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Olocenic alluvial aquifer of the River Cornia coastal plain (southern Tuscany, Italy): database design for groundwater management

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Abstract Hydrogeological research is in progress, utilizing GIS methods, with the principal aim of modelling the Olocenic alluvial aquifer of the River Cornia coastal plain (southern Tuscany, Italy), which has been exploited for drinking water, irrigation, and industrial uses. A consequence of exploitation has been the appearance of wide seawater intrusion. The alluvial aquifer has recently been subjected to new well fields for the supply of drinking water, with an increase of total average discharge of about 4×10^6 m^3/year. This paper presents results obtained from updating and integrating basic knowledge and structuring the database. The hydrogeological study allowed the recognition of the extension of areas that are characterized by a hydraulic head under the sea level, the progressive salinization of the aquifer, and the increase of water deficit in the aquifer which is produced by a progressive extraction of water superior to the natural recharge. In addition, benefits and disadvantages resulting from the location of new well fields in a hydrogeologically favourable zone, and the boundary conditions for much of the area studied have been defined. The GIS was used as support for making and updating the tabular and spatial database with the aim of integrating the local and regional hydrogeological knowledge. This study will permit the realization of a numerical simulation of the groundwater flow of the aquifer aimed at correcting the management of water resources, by means of the GIS-modelling integration.

Key words Hydrogeology · GIS · Alluvial and coastal aquifer · Italy

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Introduction

The Olocenic alluvial aquifer of the River Cornia coastal plain (southern Tuscany, Italy) is of great importance for the water supply to support human activities, especially since the area is characterized by an inadequate availability of surface waters. From the middle of the 1950s, this aquifer has been exploited progressively for potable water, irrigation, and industrial uses, with an overall withdrawal which has reached 46×10^6 m^3/year, and has caused a remarkable potentiometric drawdown (on an average of about 8 m during the 1961–1990 period). This water-level decline has caused a wide seawater intrusion, revealed by the severe degradation of the chemical quality of the groundwater. Therefore, an urgent intervention is necessary in order to improve the aquifer, to be implemented by means of an adequate phase of hydrogeological modelling, based on a correct conceptual representation of the local physical conditions on which to base the planning of scenarios of rational exploitation of the relative water resource.

Thus, the authors have planned a pluriannual program of hydrogeological research, with the application of GIS methods, the preliminary results of which were published by Barazzuoli and others (1994, 1995, 1996) and Cucini (1996). The present work demonstrates the results obtained in relation to the updating and integration of hydrogeological knowledge about the River Cornia plain and in relation to the structuring of relative databases, and leads to the following principal objectives which are strictly connected:

1. To attain a more complete and realistic regional hydrogeological synthesis, especially with respect to the static and dynamic parameters of the Olocenic aquifer.
2. To evaluate the influence exercised on the hydrodynamic and hydrochemical behaviour of the aquifer through the so-called "Anello Project", planned by C.I.G.R.I. (*Consorzio Intercomunale Gestione Risorse Idriche*) of Venturina, which consists of the installation of 18 new wells in the Casetta di Cornia, Roviccione, Macchialta, and Amatello areas (begun in summer 1994) for the supply of drinking water to the local inhabited centers with an increase of a total average discharge of about 4×10^6 m^3/year.
3. To carry out a quantitative evaluation of groundwater resources with the aim of optimizing the future extrac-

tions (hydrogeological modelling with unsteady flow and problems of freshwater-saltwater interface).

Regional hydrogeology

Geological, hydrogeological, and hydroclimatic setting

The coastal plain of the River Cornia is located in southern Tuscany, central Italy, and is made up of alluvial and swamp-lagoonal sediments which cover a surface area of about 150 km^2 (Fig. 1). A dense network of natural ditches is present in the Cornia plain, originating from the neighbouring elevations, and the artificial ditches resulting from hydraulic reclamation projects. In this area, the following geological units crop out, from top to bottom (Censini and others 1992; Costantini and others 1993; and references therein):

1. Alluvial and swamp-lagoonal deposits (Olocene), which constitute the River Cornia plain proper, whose deposition was strongly influenced by the river itself. These deposits include gravel, sand, silt, and clay in various proportions, which make up the aquifer under study.
2. Eolian-colluvial deposits (Late Pleistocene) of the S. Vincenzo-Palmentello plain, which are extraneous to the River Cornia influence. These deposits form three

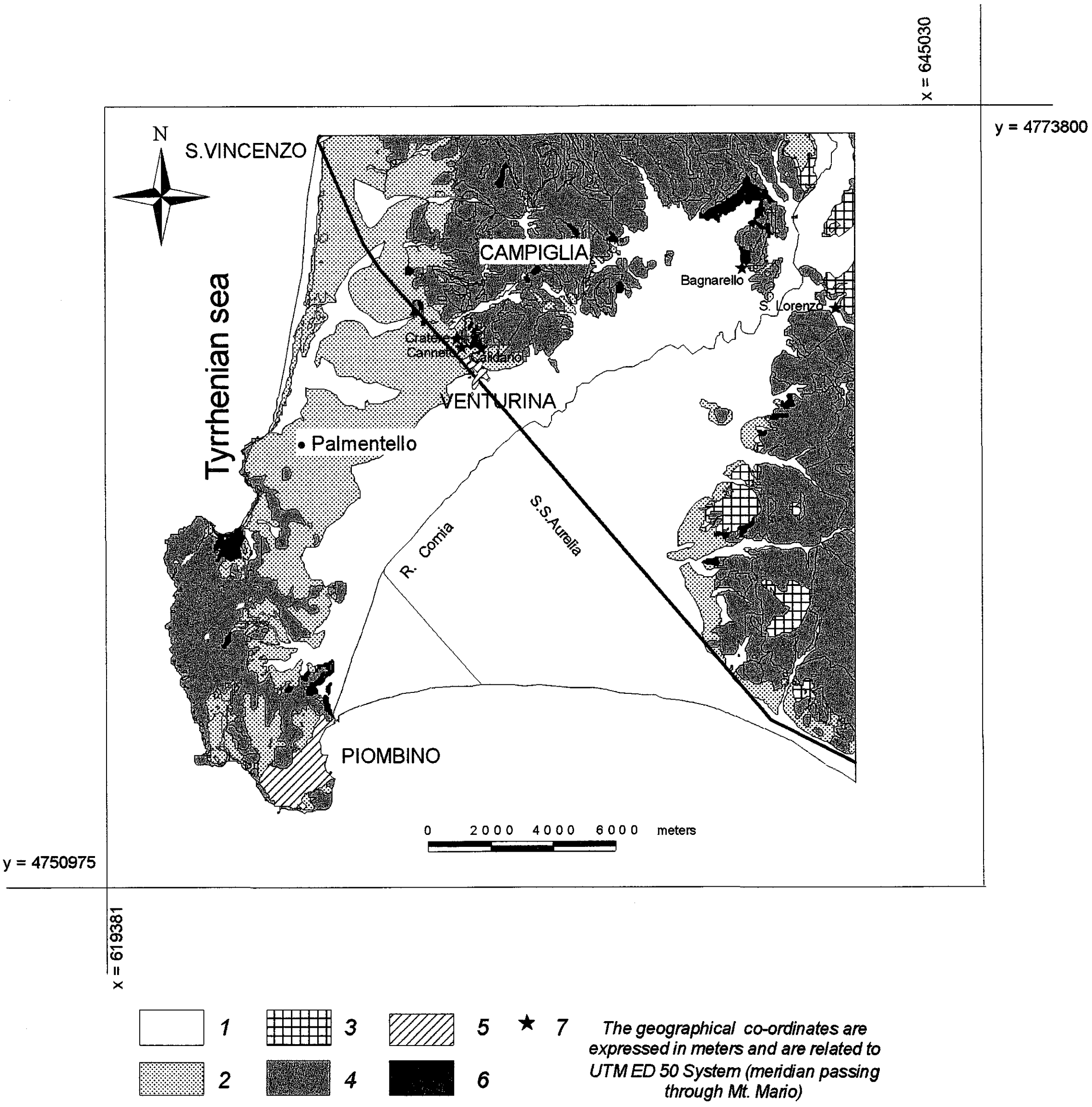


Fig. 1
Geological sketch map of the Piombino plain, southern Tuscany, Italy (after Costantini and others 1993, simplified): *1* alluvial and swamp-lagoonal deposits of the River Cornia plain (Olocene); *2* eolian-colluvial deposits of the S. Vincenzo-Palmentello plain (Late Pleistocene); *3* Montebamboli conglomerate (Upper Miocene); *4* the whole of the rocks preceding to Upper Miocene (Late Triassic-Oligocene); *5* urbanized areas; *6* debris and landfills; *7* thermomineral springs and wells

sedimentary sequences characterized by sand, conglomerate, calcarenite, and travertine and include an unconfined aquifer of minor interest.

3. Montebamboli conglomerate (Upper Miocene), which is composed predominantly of calcareous pebbles of the austroalpine and liguride formations.
4. The whole of the rocks preceding the Upper Miocene, among which it is possible to distinguish the Liguride formations complex (Late Jurassic-Paleocene), Austroalpine formations complex (Middle Eocene-Upper Cretaceous), Tuscan formations complex (Late Triassic-Oligocene). These sedimentary complexes, originally deposited in sedimentologically distinct environments (Palaeogeographic Domains), were later tectonically superimposed during the Late Oligocene-Early Miocene interval following the collision between the European and African continental margins and were dismembered during the Neogene by post-collisional extension.

With respect to the permeability, the outcropping rocks can be subdivided by means of a qualitative classification of relative categories on a formational basis (Ghezzi and others 1993) obtaining two main groups (Fig. 2):

1. *Quaternary complex*, formed by alluvial and swamp-lagoonal deposits of the River Cornia plain and by eol-

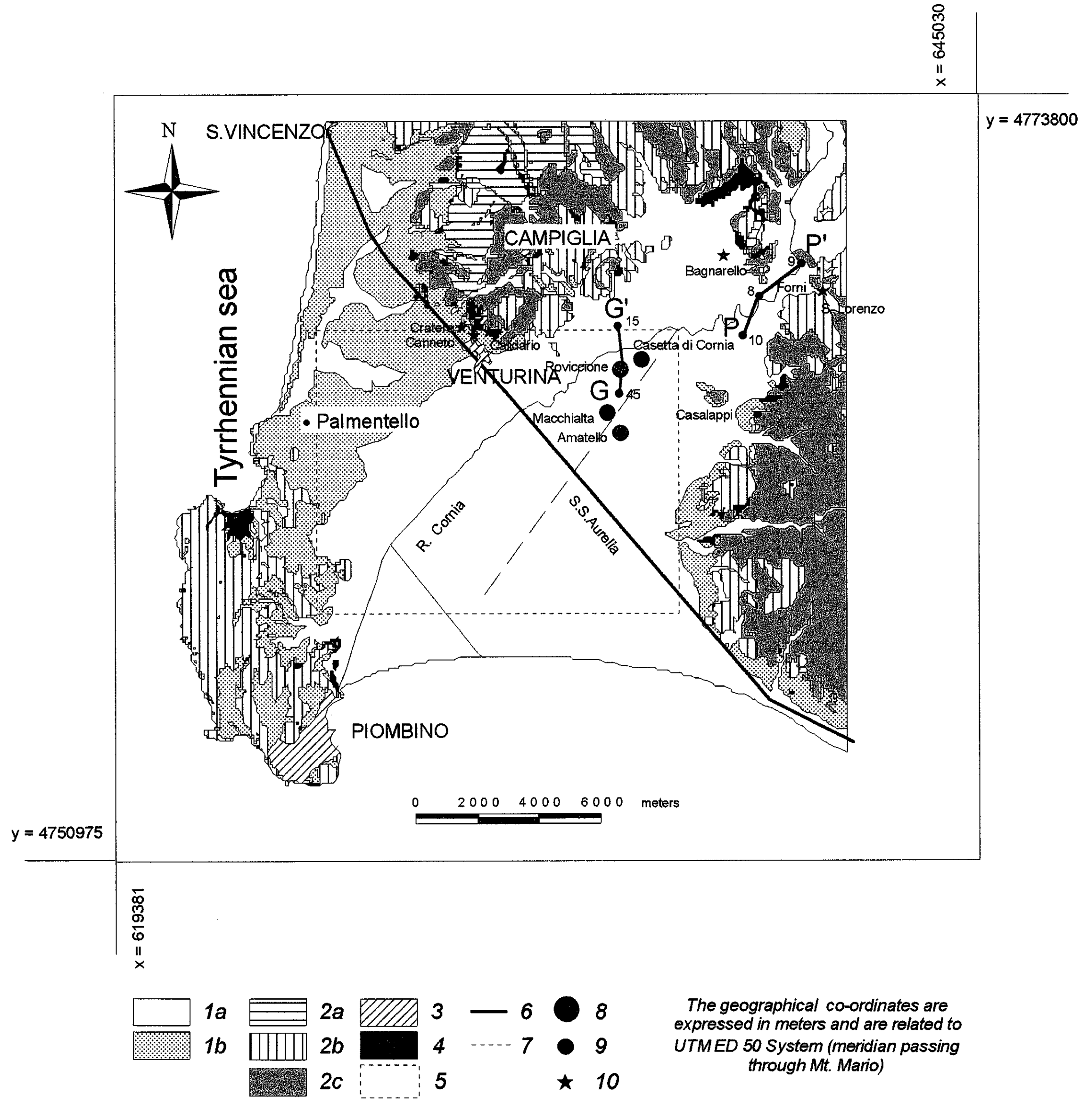


Fig. 2
Map of the degree of relative permeability on a formational basis of the Piombino plain (after Ghezzi and others 1993, simplified): *1* Quaternary complex, with sediments of various degree of permeability (*a* alluvial and swamp-lagoonal deposits; *b* eolian-colluvial deposits); *2* pre-Quaternary complex (*a* high permeability; *b* moderate permeability; *c* slight permeability); *3* urbanized areas; *4* debris and landfills; *5* area studied in a previous work (after Barazzuoli and others 1994); *6* new hydrogeological sections; *7* hydrogeological section elaborated in a previous work (Barazzuoli and others 1994); *8* new well fields; *9* boreholes; *10* thermomineral springs and wells

The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario) ian-colluvial deposits of the S. Vincenzo-Palmentello plain, which are of various degree of permeability. These deposits have weak or non-existent cementation, with prevalent primary permeability by interstitial porosity, and are highly permeable in the sandy-gravelly levels which predominate the higher sector of the River Cornia plain (Bagnarello-Casetta di Cornia area).

