean evaporation from the lake surface, calculated using the DRAGONI & VALIGI's formula (1994);

– I_{ex} = the mean groundwater flows entering from areas outside the catchment basin (in m^3/year), positive and unknown;

– U_s = the mean groundwater flows exiting from the lake towards the aquifer (in m^3/year), negative and unknown;

– Q = the sum of withdrawals from the lake plus the outflows from the outlet (in m^3/year), negative and unknown;

– ΔW = + 0.2 × 10^6 m^3/year, is the mean annual variation of the lake's volume in the period 1951-1999; it was calculated using the difference in the lake level ΔH = + 0.9 m (see fig. 14) between the beginning and end of the 48 years considered: $\Delta W = +0.9 \times S_s/48$.

Taking into consideration the conventions used and the simplifications introduced, and substituting the symbols with the values indicated above, it resulted that $(I_{ex} + U_s + Q) = -11.0 \times 10^6$ m^3. In an attempt to differentiate between the terms $(I_{ex} + U_s + Q)$, Q was estimated on the basis of the volumes extracted by local aqueducts, of the rare historical measurements available for the flow of the outlet and those measured during the current investigation. In this context it must be pointed out that such flows are entirely artificial, since the discharge of the outlet is controlled by movable sluice gates adjusted in relation to the water demand and the lake's level. Our investigation indicated that Q was between a minimum of 3.2×10^6 m^3/year (approximately 100 l/s), based on withdrawals of water from the lake and the flows of the outlet measured in 2003, and a maximum of 6.0×10^6 m^3/year (approximately 190 l/s), taking the various sources of historical flow data of the outlet into consideration. The latter, however, often seem to be rough estimates rather than actual measurements. Taking the foregoing into account, it is found that:

if $Q = -3.2 \times 10^6$ (10^6 m^3), $(I_{ex} + U_s) = -7.8 \times 10^6$ m^3/year;

if $Q = -6.0 \times 10^6$ (10^6 m^3), $(I_{ex} + U_s) = -5.0 \times 10^6$ m^3/year.

If we consider a *CIP* = 0.5 (corresponding to the lower value of the *CIP* used for the whole system, in consideration of the permeability and morphology) for the area outside of the catchment basin, which produces I_{ex}, we find that I_{ex} is 1.7×10^6 m^3/year, while U_s is between -9.5 and -6.7×10^6 m^3/year. The order of magnitude of U_s obtained as above is consistent with the value based on the gradients and the transmissivity measured in the eastern, southern and western sectors outside the caldera containing the lake (see figs. 9 and 11). It is currently not possible to assess the water balance of the lake more precisely due to the lack of reliable, continuous measurements of important parameters, such as the outlet's flow and evaporation. Being necessarily based on a series of indirect estimates, some degree of uncertainty is inevitable. To stress the definite need to set up a suitable data acquisition network, it should be considered that the above results are based on evaporation of the lake calculated using a formula providing an estimate of evaporation from evaporimeters, and as such applicable essentially to shallow lakes (a few metres at the most), whereas Lake Vico is of several tens of metres deep. In this specific case the evaporation value adopted ($E_v = 1.086$ m/year) should probably be reduced. On the other hand, if evaporation were to be estimated by means of Visentini's empirical formula (VISENTINI, 1937), commonly used in Italy, it would amount to 1.196 m/year, with considerable effects on the water budget (which in any case would no longer be compatible with the transmissivities, gradients and other estimated quantities determined by independent methods).

Overall, the results of our study here are similar to those of DRAGONI *et alii* (2002). The main differences concern the water exchanges between the aquifer and the lake and the outlet's outflows. The former were determined by us on the basis of a more detailed knowledge of the potentiometric surface and transmissivity. As far as the outlet's discharges are concerned, it was possible to show that they were extremely low in the study period (from several litres per second to several tens of litres per second). Furthermore, our investigation revealed the existence of a small number of wells up-slope from the lake and a higher concentration down-slope in the south-eastern sector. The latter can affect the flows from the lake to the aquifer, since pumping will result in a local increase in the hydraulic gradient.

