Intensive exploitation effects on alluvial aquifer of the Catania plain, eastern Sicily, Italy

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Received: July 22, 2003; accepted: May 4, 2004

RESUMEN

El crecimiento de un área industrial en la parte este de la Llanura de Catania en Sicilia ha causado una intensa explotación del agua subterránea, con consecuencias negativas en su equilibrio hidrodinámico y en la degradación de la calidad del agua. En este trabajo, la porción este de la llanura localizada entre el Monte Etna y la meseta Hyblean, es analizada por medio de las características litológicas de perforaciones y datos de resistividad, los cuales han permitido la reconstrucción de las relaciones geométricas en el depósito y sus variaciones de espesor. La variabilidad granulométrica de los depósitos aluviales (arena, cieno y grava) y su permeabilidad relativa son características de un típico acuífero multicapa que es libre en la parte superior y parcialmente confinado en su porción inferior. Descansa sobre un susbstrato de arcillas marinas cuya morfología es afectada por estructuras tectónicas controlando el espesor del acuífero. La piezometría muestra una pronunciada depresión causada por el descenso del nivel estático cercano a los 2 m anuales desde 1962 debido al bombeo de los pozos industriales. Esto también ha inducido infiltración de agua de mala calidad desde el acuífero contaminado sobreyaciente, mientras que perforaciones exploratorias profundas han causado una extensa contaminación del acuífero debido a los cloruros contenidos en el agua de las lentes arenosas dentro de las arcillas marinas subyacentes.

PALABRAS CLAVE: Llanura aluvial, acuífero multicapa, asentamiento industrial, contaminación acuífera.

ABSTRACT

Industrialization in the eastern part of the Catania plain has caused an intensive exploitation of groundwater, with negative consequences on its hydrodynamic equilibrium and water quality degradation. Lithological characteristics from boreholes and resistivity data have permitted the reconstruction of the geometrical relations within the deposit and its thickness varations. The granulometric variability of the alluvial deposits (sand, silt and gravel) and its relative permeability are characteristics of a typical multilayered aquifer system that is unconfined in the upper part and partially confined in its lower portion. It rests on a clayey marine substratum whose morphology is affected by buried tectonic structures controlling the aquifer thickness. The piezometric surface shows a pronounced depression caused by the falling of the groundwater level by about 2 m year^{-1} since 1962 due to pumping from industrial wells. This has also induced infiltration of poor quality water from the overlying polluted aquifer, while deep test holes have caused further pollution of the aquifer owing to chloride water contained in sandy lenses within the underlying marine clays.

KEY WORDS: Alluvial plain, multilayered aquifer, industrial settlement, groundwater pollution.

INTRODUCTION

The Catania plain in eastern Sicily, Italy, with a surface of about 428 km^2, is the most extensive of Sicilian plains. It is constituted by the deposits of three rivers, Simeto, Dittaino and Gornalunga.

The outcropping units consist of recent alluvium and sediments of the regressive Plio Pleistocene series that constitute an aquifer of notable economic interest for the area.

The Catania plain is the site of extensive agricultural activity, and its eastern portion is occupied by industrial infrastructures, two airports, and lifelines of great importance for the entire eastern sector of Sicily. The development of productive activity and of infrastructures have strongly influenced the quantity and quality of groundwater and led to a degradation of the water resources.

In this work, we analyze the consequences of intense exploitation of groundwater resources on the hydrodynamic conditions of the aquifer and on the chemical characteristics of the water, using data derived from boreholes and production wells, from geophysical investigations and from water analysis. This has allowed to reconstruct the geometry of the aquifer and the evolution of the piezometric surface, distinguishing the areas that are most exposed to excessive exploitation. With the aid of data from chemical analysis of water samples taken during the period 1997-2000 from wells in the industrial area, a deterioration of the water quality was observed and can be attributed to the drawing of poor quality water.

GEOLOGICAL CONTEXT

The Catania plain, located between Mt. Etna and the Hyblean Foreland (Figure 1), lies within the Plio-Quaternary foredeep (Lentini, 1982; Ben-Avraham *et al.*, 1990; Lentini *et al.*, 1994) that originated from the collapse of the northern margin of the Hyblean Plateau due to extensional faulting (Grasso, 1993).

The geological and geophysical data suggest that this collapse occurred after the Late Pliocene (Torelli *et al.*, 1998) as a result of the progressive migration of the Maghrebian thrust wedge (the "Gela Nappe" front) toward the foreland (Butler *et al.*, 1992). Data from gas and oil research drilling has revealed the presence of about 600 m of Plio-Pleistocene sediments (Yellin-Dror *et al.*, 1997).