2. *Pre-Quaternary complex*, characterized by diagenous formations, with prevalent secondary permeability by fissuring or fissuring and porosity, which can be classified in the following ways:
   - *High permeability*. This class comprises carbonate formations of Tuscan and Liguride facies. Within this class, the most important formations are the Mesozoic carbonate-siliceous formations of Tuscan facies which crop out principally to the northwest of Campiglia and in the Bagnarello area; they comprise an important hydrothermal system of regional extension, which includes Triassic evaporite at the bottom, and are limited by underlying Paleozoic metamorphic formations. The system locally feeds the Cratere, Canneto, and Calidario thermomineral springs and the S. Lorenzo and Bagnarello thermomineral wells, all together with a variable discharge from a minimum of 100 l/s up to a maximum of 700 l/s and with temperatures from 25 to 47 °C (Calore and others 1990; Celati and others 1991). It should be noted that the hydrothermal system contributes an appreciable quantity to the recharge of the local Quaternary aquifers, causing geothermal and geochemical anomalies in the Venturina and Forni areas (Calore and others 1990; Grassi and Squarci 1993).
   - *Moderate permeability*. This class includes formations of several geological units: carbonate-marly flysches, stratified sandstones, ophiolitic rocks, jaspers, Mio-Pliocenic sandy-conglomeratic formations.
   - *Slight permeability*. This class comprises marly and argillitic formations of various facies and age.

From a climatic point of view, the precipitation in the plain is about 750 mm and the temperature is about 16 °C on an annual average basis. Figure 3 demonstrates that the effective precipitation is rather low, varying from 150 mm/year in the low plain to 300 mm/year in the surrounding hilly areas. In fact, as occurs along the entire coastline of southern Tuscany, most of the precipitation is returned to the atmosphere by means of actual evapotranspiration with an average higher than 70% (Barazzuoli and others 1993). According to the climatic classification proposed by Thornthwaite (1948), the area studied can be considered subarid C_1 (moisture index from –33.3 to 0). Thus, the recharge of the aquifer, by virtue of infiltrating rainwater which is a mere fraction of the effective precipitation over the entire alluvial complex, is slight.

The annual average discharge of the River Cornia at S.S. Aurelia subwatershed is 3.2 m^3/s, and is surpassed only 56 days per year; in addition, given that the river has the lowest average values for minimum discharge among the principal watercourses of southern Tuscany (Barazzuoli and Salleolini 1993), one can conclude that its hydraulic flow is distinctly torrential. Therefore, the runoff occurs rapidly through brief flood waves during the few days of most intense rainfall and the water yield recharge of the alluvial aquifer coming from the river is practically absent during the summer (at least in the lower sector of the plain); in fact, during drought periods, it is possible to notice the presence of a completely dry, wide reach in the south of Venturina (Barazzuoli and others 1994).

Collecting and structuring data

The structuring of data coming from different sources and relative to different periods of observation, has required an accurate archival research and numerous field surveys in order to verify the reliability and correctness of the starting data, which must be precise and trustworthy. The data were then inserted in a tabular and spatial database, 290 water points and boreholes relative to period 1961–1995 (all georeferenced) which allowed the identification of the aquifer lithology and geometry, and its hydrodynamic and hydrochemical characteristics (Cucini 1995; Barazzuoli and others 1996). In order to illustrate the procedure by which this database was conceived, Table 1 shows an extract of a schedule elaborated on an electronic page which represents the progression of the typical information used for the observation points of the hydraulic head, of the physical-chemical and hydrogeological parameters.

The GIS used provided the opportunity to manage a high quantity of raw data which increase and change in time, allowing for the existent relationships between the additional spatial information connected thereto (Fig. 4). In addition, the GIS has permitted filing, integration, elaboration, and presentation in the form of thematic maps of remarkable masses of geographically identified data (Fig. 5).

Geometric-structural and hydrogeological characteristics of the aquifer

A previous work (Barazzuoli and others 1994) demonstrated the main geometric-structural characteristics of the Olocenic aquifer in the sector located to the southwest of Casetta di Cornia, and the hydrogeological section shown in Fig. 2 was elaborated. The acquisition of new stratigraphic data relative to wells and boreholes (Cucini 1995) has allowed the confirmation of the previous hydrogeological hypotheses, and therefore, the broadening of knowledge as far as the Forni zone, so that the entire River Cornia coastal plain is included. Among the new stratigraphies available, only those (about 50) endowed with the greatest amount of base information relative to single wells, i.e. stratigraphy, well code, kind of measurement point, length and position of screens, date of construction, hydraulic conductivity values, potentiometric levels, were considered. In this way, the sector characterized by the presence of new well fields (Fig. 2) was studied in detail. Thus, 15 hydrogeological sections were elaborated, 7 transversal and 8 longitudinal

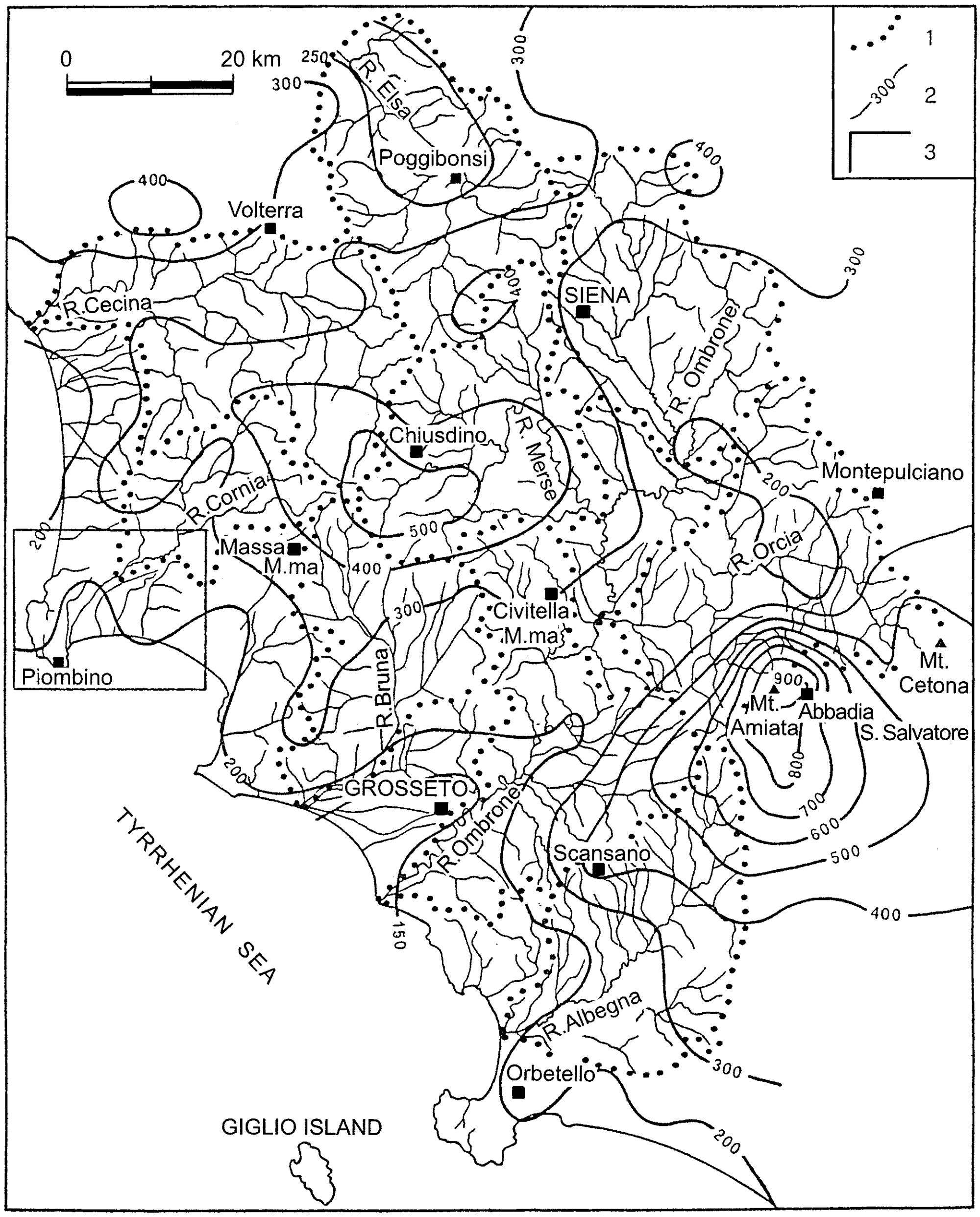


Fig. 3
Average effective precipitation map of the southern Tuscany (hydrologic year, mean of 1951–1980; after Barazzuoli and Salleolini 1993, modified): *1* drainage divide; *2* isolines (values in mm/year); *3* area studied

to the fluvial axis, the most significant of which are highlighted in Fig. 6 (P-P' section summarizes the configuration of the aquifer in the area between Casetta di Cornia and Forni, while the G-G' section represents the aquifer geometry in the new well fields zone).

The present acquired stratigraphic knowledge allows the affirmation that, in the higher sector of the plain, the aquifer is largely composed of a powerful gravel lithology with a silty-sand matrix that crops out or underlies a subtle covering of silt from fluvial overflow. Proceeding toward the southern coast, the gravel horizon tends to deepen and subdivide in various levels separated by clay-silt layers of low permeability (aquiclude or aquitard) and buried by a covering of clay and silt, of increasing thickness. In the area nearer the sea, it is possible to verify the presence of powerful silt-clay layers to remarkable depths, while the previous gravel levels deepen abruptly. It should be noted that in various areas of the plain the presence of only one gravelly-sandy horizon has been observed, owing to the lack of clay-silt deposits of separation. This allows a better hydraulic continuity in the aquifer (Barazzuoli and others 1994).