The water budget discussed here indicates that evaporation corresponds to roughly 50% of the total losses of the lake. Another element which should not be disregarded is the flow from the lake to the aquifer, which appears to account for between 26 and 37% of the total losses, depending on the value attributed to the sum of withdrawals plus outlet flow. By contrast, the groundwater flow from areas outside the catchment basin towards the lake seems to be fairly limited (around 6% of the total input).

Notwithstanding the underlying uncertainties, the results of the water budget of the lake are useful for giving an idea of the impact further withdrawals could have on the level of the lake and on groundwater flow.

To apply these ideas, let us suppose that at present the inflows and outflows from the lake balance each other out, and that, apart from any increases in withdrawals ΔQ, the average climatic conditions remain the same as in the last decades (i.e. in [3], P_i, P_{ef} and E_v remain unvaried). As soon as ΔQ is activated, the lake would react reducing the reserves ΔW, that is to say its volume, and consequently its level would drop. This would entail a reduction of the lake surface and of the overall volume of evaporation and, according to Darcy's equation, a (positive) increase ΔI_{ex} in groundwater inflows from external basin, as well as a variation (also positive) ΔU_s in groundwater outflows. In the long term, when the new equilibrium is reached, the surface would stop contracting ($\Delta W = 0$). Finally, at the point of equilibrium [3] would become:

$$(P_i \times S_{ln}) + P_{ef} \times (S_i - S_{ln}) + (E_v \times S_{ln}) + I_{ex} + U_s + Q + \Delta I_{ex} + \Delta U_s + \Delta Q = 0 \qquad [4]$$

where S_{ln} is the new mean lake surface in equilibrium following ΔQ, whereas ΔI_{ex} and ΔU_s are variations in groundwater flows towards and from the lake.

Substituting in [4] the terms with known values, we obtain:

$$S_{ln} = (6.0 \times 10^6 + \Delta I_{ex} + \Delta U_s + \Delta Q)/0.471 = 0 \qquad [5]$$

Having established an increase in withdrawals ΔQ, S_{ln} can only be calculated if we evaluate ΔI_{ex} and ΔU_s simultaneously and independently. This is possible, in principle, but complex and lies beyond the scope of this study. It is sufficient to observe that an increase in withdrawals would lower the water level in the lake, leading to an enlargement of the northern sector of the hydrogeological basin and to a reduced outflow into the aquifer in other sectors. Nevertheless, it is interesting to note that even small values of ΔQ, before attaining equilibrium, would have far from negligible effects on the lake level. Let us suppose, for example, an increase in withdrawals from the lake of 5% of the overall current exits. This would correspond to about 41 l/s, equivalent to a $\Delta Q = -1.3 \times 10^6$ m^3/year. Referred to the current lake surface, this volume would lead, in a single year of activity of ΔQ, to a drop in the lake level of 0.1 m, which would certainly not be offset by changes in the surface area of the lake (not easily appreciable on observing the bathymetric contour lines), or of ΔI_{ex} and ΔU_s , since decreases of this order of magnitude are not significant in relation to the lake depth of 48 m, and therefore to the seepage surface. Obviously, in a dry year, after maintaining an equilibrium for some years, the decrease would be far more marked.

A process similar to the one outlined above, but in the opposite direction, probably occurred in the years preceding 1960. As shown in the graph in fig. 14, the water level of the lake rose rapidly in that period. This could be explained by the fact that a number of hydroelectric power stations and industrial establishments were installed in the late 19th century immediately downstream from the underground outlet of the lake. These establishments, which used the outlet water flow, were decommissioned in the late 1960s. Since the flow from the outlet was no longer needed, it was decreased, so that the level began to vary around its present mean level, about one metre higher than previously.