The most recent unit of this succession, on which lie the clastic deposits of the plain, is represented by Pleistocene marine marly clays, which also constitute a part of the sedimentary basement of Etna. Biostratigraphic study (Lanzafame *et al.*, 1997; Di Stefano and Branca, 2002) has attributed an age of 1.2-0.589 Ma to these sediments, and a different paleobathymetric value proceeding from north to south has been interpreted as being caused by differential uplift of the area (Stewart *et al.*, 1993). The marine clays show synsedimentary structures which testify to their involvement in the compressional front of the Maghrebian chain (Bousquet and Philip, 1986), subsequently cut by normal faults (Labaume *et al.*, 1990).

The marly clays are exposed along the northern margin of the plain, at the base of the Terreforti hills (Francaviglia, 1962) (Figure 2), and are overlain by sandy gravels and continental conglomerates containing volcanic clasts referable to the first subaerial Etnean lava flows of tholeitiic composition (about 320-250 ka; Gillot *et al.*, 1994). These deposits, which are of middle Quaternary age (Lentini *et al.*, 1979), particularly of the Riss (Kieffer, 1971), are affected by reverse faults connected to a N-S compressive tectonic regime (Labaume *et al.*, 1990).

The Pleistocene succession is unconformably overlain by alluvial deposits as a result of an erosional phase connected with the uplift of the whole area (Bousquet *et al.*, 1988). These consist of sandy silts with intercalated lenses of gravels and sands. These deposits correspond to the stratigraphic-depositional model proposed by Miall (1978), characterized by a lateral and vertical continuity depending on the modes of deposition in a deltaic plain environment, as also shown by the frequent peat levels and carbonatic concretions that were discovered at various depths within the stratigraphy of boreholes of the industrial area. The peat levels are only a few centimeters thick and occur along a N-S alignment parallel to the present coastline, lying about 1.5 km inland.

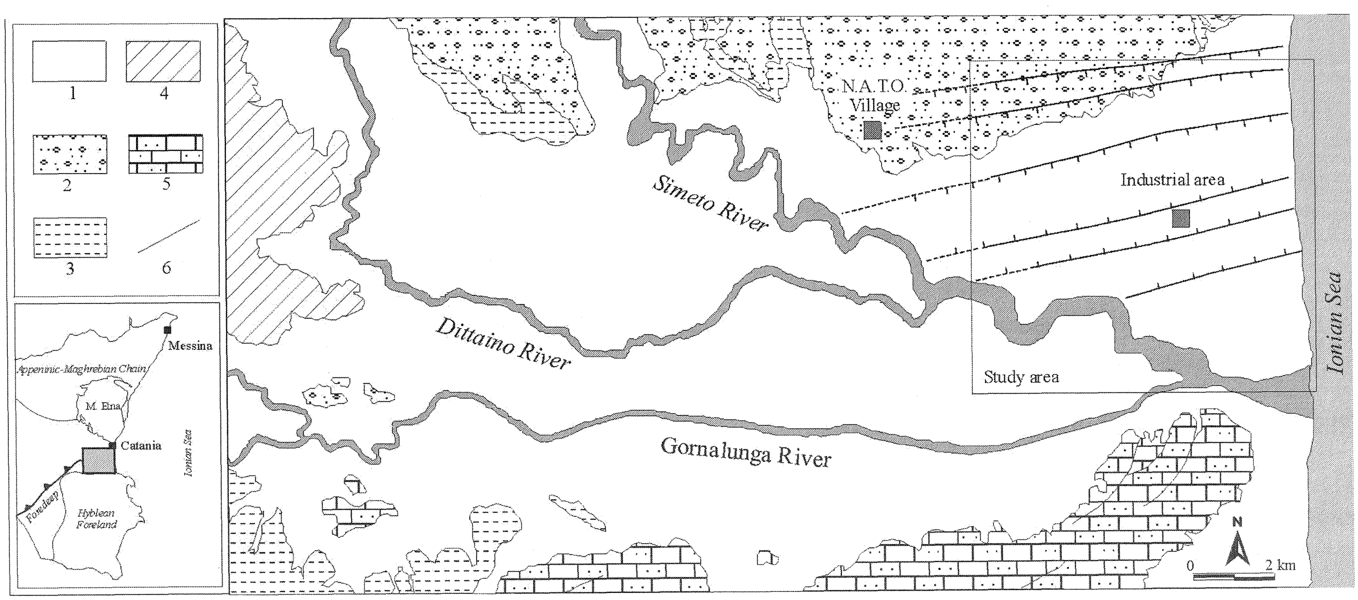

Fig. 1. Geological setting of the Catania Plain. 1) Recent alluvial deposits; 2) Pleistocene sands and conglomerates; 3) Pleistocene marly clay; 4) Sedimentary terrains of Maghrebian Chain; 5) Pli-Pleistocene sediments of Hyblean Foreland; 6) Normal fault (modified after Ferrara, 1999).