In addition, on the basis of the hydraulic head measurement, the aquifer complex is constituted by an unconfined/semiconfined aquifer (A/B) in the Forni zone which becomes semiconfined (A'/B) in the new well fields zone (Fig. 6), where it is frequently dry. Proceeding further southwest, this aquifer deepens, decreasing its thickness and often assuming the characteristics of a perched aquifer (as already hypothesized by Barazzuoli and others 1994). Beginning from the zone occupied by new well fields, it is possible to notice the presence of a multi-

Table 1

Extract from a table elaborated on an electronic page that represents the sequence of the typical information used for the observation points of the hydraulic head, of the physical-chemical and hydrogeological parameters (after Barazzuoli and others 1996, modified) Codes (1)–(5) refer to previous work, Code (6) is used in the present work. A Piezometer; B Hydrographic Service piezometer; C "Artesiano" well for irrigation use; D "Ad anelli" well for irrigation use; E "Romano" well for irrigation use; F well for industrial use; G well for potable use; GDIS obsolete well for potable use

(1)	Code (2)	Code (3)[a]	Code (4)	Code (5)[b]	Code (6)	UTM ED50 co-ordinates x (m)	UTM ED50 co-ordinates y (m)	Altitude (m asl)	Well-head height ground (m)	Well-head altitude (m asl)	Well-head depth (m)	KIND	Screen number[c]	Screen position	Well diameter (inch)	Well discharge (l/min)
1	–	630	–	–	1	632057	4766441	24,30	0,18	24,48	24,00	A	–	–	6	–
2	A15	**216**	–	A15 (cod.str.)	2	632473	4765861	13,70	0,27	13,97	34,50	A	1	63a	2	–
3	–	589	–	–	3	634425	4767963	25,50	0,45	25,95	15,00	A	–	–	8	–
4	1bis	**520**	–	–	4	635720	4766795	24,50	0,00	24,50	30,00	A	0	55a	4	–
5	V12	**219**	–	V12 (cod.str.)	5	637235	4767171	27,50	0,00	27,50	40,00	A	0	55a	4	–
6	–	291	–	–	6	637513	4767438	28,50	0,20	28,70	50,00	C	–	–	8	700
7	3bis	**524**	–	–	7	637817	4767531	29,00	0,10	29,10	30,00	A	0	55a	4	–
8	5bis	**527**	–	–	8	639155	4768318	35,00	0,10	35,10	15,00	A	0	55a	4	–
9	6bis	**529**	–	–	9	639812	4769501	42,80	0,13	42,93	30,00	A	0	55as1	4	–
10	4bis	**420**	–	–	10	638615	4767095	31,80	0,00	31,80	25,00	A	0	55as2	4	–
11	2bis	**521**	–	–	11	637042	4766561	26,00	0,10	26,10	30,00	A	0	55a	2	–
12	A35	**220**	–	–	12	637599	4766752	27,40	0,85	28,25	60,00	G	2	56a	2	–
13	–	223	–	50	13	636571	4764441	19,00	0,00	19,00	53,00	A	0	55a	5	–
14	–	**108**	–	51	14	636119	4765840	21,30	0,25	21,55	77,00	A	1	1a	7	–
15	A16	**218**	–	A16(cod.str.)	15	634529	4766664	19,50	0,25	19,75	49,50	A	0	55a	4	–
16	–	141	510	53	16	635372	4762687	13,10	0,20	13,30	60,00	C	–	–	7	360
17	–	295	–	49	17	633647	4763656	14,20	0,35	14,55	35,00	C	–	–	7	–
18	A38	**240**	–	48	18	632832	4762296	9,60	0,25	9,85	54,00	C	1	2a	7	–
19	767	**160**	767	767(cod.str.)	19	635749	4759739	9,00	0,20	9,20	60,00	C	–	–	7	720
20	A4	**162**	–	813(cod.str.)	20	632390	4758405	2,50	0,20	2,70	55,00	C	2	51a	10	–
21	c4	**157**	–	4c(cod.str.)	21	633449	4759536	4,00	0,82	4,82	26,00	A	2	58a	4	–
22	–	333	–	41	22	629743	4762646	6,70	0,18	6,88	45,00	C	–	–	7	–
23	–	133	724	44	23	631180	4764460	9,80	0,20	10,00	64,00	C	–	–	8	750
24	–	673	–	–	24	638673	4767625	33,00	0,70	33,70	8,00	A	0	55a	4	–
25	–	**170**	758	42	25	628565	4763324	5,00	0,50	5,50	48,00	C	1	3a	7	120
26	–	178	–	19	26	628233	4760689	2,09	0,10	2,19	30,00	C	–	–	7	–
27	–	327	–	–	27	625427	4758290	12,50	0,90	13,40	23,00	D	–	–	118	–
28	1093	**126**	–	–	28	626017	4764103	5,30	0,20	5,50	62,00	C	1	57a	7	–
29	–	127	–	–	29	625608	4764631	5,40	−0,10	5,30	42,00	C	–	–	7	–
30	–	15	–	–	30	626346	4768069	7,40	0,00	7,40	35,00	C	–	–	7	–
31	–	317	–	–	31	628271	4767191	22,30	0,15	22,45	30,00	C	–	–	7	–
32	–	96	–	–	32	630234	4766389	18,80	0,30	19,10	60,00	C	–	–	12	–
33	Z10	**659**	–	–	33	626376	4771390	26,50	0,70	27,20	48,00	A	1	4a	4	–
34	–	670	–	–	34	639271	4767941	34,80	0,80	35,60	8,50	A	0	55a	4	–
35	–	676	–	–	35	639044	4767330	32,80	0,80	33,60	8,00	A	0	55a	10	–
36	–	677	–	–	36	638799	4767368	32,00	0,80	32,80	8,00	A	0	55a	6	–
37	–	679	–	–	37	638392	4767139	30,50	0,90	31,40	8,00	A	0	55a	10	–
38	–	681	–	–	38	637972	4767264	29,30	0,80	30,10	8,00	A	0	55a	4	–
39	–	667	–	–	39	636834	4766682	26,00	1,40	27,40	30,00	A	0	55a	4	–
40	s1	**805**	–	–	40	635676	4766086	20,80	0,71	21,51	56,50	A	5	5a	4	–

[a] Numbers printed in boldface represent a point endowed with stratigraphic documentation and used in present work

[b] (cod.str.) represents a point already existing in the Arc/Info database maked by Cucini (1995) as stratigraphy

[c] n Number of present screens (0 = piezometer open to bottom)

Example of table connected with "Screen position" column, by means of respective code, which represents the screen kind:

5a	from 18 m to 19 m from 23 m to 24 m from 25.5 m to 26 m from 30 m to 40 m from 44 m to 52 m

layered confined aquifer (C) composed of various gravel levels separated by clay-silt layers.

This study has allowed the indication of the existing hydraulic relationship between the River Cornia and the aquifer complex. It has been verified that the river flows upon sediments of moderate and high permeability which help the recharge due to seepage in the sector characterized by the unconfined/semiconfined aquifer (see Fig. 6a).

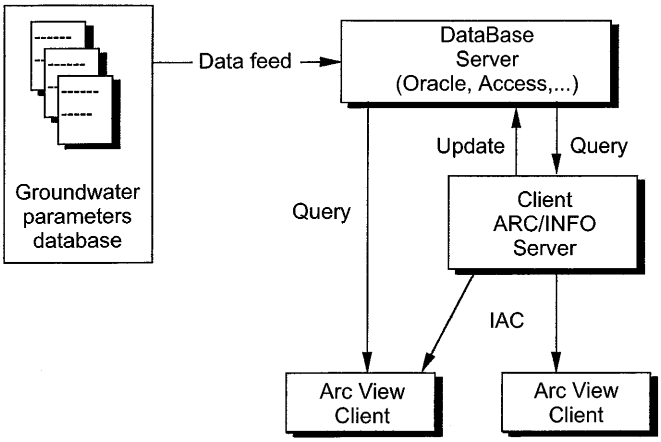


Fig. 4
Client/Server implementation of the Olocenic aquifer GIS application of the River Cornia coastal plain

On the contrary, in the zone characterized by semiconfined or confined aquifers, the river flows upon thick sediments of low permeability which prevent this recharge, and assume consequently the characteristics of a watercourse suspended above the aquifer complex.

Hydraulic conductivity and transmissivity of the aquifer

As mentioned above, the stratigraphic and hydraulic continuity of the various aquifer layers has allowed incorporation in only one aquifer complex and, therefore, it is possible to unify the results of the permeability tests which refer to both Lefranc tests carried out predominantly in the unconfined/semiconfined aquifer, and the pumping test concerning the multilayered confined aquifer. In order to unify the values obtained with two different types of measurements, the following operations have been conducted (Cucini 1995): (a) in the cases in which the Lefranc tests provided two or more values of hydraulic conductivity for only one aquifer level, the average value has been calculated; (b) the precise values obtained

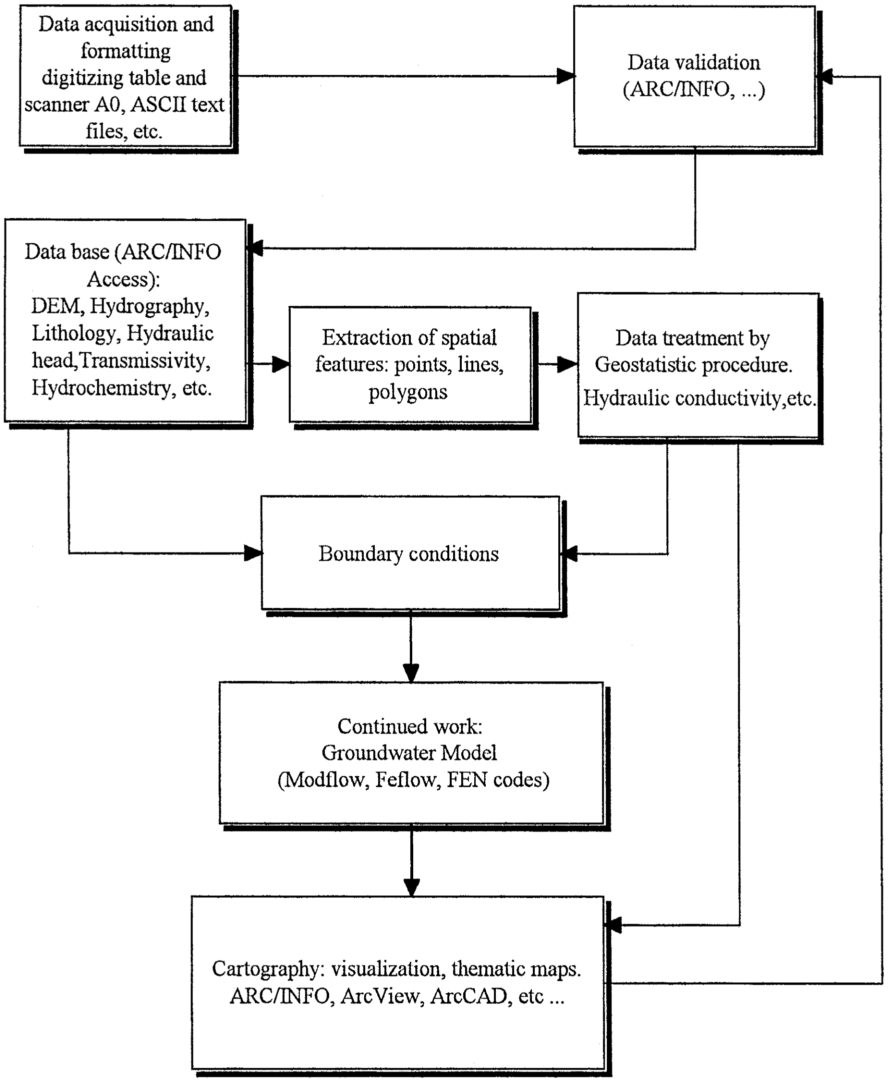


Fig. 5
Linkage between the GIS raster and vector database, the geostatistics treatment and cartography (Bouzelboudjen and Kimmeier 1998, modified)

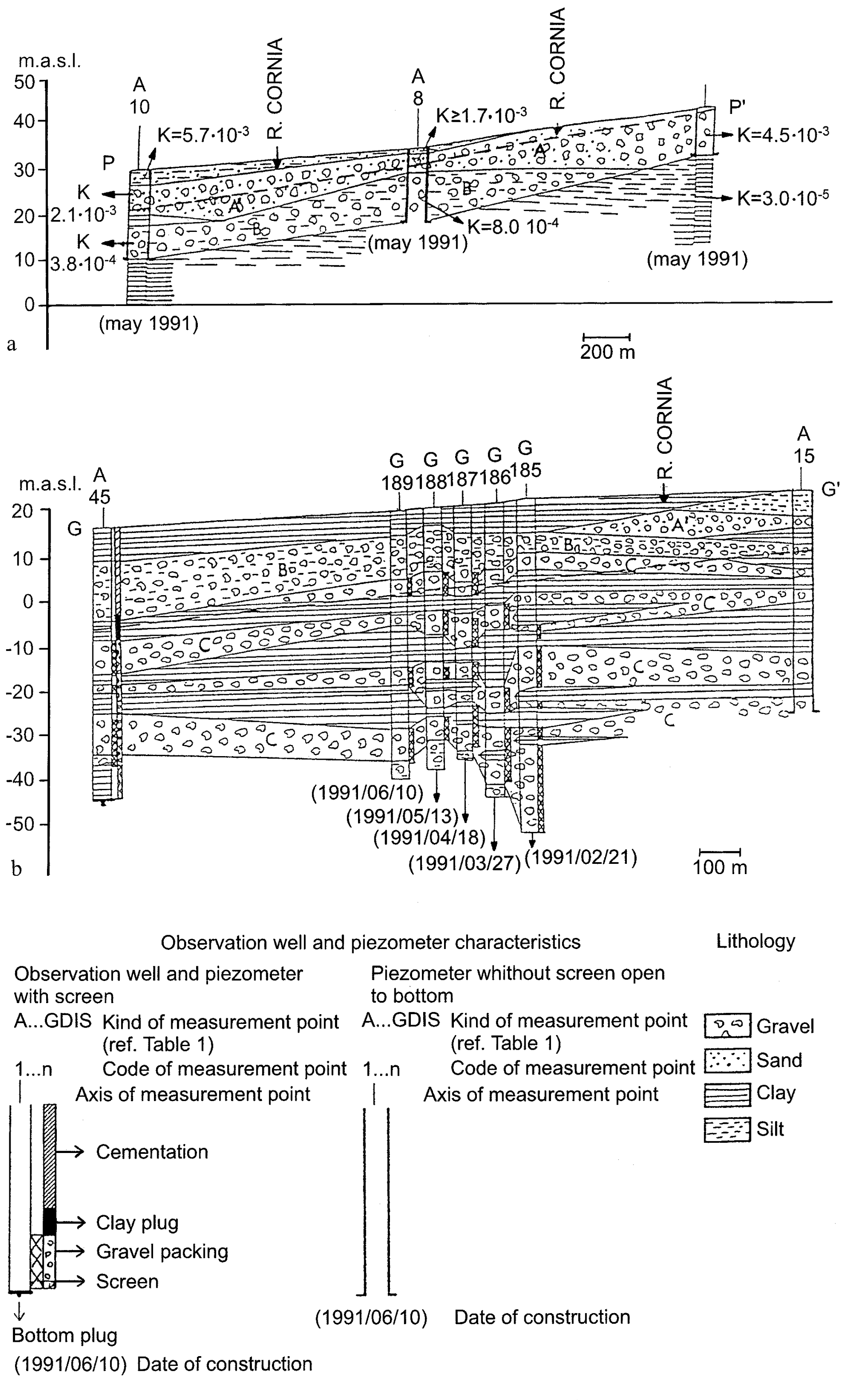


Fig. 6
Hydrogeological sections, which track is reported in Fig. 2. A unconfined aquifer; A′,B semiconfined aquifer; C multilayered confined aquifer. The hydraulic conductivity values (K) are expressed in m/s