This hypothesis is supported by some outlet' discharge measurements and estimates in the early of the 1900s, indicating a rate of about 300 l/s, which is definitely higher than the rate during the recent decades. The mean level of the lake in 1908 and 1917, when the establishments were operational, approached 506.5 m asl (PERRONE, 1908; VIAPPIANI, 1917), versus to the current 510 m asl.

On the basis of the above, and ignoring the uncertainties, it seems clear that any plans to increase the outflow of the outlet (or and any withdrawals at all) will have to be very carefully considered.

CONCLUSIONS

The main results of the investigations carried out can be summarised as follows.

– The stratigraphic, volcano-tectonic and morphological characteristics of the Cimino and Vico volcanic complexes give rise to a specific hydrogeological identity.

– The hydrogeological system defined covers an area of about 900 km^2 and is made up of volcanic and volcanoclastic rocks which are permeable due to their dual primary and secondary porosity, giving rise to an extensive basal aquifer as well to as some perched aquifers of limited continuity and thickness.

– The basal water-table has a centrifugal radial flow with its main discharges towards streams, especially to the south-east, west and north, and flows towards adjacent aquifers, especially in the eastern sector towards the Tiber's alluvial deposits, where the lowest groundwater levels of the volcanic aquifer occur.

– Generally speaking, the layout outlined above is consistent in terms with that of CAPELLI *et alii* (2005). It differs, however, from those authors' reports in terms of the hydrogeological role of the north-eastern edge of the volcanic aquifer. In our study, a possible limited groundwater flow towards the Tiber valley was observed in this sector. By contrast, during our investigation considerable flows were found in the hydrogeological system towards the alluvial aquifer on the south-eastern margin. Furthermore, the current findings agree only partly with those reported by CAPELLI *et alii* (2005), in that the former seems to show that the groundwater of the western sector of the hydrogeological system flows mainly into the lower reaches of the streams Biedano and Rigomero, and only partly into the Leia.

– The reconstruction of the transmissivity of the volcanics, which is a new factor not considered in earlier studies, points to areas characterised by a wide range of values (from 10^{-6} to 10^{-2} m^2/s), indicative of the considerably heterogeneous nature of the medium, with very low local permeability. This is due to the complex bedding relationships of the products emitted, to the variable degree of fracturing and to the volcano-tectonic structures. The highest transmissivity values are found in the south-eastern sector of the aquifer, consistently with the considerable groundwater flows towards the Tiber valley.

– The new investigation also enabled a first estimate of the overall groundwater yield of the system, resulting in an overall flow of between 5 and 7 m^3/s, equivalent to a mean specific groundwater yield of the area of between 6 and 8 l/s per km^2. The groundwater outflows from the system consist primarily of increases in streamflow, of flows towards adjacent aquifers, of spring outflows and of well-pumping (the latter mainly for drinkable water and irrigation purposes). As is the case for other assessments for this hydrogeological environment, the precision of our estimate was negatively influenced by a serious lack of basic data over a continuous period of time.

– Lake Vico is the upper outcrop of the basal water-table. The potentiometric surface shows that the lake is fed in the north by that (low-transmissivity) section of the aquifer corresponding to the morphological high of the Cimini Mountains. To the west, south and especially to the east of Lake Vico, the aquifer is fed by the lake, and that has a significant impact on the mean annual water budget of the lake. The evaluation shows that the water level of the lake is very sensitive to the discharge of the outlet, whose management is not always consistent with the rational conjunctive use of the water resources, as warranted by the environmental problems of the lake itself.

– Our investigation did not reveal any large alterations to the hydrogeological equilibrium of the system as a whole, although there is need to rationalise the current water extraction plans, especially considering the decreasing trend of average yearly rainfall over the region (DRAGONI, 1998; MILLY *et alii*, 2005). Such rationalization can only be achieved by closely monitoring the hydrogeological parameters outlined above. Specifically, it will not be possible to formulate suitable management plans unless a system of continuous measurement of the flow of the main streams and the extraction of water from the aquifer and surface waters is established.

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