have been applied to the aquifer thickness so that it was possible to use them together with the pumping tests. These hydraulic conductivity values were derived from C.I.G.R.I. collection and Ghezzi and others (1993) and refer to the years from 1983 to 1994. They have been verified and updated during a campaign in 1994 conducted by C.I.G.R.I. The hydraulic conductivity map obtained is shown in Fig. 7, where one can notice that the maximum values (superior to about 1×10^{-3} m/s) are located at the Bagnarello-Casetta di Cornia-Campo all'Olmo sector.

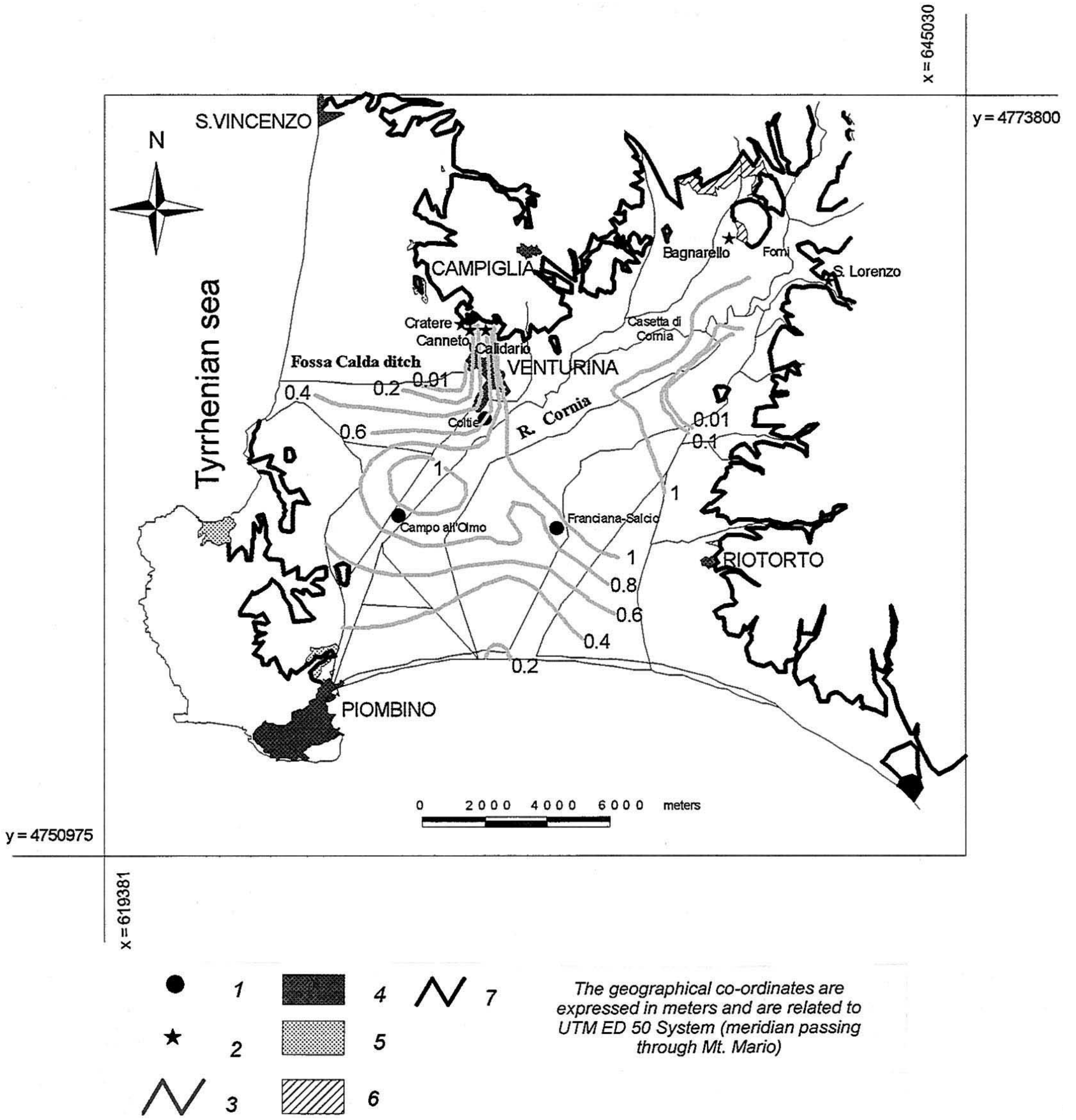
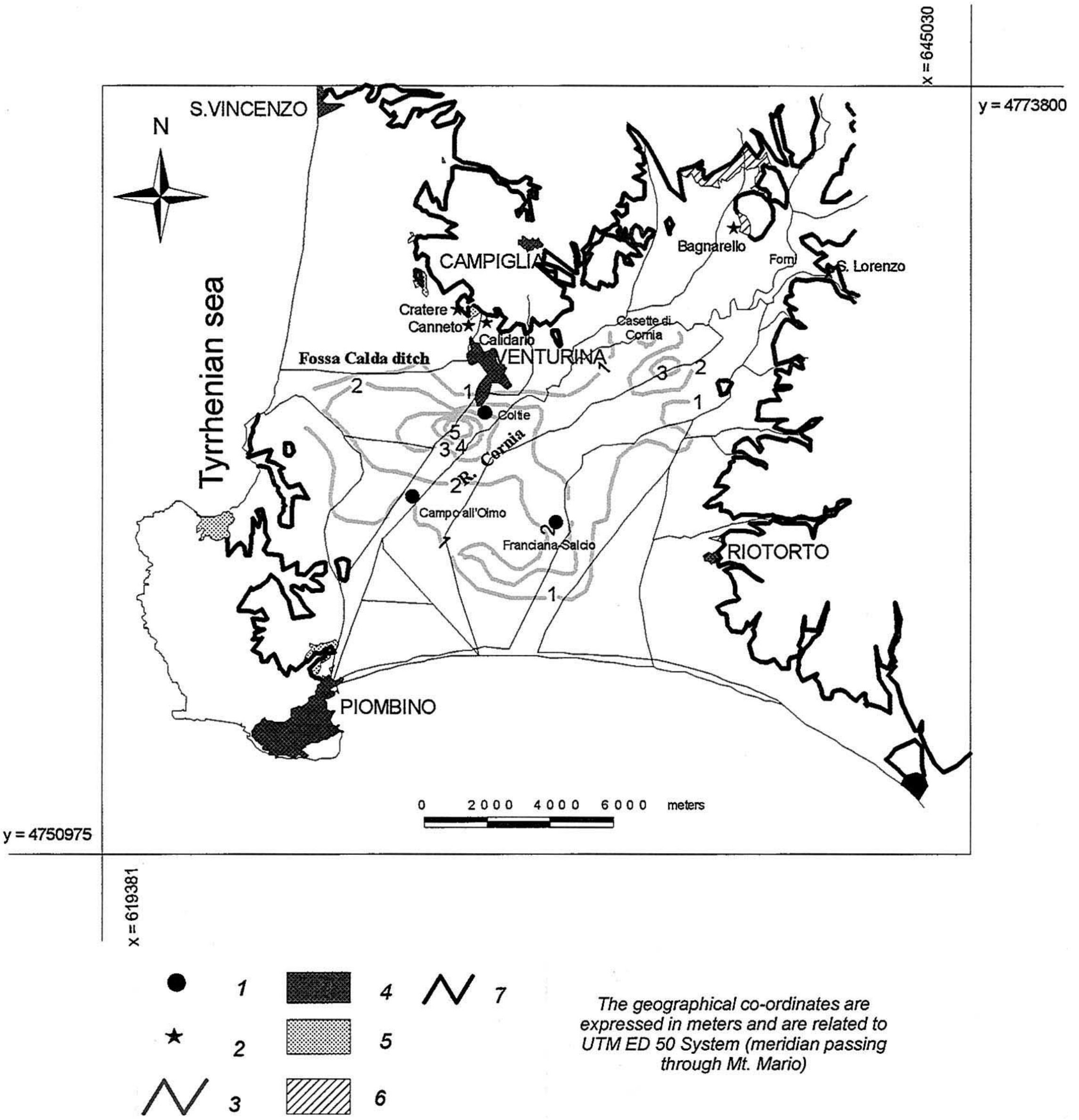


Fig. 7
Hydraulic conductivity map of the Olocenic aquifer: *1* old well fields; *2* thermomineral springs and wells; *3* isolines (values in 10^{-3} m/s); *4* urbanized areas; *5* landfills; *6* debris; *7* boundary of pre-Quaternary formations

The scarcity of data obtained by pumping tests and the concurrent remarkable density of data relative to vertical electrical sounding (about 80 VES) has suggested the opportunity of evaluating the hydraulic transmissivity of the Olocenic aquifer beginning from the estimation of the transverse resistance of the water-bearing lithologies. In fact, both measures are generally considered associated through a direct relationship. Also, concerning the area studied, the existence of a direct relationship between the transmissivity values relative to four pumping tests and those sampled at the same points on the matrix of the normalized total transverse resistance was verified (Barazzuoli and others 1995, and references therein). In this way, it was possible to construct the transmissivity matrix and, therefore, the relative map (Fig. 8), where one can notice that the maximum values (up to 5×10^{-2} m^2/s) are located slightly south of Venturina.

The comparison between the two maps shows that the Coltie-Campo all'Olmo sector is characterized by high values of hydraulic conductivity and transmissivity. This allows the hypothesis of the local presence of a practically constant thickness of the aquifer. On the contrary, in the southeast zone of Casetta di Cornia, one can notice a remarkable decrease in the hydraulic conductivity coinciding with a substantial constancy of the transmissivity. Therefore, one can assume a local thickening of the aquifer, which is also confirmed by an examination of the local stratigraphies.



The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario)

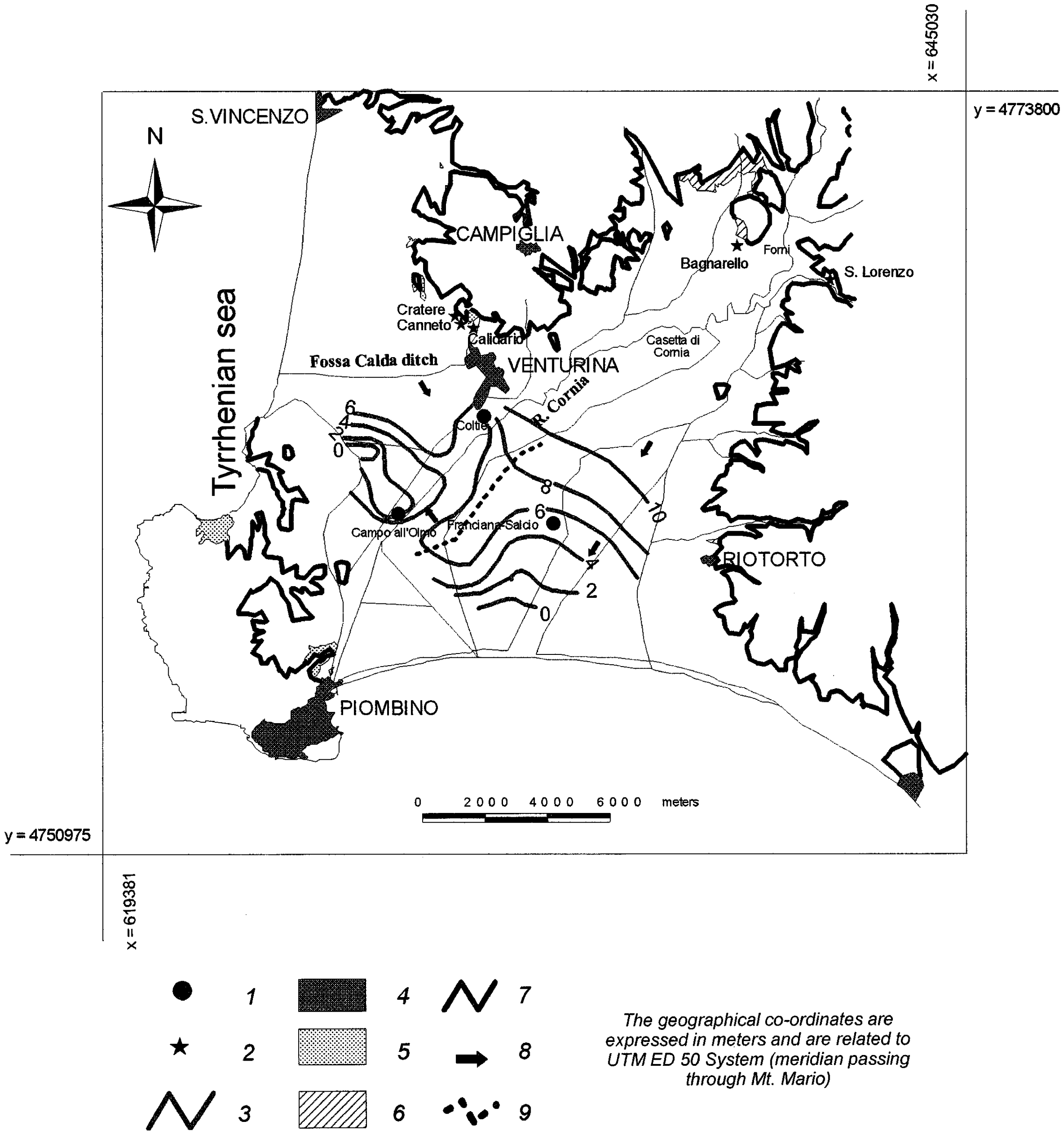
Fig. 8
Hydraulic transmissivity map of the Olocenic aquifer (after Barazzuoli and others 1995): *1* old well fields; *2* thermomineral springs and wells; *3* isolines (values in 10^{-2} m^2/s); *4* urbanized areas; *5* landfills; *6* debris; *7* boundary of pre-Quaternary formations

Potentiometric evolution until 1990

The lack of hydraulic head and conductivity measurements at various levels of depth did not allow a detailed study of the hydrodynamics of the Olocenic aquifer. In spite of this, the partial stratigraphic continuity of the aquifer levels, the widespread presence of semipervious interlayers, and the large variety of connections between the different levels caused by hundreds of multiaquifer wells, warrant an efficient hydraulic continuity into the aquifer complex. Therefore, the potentiometric measures correspond to the total hydraulic head of all the aquifers levels which constitute all together only one hydrological system in hydraulic equilibrium.

The piezometers and observation wells subjected to measurements of potential have been selected considering only those that involve aquifer levels with a reliable hydraulic continuity (Cucini 1995). For example, those relative to perched or superficial aquifers have not been observed. It should be noted that the continuous extraction of the groundwater from the various wells present in the zone involves the only possibility of measuring the dynamic water level, and as a consequence, the hydraulic head results highly falsified with respect to the natural conditions.

With regard to the seasonal fluctuation of the hydraulic head, generally the maximum levels are reached from November to March and the minimum levels from late June to September. The maps presented with this article

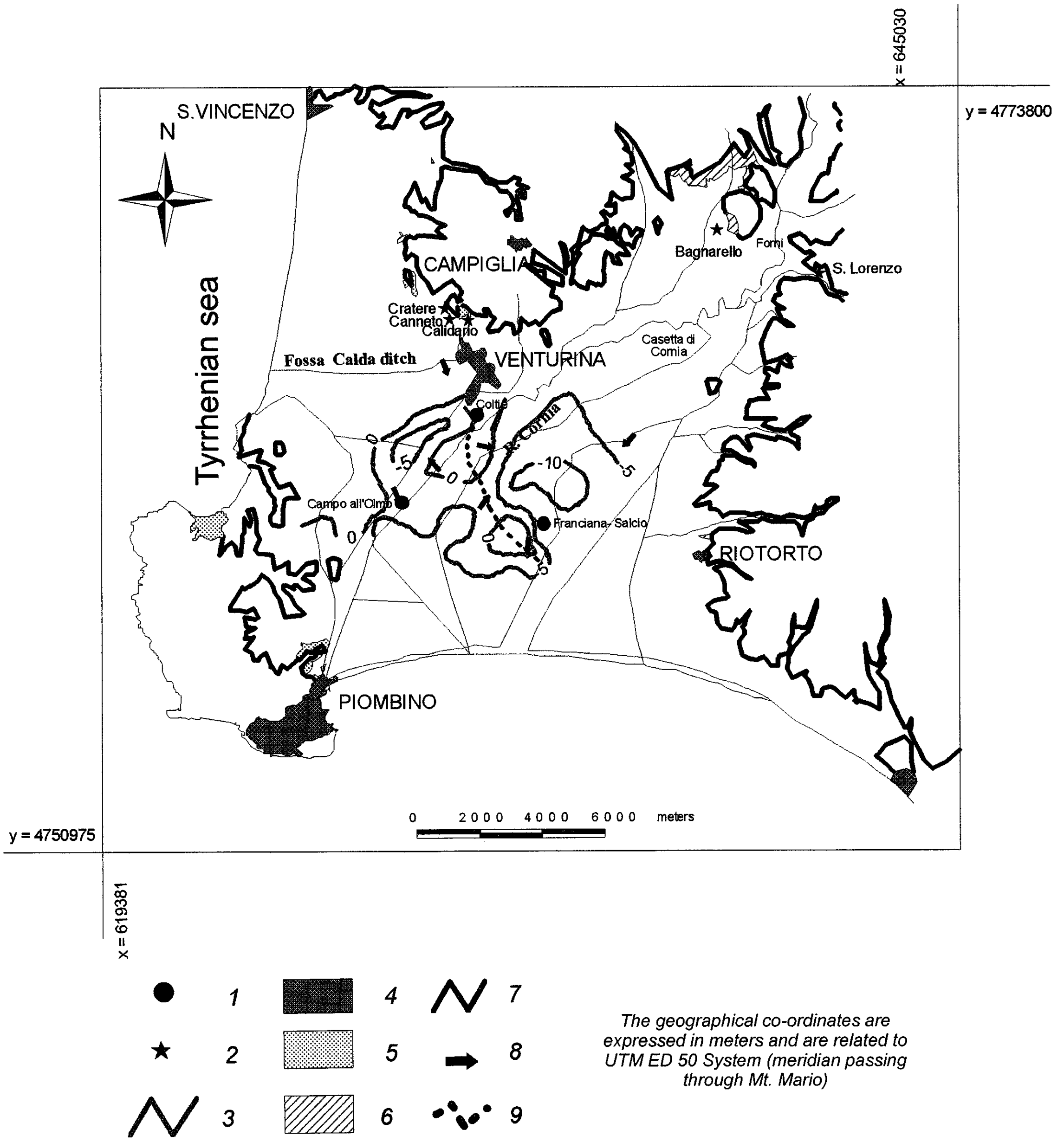


The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario)

Fig. 9
Groundwater level contour map for the Olocenic aquifer, September 1961 (after Bendini 1966, redrawn): *1* old well fields; *2* thermomineral springs and wells; *3* isolines (values in m asl); *4* urbanized areas; *5* landfills; *6* debris; *7* boundary of pre-Quaternary formations; *8* main groundwater flows; *9* groundwater divide

always refer to periods of potentiometric minimums. Such a choice is especially derived from a lack of data relative to periods of potentiometric maximums during the same months in the following years, thus failing the possibility to obtain correct evaluations on the temporal evolution of the hydraulic head during the high level phases. The potentiometric configuration of the Olocenic alluvial aquifer is remarkably changed over the passing of time. It is sufficient to remember that before the land improvement of the nineteenth and twentieth centuries, the sector between the River Cornia outlet and Venturina was filled prevalently by marshlands (Censini and others 1992, and references therein), and that the wells drilled at the beginning of the twentieth century in the southern coastal area were flowing wells (Canavari 1928).

The first potentiometric reconstruction of the River Cornia coastal plain occurred in September 1961 (Fig. 9), during the initial phases of the major exploitation. This demonstrates that, already then, a groundwater flow influenced by pumping wells for industrial and potable uses was present at Campo all'Olmo. The main intake areas of the aquifer are located to the northeast and west of Venturina. The groundwater flows are predominantly directed towards the southern coast, with an average hydraulic gradient of about 0.2% (Barazzuoli and others 1994). The hydraulic relationships between the River Cornia and the groundwater are not verifiable by means of

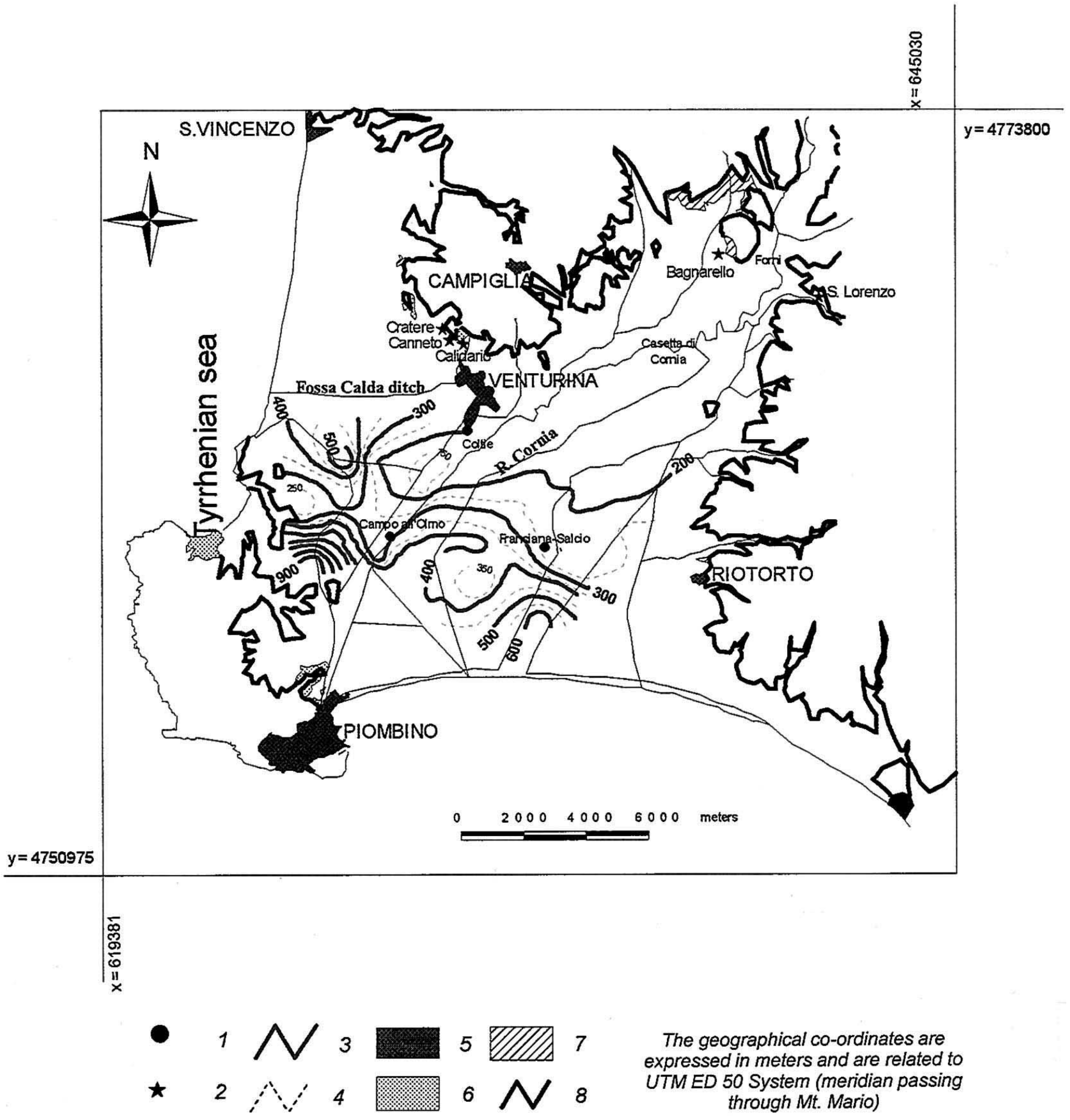


The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario)

Fig. 10
Groundwater level contour map for the Olocenic aquifer, July 1990 (after Barazzuoli and others 1994): *1* old well fields; *2* thermomineral springs and wells; *3* isolines (values in m asl); *4* urbanized areas; *5* landfills; *6* debris; *7* boundary of pre-Quaternary formations; *8* main groundwater flows; *9* groundwater divide

hydraulic head. In view of the previous observations on the geometric-structural characteristics of the aquifer complex, it is sufficient to remember that in the central-southern sector of the plain the river flows upon thick sediments of low permeability and, therefore, is essentially suspended. On the other hand, it should be noted that the Fossa Calda ditch, supplied by the discharge of the Calidario thermal baths, and thus with an almost constant outflow, is drained by a Pleistocenic unconfined aquifer, which in turn feeds the Olocenic aquifer (interaquifer flow). In fact, in this area the Olocenic aquifer is much more superficial and comes into contact with the Pleistocenic sands of good permeability of the S. Vincenzo-Palmentello plain (Cucini 1995).

The potentiometric order changed remarkably in July 1990 (Fig. 10). Compared to the previous situation, it is possible to notice the formation of large areas of negative hydraulic head which almost coincide with the main well field of that period. In fact, the water drawings for potable water, irrigation, and industrial uses are highly increased with respect to those of 1961, totalling 40×10^6 m^3/year. It should be noted that the groundwater flows directed toward the southern coast can be recognized again, with the same average hydraulic gradient of about 0.2%. The general lowering of the potentiometric



The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario)

Fig. 11
Chloride concentration contour map for the Olocenic aquifer, November 1990 (after Barazzuoli and others 1994): *1* old well fields; *2* thermomineral springs and wells; *3* main isolines (values in mg/l); *4* auxiliary isolines (values in mg/l); *5* urbanized areas; *6* landfills; *7* debris; *8* boundary of pre-Quaternary formations

level compared to 1961 was on the average equal to about 8 m and it had determined a decrease of the hydraulic head with the consequence lifting of the freshwater–saltwater interface, and the advancement toward the hinterland of a wedge of seawater intrusion (Barazzuoli and others 1994).

The lowering of the groundwater has accelerated the natural compaction of the recent sediments of the plain, with a subsidence rate that in recent years has locally exceeded 10 mm/year. This phenomenon involved, furthermore, a higher capacity for the increased presence of salt water along all of the watercourses which flow into the sea, contributing thus to the aggravation of the chemical quality of the groundwater present in the proximity of the coast (Bartolini and others 1989; Focardi and others 1992).

Chloride concentration in 1990

Figure 11 shows the distribution of the chloride concentration relative to November 1990 which constitutes the oldest information of its kind in large sectors of the plain. An examination of the map clearly shows that the groundwater quality is variable from mediocre to rather poor, at least as far as potable and irrigation uses are concerned. In fact, with an average content of chloride equal to 300 mg/l, it easily enters into the parameters of brackish water. This confirms that the groundwater pollution is mainly caused by seawater intrusion into the aquifer complex, especially in the areas facing the sea mainly involved in the hydric exploitation of that period.

Influence of new well fields on regional hydrogeology

Anello Project

In July 1994, new well fields at the Casetta di Cornia, Roviccione, Macchialta, and Amatello zones, for the purpose of a redistribution project (Anello Project) on the plain for drinking water extraction, were installed (Fig. 2). The new well fields began fully functioning in September 1994. In a programmed utilization framework of the local hydric resources, this project has displaced some continuous extractions (drinking water) far from the coast, where the qualitative condition of the waters had become critical by this time. In fact, maintaining in the proximity of the coast the summer extractions (irrigation water), and removing a part of the continuous extraction (drinking water, but not industrial water), the reduction of hydric extraction in the winter period can permit the partial systemic recuperation of hydrogeological balances modified during the drought period. The drinking-water wells must satisfy water requirements of some coastal communities and of the nearby Isle of Elba to which they are connected by a submarine pipe. The new wells substitute 18 of the 21 present at the Campo all'Olmo (aqueduct of Piombino), while the Coltie and Franciana-Salcio well fields are still operating.

The project's name is derived from the fact that all the drinking-water wells of the area were interactively connected by subsurface pipes. A telecontroled system composed of two central computers and by a peripheral network monitor, several parameters of the new wells (temperature, pH, and electrical conductivity of the water, potentiometric level, well discharge); the system is able to autonomously follow the progress of the water requirements of single users, conforming the extraction in quantity and location, according to a prioritization of optimal utilization of the groundwater (so that predetermined qualitative and quantitative groundwater characteristic base levels are not exceeded). As a consequence, the discharge of every drinking-water well currently varies from day to day and from season to season. During the winter, the wells exclusively serve the resident population and, therefore, it is possible to hypothesize a situation of a smallest exploitation of the aquifer. During the summer, the situation completely changes owing to a remarkable tourist influx in the coastal area and on the Isle of Elba (the population practically doubles with a dramatic increase of water requirements). By means of confirmation, it is sufficient to compare the average discharge drawn by the new well fields in the month of January 1995 (about 60 l/s) with that of the month of July of the same year (about 280 l/s).

Influence on potentiometric surface

In order to update the previous hydrogeological knowledge of the plain and to show the influence exercised by the new well fields on the potentiometric surface of the groundwater, two hydraulic head surveys were carried out in August 1994, and in September 1995. The first was conducted before the beginning of the full operation of the new well fields which occurred in September 1994, and the relative data have been collected by C.I.G.R.I.. The second, on the other hand, was conducted one year after the first, through direct observation by the authors (in collaboration with C.I.G.R.I.). The results obtained are presented in maps in Figs. 12 and 13, the examination and comparison of which permit the following observations (Cucini 1995).

In the first place, it is possible to observe locally an evident aquifer recharge due to fluvial seepage in the Casetta di Cornia zone, although it is difficult to identify the river–groundwater relationship in the sectors characterized by a hydraulic head strongly modified by pumping. Unfortunately, there are no available piezometers nor observation wells sufficiently close to Cornia affluents and artificial ditches in order to provide clear indications on the relationships between the secondary drainage pattern and the groundwater, by means of the analysis of the potentiometric surface. In addition, the comparison between the two potentiometric surfaces permits the identification of a notable change in groundwater flows. The surface relative to August 1994 is characterized by a regular potentiometric depression with a principal axis of NW–SE and by a isopiestic line 0 m asl located in the area of Venturina. The surface of September 1995 shows a depression significantly deeper and articulated. A marked groundwater divides to the west of Coltie, and especially has a considerable shift toward the north of the isopiestic line 0 which intrudes into the Casetta di Cornia zone. It is therefore possible to suppose that the introduction of functioning new well fields has provoked a rapid evolution of the potentiometric situation toward conditions of inferior protection of the aquifer from instances of seawater intrusion. By way of confirmation, it is sufficient to consider that the average hydraulic gradient along the NE–SW direction flow is equal to 0.35%, and thus, is almost doubled compared with that of 1961 and 1990.

The comparison between the hydraulic conductivity map of Fig. 7 and the potentiometric maps of Figs. 9, 10, 12, and 13, confirms the presence of water-bearing lithologies of low permeability on the left bank of the River Cornia to the southeast di Casetta di Cornia, and at the foot of the Campiglia hills in the thermomineral springs zone (where the hydraulic gradient is higher) and, vice versa, a situation of high permeability in the central sector of the plain (where the hydraulic gradient is lower).

Influence on chloride concentration

The chloride concentration is slightly altered by ionic exchange, precipitation, etc., with the result of rendering it an excellent natural tracer. Thus, the time evolution of such a parameter can confirm flow directions, and can

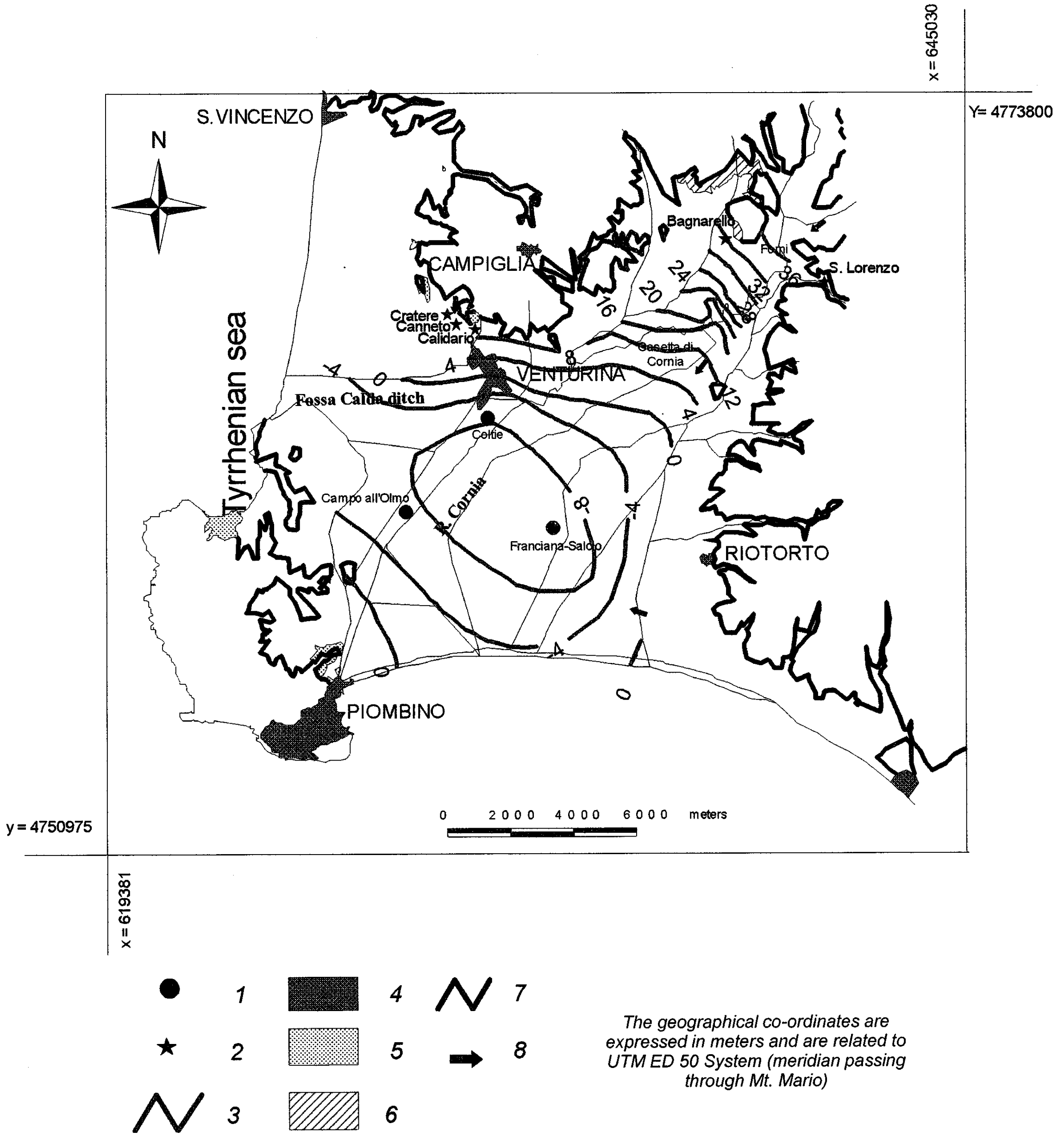
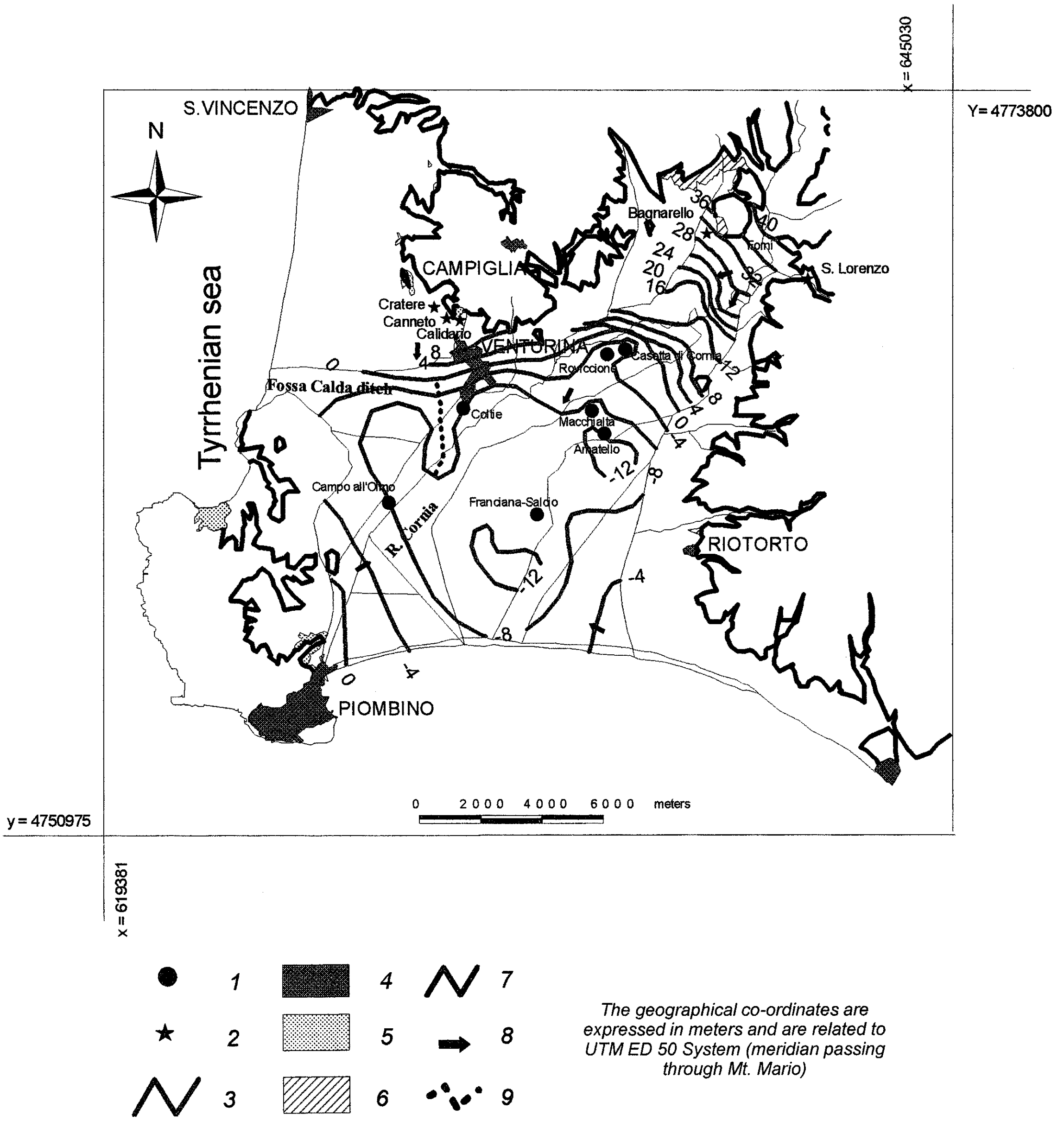


Fig. 12
Groundwater level contour map for the Olocenic aquifer, August 1994: *1* old well fields; *2* thermomineral springs and wells; *3* isolines (values in m asl); *4* urbanized areas; *5* landfills; *6* debris; *7* boundary of pre-Quaternary formations; *8* main groundwater flows

provide indications on the effect of the pumping increase principally in the areas characterized by seawater intrusion.

The comparison between the situation in September 1994 (Fig. 14), the data of which have been collected by C.I.G.R.I., and that in September 1995 (Fig. 15), based on the direct observations of the authors in collaboration with C.I.G.R.I., shows that in the new well field zones the chloride concentration has increased on an average of only 10 mg/l (the maximum values are always below the limits of 100 mg/l for freshwater) despite the remarkable decrease of the local potentiometric level (Figs. 12 and 13). It is necessary to take into consideration, however, that the change in the chemical equilibrium of the groundwater moves slower than that of the hydraulic head, and, therefore, it is logical to expect an increase of the chloride content in the next years, even in the zones currently exempt from problems of salinization. Thus, the chloride concentration increase can be underlined by the examination of the situation present in the Franciana-Salcio well field zone, where, following a reduction of the potentiometric level, the chloride concentration became elevated from 100 to 1000 mg/l in a period of one year (Cucini 1995).

One can notice that the pumping increase in the higher sector of the plain is causing a change in the direction of the wedge of seawater intrusion; while in September 1994



The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario)

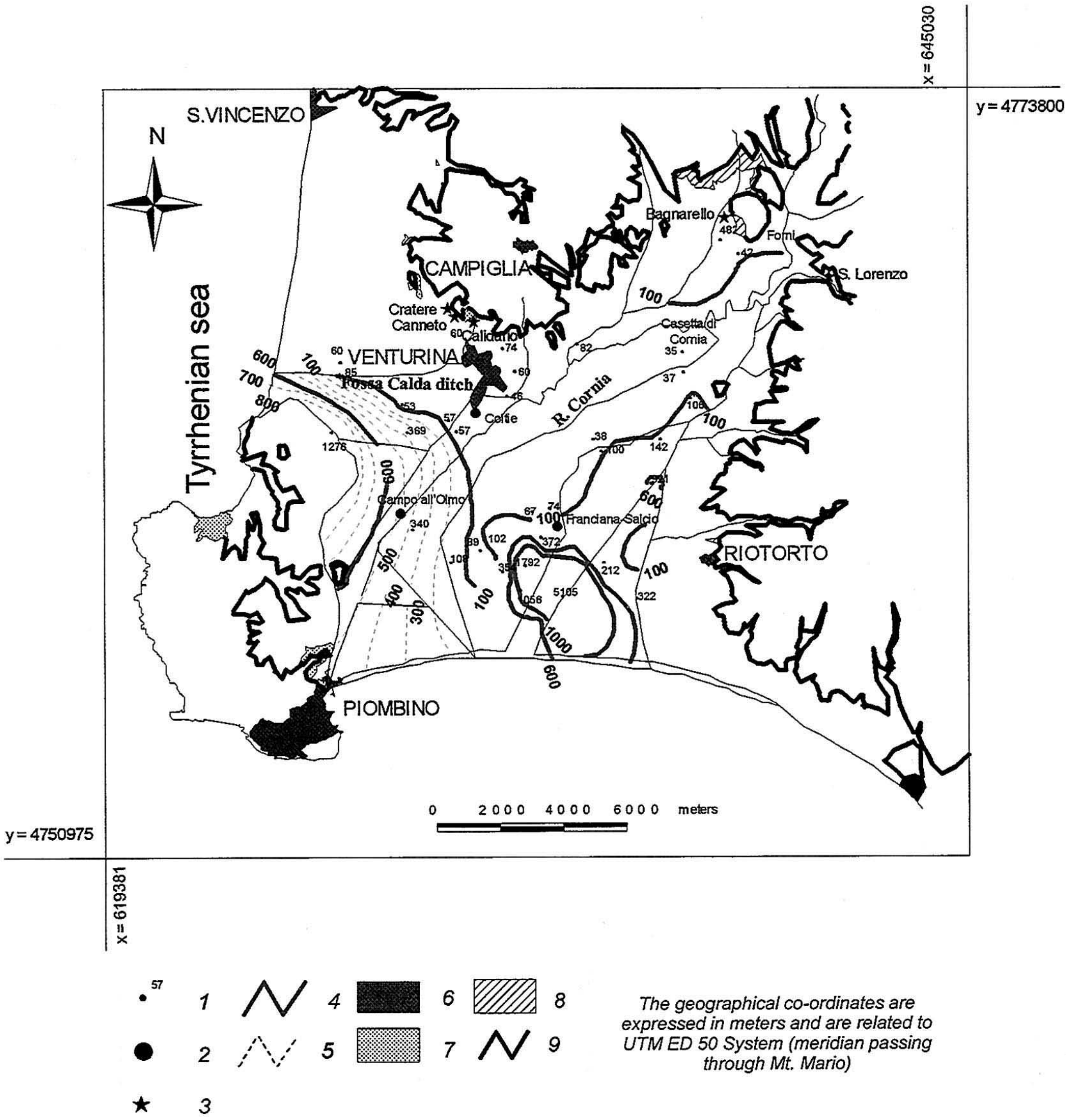
Fig. 13
Groundwater level contour map for the Olocenic aquifer, September 1995: *1* old and new well fields; *2* thermomineral springs and wells; *3* isolines (values in m asl); *4* urbanized areas; *5* landfills; *6* debris; *7* boundary of pre-Quaternary formations; *8* main groundwater flows; *9* groundwater divide

it was directed toward northwest (that is, along the Franciana-Salcio-Campo all'Olmo direction). In September 1995 it expanded toward the new well fields zones improving the chemical situation in the western coast (improvement which is also due to the local diminution of extraction).

Influence on groundwater balance

In order to evaluate the influence of new well fields on groundwater resources, preliminary calculations of hydrogeological balance were carried out in relation to periods preceding and following the implementation of the Anello Project (Table 2). The data relative to natural average inflow, and artificial outflow, were, for the most part, derived from C.I.G.R.I. collection and Ghezzi and others (1993). In particular:

1. The A inflow represents the water amount of meteoric recharge in the higher sector of the plain (Bagnarello-Casetta di Cornia zone), which total area (S) is about 40 km^2, and includes the direct infiltration into the alluvial deposits, and the contribution coming from neighbouring elevations, and the seepage of local streams and ditches. Owing to the fact that in this sector the aquifer complex crops out or is very superficial, and is characterized by high values of hydraulic conductivity (Fig. 7), it was hypothesized that the infiltration (I) into the aquifer corresponds to the local effective precipitation (P_e) which is equal to 250 mm/



The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario)

Fig. 14
Chloride concentration contour map for the Olocenic aquifer, September 1994: *1* measurement point with chloride concentration value; *2* old well fields; *3* thermomineral springs and wells; *4* main isolines (values in mg/l); *5* auxiliary isolines (values in mg/l); *6* urbanized areas; *7* landfills; *8* debris; *9* boundary of pre-Quaternary formations

year (Barazzuoli and Salleolini 1993). It was calculated as follows:

$$I=(S\cdot P_e\cdot 10^6)/(86{,}400\cdot 365)=317 \tag{1}$$

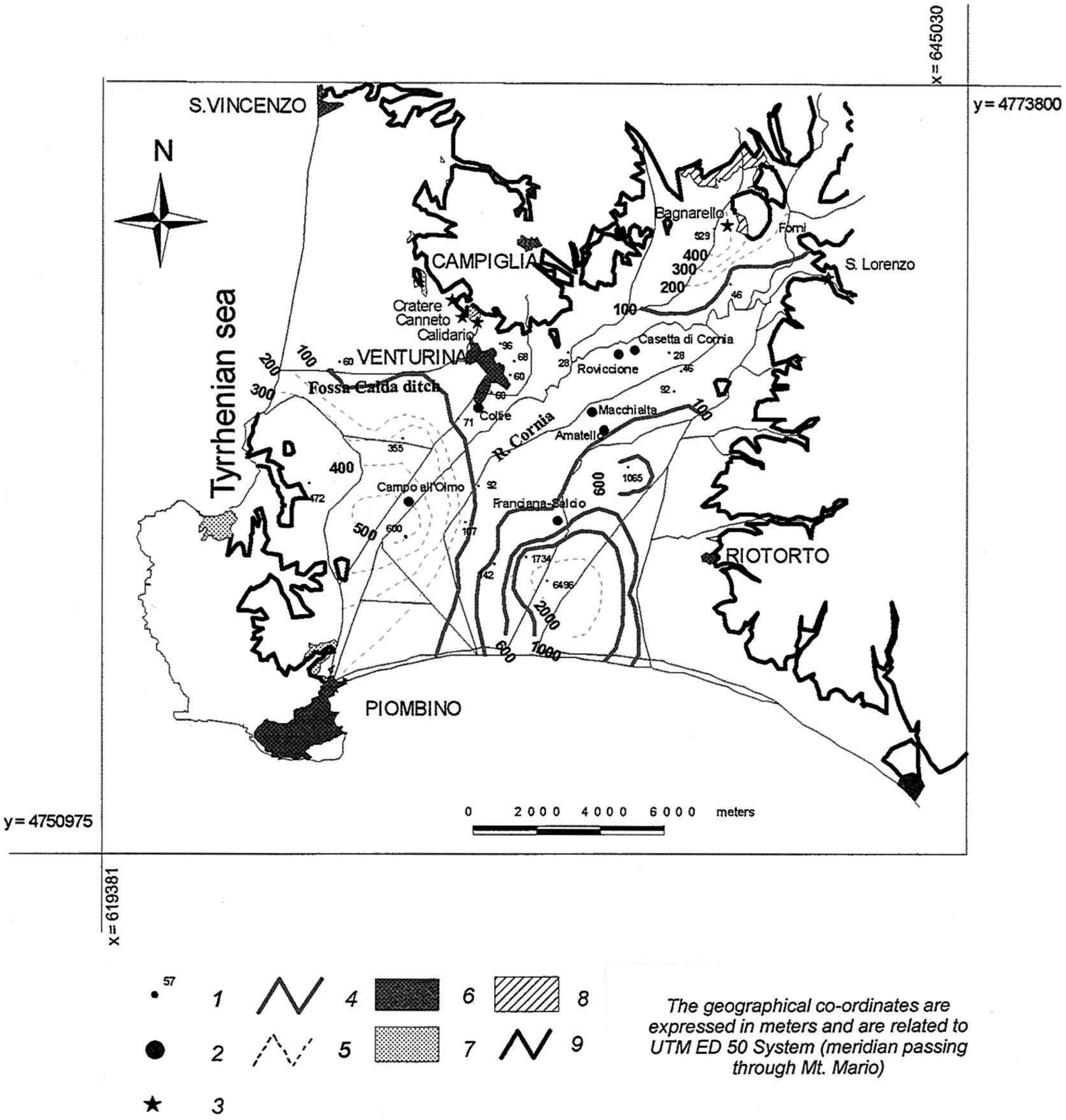
where *I* is expressed in l/s, *S* in km^2, and P_e in mm/year. This result was confirmed by means of the annual average potentiometric range (Δh) in the same zone (about 2 m), and the effective porosity (n_e) of the aquifer complex (equal to 12%; Barazzuoli and others 1994). It was calculated as follows:

$$I=(S\cdot \Delta h\cdot n_e\cdot 10^9)/(86{,}400\cdot 365)=304 \tag{2}$$

where *I* is expressed in l/s, *S* in km^2, Δh in m/year, and n_e is dimensionless. The validity of the latter evaluation is supported by the scarcity of water extractions in this sector and the absence of extraction of the salt water.

On the contrary, in the medium and low sectors of the plain, one can suppose that the infiltration into the aquifer is practically absent because of the lower values of effective precipitation and above all because of the remarkable thickness (above 10 m) of the clays on the top of the multilayered confined aquifer.

2. The B inflow corresponds to the River Cornia seepage in the Forni-Casetta di Cornia reach. It was evaluated by means of discharge measurements in correspondence with several fluvial sections, obtaining a contribution of about 475 l/s.



The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario)

Fig. 15
Chloride concentration contour map for the Olocenic aquifer, September 1995: *1* measurement point with chloride concentration value; *2* old and new well fields; *3* thermomineral springs and wells; *4* main isolines (values in mg/l); *5* auxiliary isolines (values in mg/l); *6* urbanized areas; *7* landfills; *8* debris; *9* boundary of pre-Quaternary formations

3. The C inflow represents the water contribution coming from the Campiglia hydrothermal system, equal to about 222 l/s, which can be subdivided in 190 l/s from the Venturina zone and 32 l/s from the Forni zone.
4. The D inflow corresponds to the water contribution coming from the Pleistocenic unconfined aquifer of S. Vincenzo-Palmentello plain, which is about 63 l/s.
5. The E inflow represents the groundwater discharge in correspondence with the Forni pass from which the coastal plain begins. It was evaluted by means of application of Darcy's law, obtaining a contribution of about 20 l/s.

Finally, it should be noted that the total inflow is to be considered as an underestimation because of the unknown contribution due to leakage from the depth aquifer.

With respect to the outflow, there are various factors of inaccuracy that can be considered equal to zero as a whole, among which would be the indication of natural outflow toward the sea and illegal use of the water, as factors contributing to an underestimation, and extraction of salt water during the pumping, as factors contributing an overestimation.

Table 2 shows that before the implementation of the Anello Project, the total inflow was 1097 l/s (equal to about 35×10^6 m^3/year) and the total outflow was 1330 l/s (equal to about 42×10^6 m^3/year), with a water deficit of

Table 2
Groundwater balance of the Olocenic aquifer of the River Cornia coastal plain. The meaning of the A, B, C, D, and E inflows is explained in the text

NATURAL AVERAGE INFLOW			ARTIFICIAL OUTFLOW		
	Recharge (l/s)	Recharge (%)	Values preceding to entrance in function of the "Anello Project"	Discharge (l/s)	Discharge (%)
A From effective precipitation in the Bagnarello-Casetta di Cornia area	317	29	A. by wells for industrial use	409	31
			B. by wells for irrigation use	652	49
B From River Cornia seepage in the Forni-Casetta di Cornia reach	475	43	C. by wells for potable use	269	20
			TOTAL OUTFLOW	1330	100
C From Campiglia hydrothermal system	222	20	Values following to entrance in function of the "Anello Project"	Discharge (l/s)	Discharge (%)
D From pleistocenic unconfined aquifer of S.Vincenzo-Palmentello plain	63	6	A. by wells for industrial use	409	28
E From groundwater discharge through the Forni pass	20	2	B. by wells for irrigation use	652	45
			C. by wells for potable use	387	27
TOTAL INFLOW	1097	100	TOTAL OUTFLOW	1448	100

about 7×10^6 m^3/year. Subsequently, the deficit increases as far as 11×10^6 m^3/year; the outflow wells for potable use increases by 7%, although it remains inferior with respect to the other outflows.

Boundary conditions of the Olocenic aquifer

The entire collection of the observations and elaborations conducted allowed the attainment of a profound knowledge of the Olocenic alluvial aquifer, of which have been defined the boundary conditions for the most part of the area studied (Fig. 16). This aquifer presents the following types of boundaries (Cucini 1995):

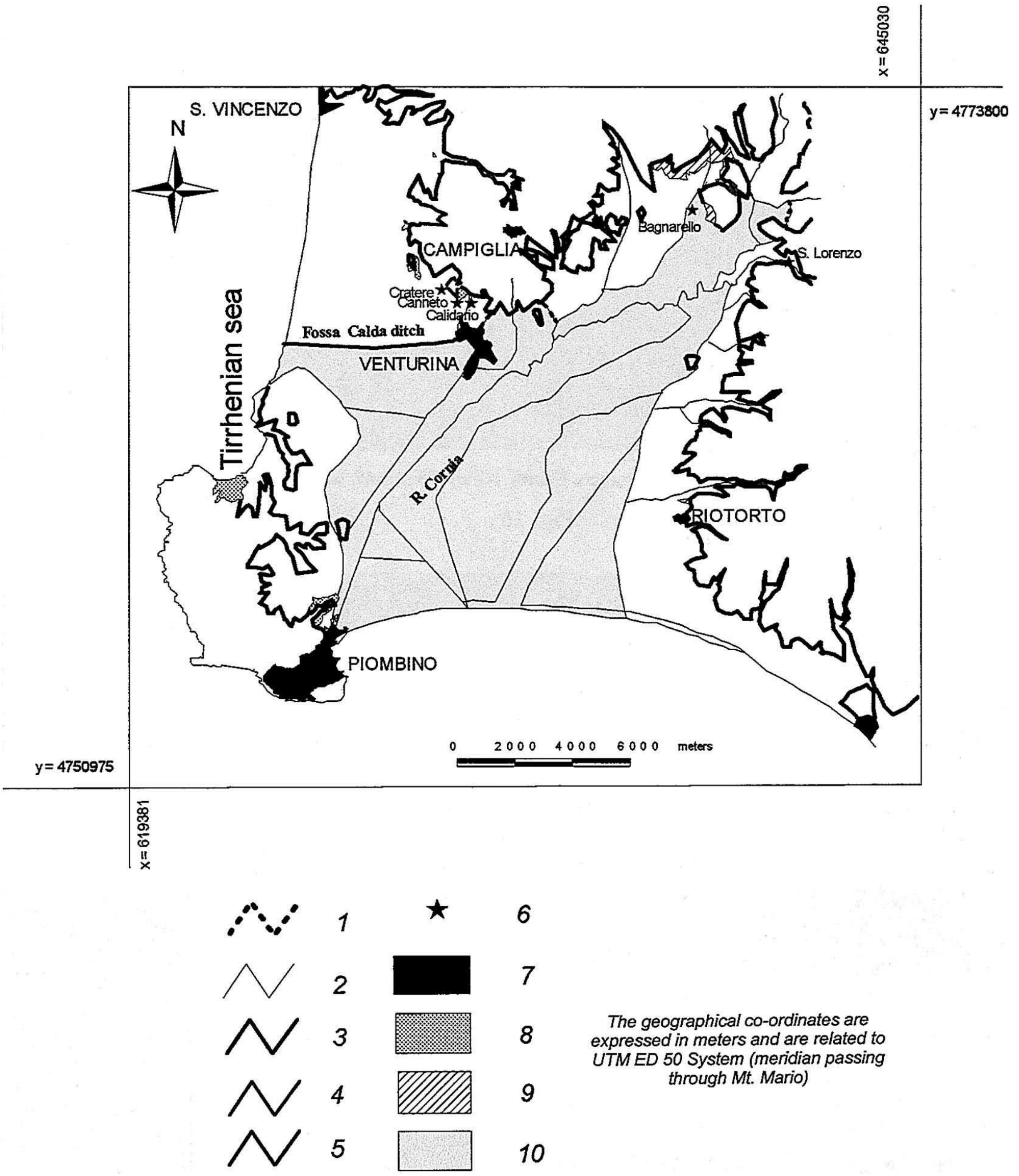
1. Boundary of prescribed hydraulic head, represented by coastline, River Cornia, and its affluents.
2. Boundary of zero flux, where the pre-Quaternary impervious formations crop out.
3. Boundary of prescribed flux, where the aquifer is directly in contact with the Mesozoic carbonate-siliceous formations of Tuscan facies. In fact, the present knowledge (Calore and others 1990; Grassi and Squarci 1993) confirms the intrusion of thermomineral waters of local and regional circulation into the Quaternary deposits. Therefore, one is presumably facing a hydrogeological discontinuity (lateral passage between Mesozoic and Olocenic formations with change of the kind and degree of permeability) which allows the passage of determinable water discharge from one aquifer to another.
4. Boundary of prescribed flux and hydraulic head, corresponding to the Fossa Calda ditch that collects the waters coming from the thermomineral springs of Mesozoic carbonate-siliceous formations, and recharges the underlying Pleistocenic unconfined aquifer of S. Vincenzo-Palmentello plain. In fact, this recharge occurs in a sector likely characterized by the passage between Pleistocenic and Olocenic domains, which is represented by the lateral continuity between the sand present underground in the Pleistocenic terrace, and the gravel present in the River Cornia plain at a depth of 50–60 m (Ghezzi and others 1993). In addition, the analysis of the isopiestic maps shows the presence of groundwater flows directed toward the Olocenic aquifer in the Fossa Calda zone.

The following step in the hydrogeological modelling of the Olocenic aquifer was to define the zone object of numerical simulation of the groundwater flow (Fig. 16), on the basis of the boundary conditions, and the analysis and distribution of collected data.

Conclusions and future research

The analyses and results described above can be summarized thus:

1. The local and regional hydrogeology has been organically reconstructed and synthesized on the basis of the studies and works previously conducted on the River Cornia coastal plain and of the measurement campaigns conducted during the present work. This allowed the recognition of:



The geographical co-ordinates are expressed in meters and are related to UTM ED 50 System (meridian passing through Mt. Mario)

Fig. 16
Definition of the sector of the Olocenic aquifer which will be object of hydrogeological modelling: *1* boundary to define during modelling stage; *2* boundary of prescribed hydraulic head; *3* boundary of zero flux; *4* boundary of prescribed flux; *5* boundary of prescribed flux and hydraulic head; *6* thermomineral springs and wells; *7* urbanized areas; *8* landfills; *9* debris; *10* zone object of future numerical simulation of the groundwater flow

- The expansion of areas characterized by a hydraulic head under the sea level.
- The progressive salinization of the groundwater subjected to extraction.
- The increase of water deficit in the Olocenic aquifer complex, that is produced by a water drawing progressively superior to the natural rate of recharge.

In addition, the benefits and disadvantages resulting from the location of the new well fields in a favourable zone from a hydrogeological point of view were defined. Actually, even if the seawater contamination does not reach the height of the new well fields, and the water quality in said zones maintains good values, a worsening in the zones previously contaminated is registered. The reduction of the fresh water recharge coming from the north, which is caused by extractions in the new well fields, has resulted in the expansion of the wedge of seawater intrusion near the southern coast, already highly contaminated. This conclusion cannot be extrapolated on a long-term basis because it is derived from restricted observations in time (the Anello Project lasted only one year).

It should be noted that the results obtained in the present work concern a period of potentiometric minimum limited in time. It is necessary to extend the surveillance of the aquifer during periods of potentiometric maximum in order to evaluate the quantity of recharge during the winter, and, consequently to draw conclusions of higher certainty.

2. A trustworthy and well-documented tabular and spatial database has been constructed and integrated with the preceding study on paper. The database can be further elaborated in a GIS system, allowing for the aspects emerging from local and regional hydrogeological study. This will allow, by means of GIS-modelling integration, the attainment of a numerical simulation of groundwater flow of the Olocenic aquifer, in the interior of the area represented in Fig. 16.

Therefore, the present work constitutes the basis for further developments. The GIS was used in support of making and updating the tabular and spatial database, with the aim of integrating the local and regional hydrogeological knowledge in view of a future modelling of the aquifer, and for a correct management of groundwater resources.

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