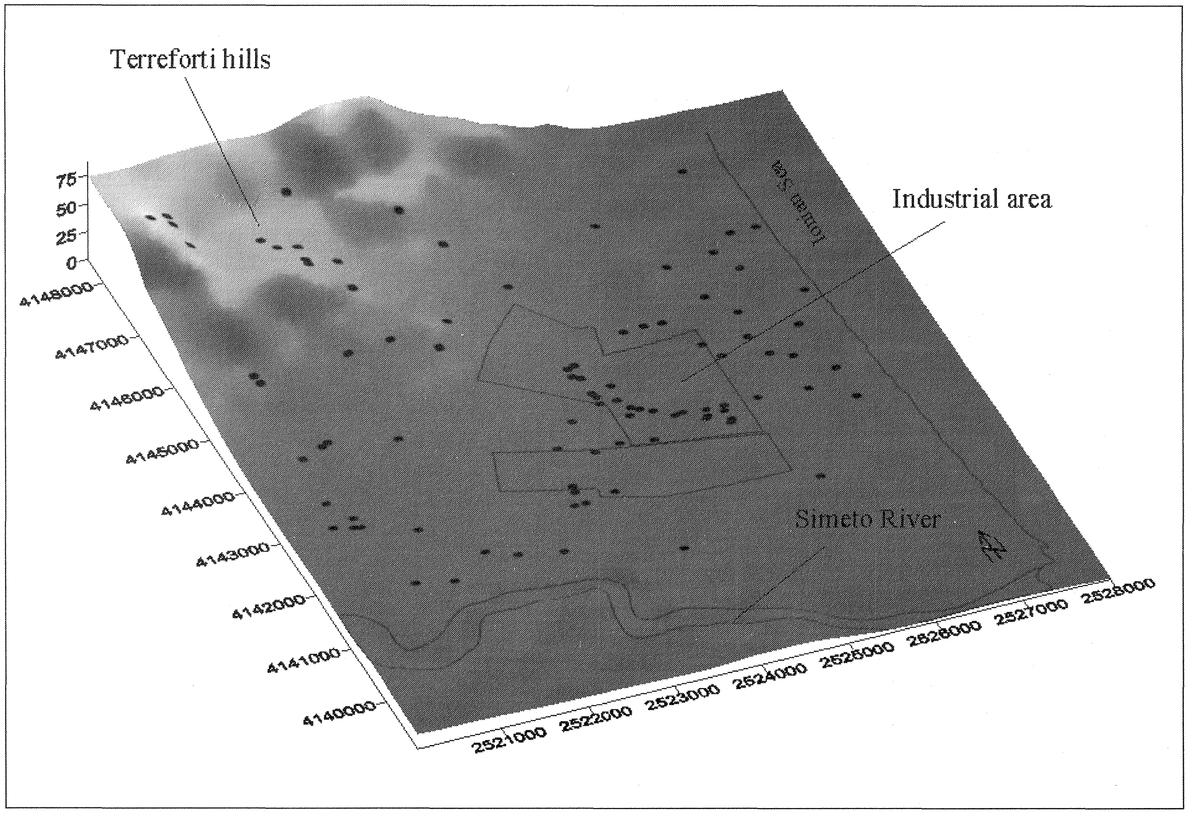

Fig. 2. Digital Terrain Model (DTM) of the study area.

The structure of the detritic deposits and the morphology of their substratum constituted by the marine clays have been reconstructed by means of borehole and well data (Figure 2). The resulting framework has been compared to a previous reconstruction based essentially on geoelectric investigations (Breusse and Huot, 1954) (Figure 3), showing good agreement regarding the position of an E-W trending buried valley that can be attributed to the ancient course of the Simeto river. However, our data show the depth of the clayey substratum to be 20-30 m greater than determined by the geophysical investigations (Figure 4). The maximum thickness of the clastic deposits is thus 110 m rather than the previously assumed 80-90 m, particularly evident in the central portion of the area, where there is a deep depression of the substratum corresponding to a graben delimited by a system of NNE-SSW trending faults (Figure 3). The depression furthermore appears to be bounded to the E by a structural high where the thickness of the alluvial deposits drops to about 60 m, constituting a partial permeability threshold.

LITHOLOGY AND GEOMETRY OF THE ALLUVIAL DEPOSITS

The lithology of the alluvial deposits is characterized by discontinuous levels of sandy and clayey silts whose thickness shows strong variations, and which alternate with sandy-gravely lenses without any sorting (Figure 5).

Below the recent alluvial deposits there are Pleistocene sandy-gravely deposits and conglomerates, whose average thickness is 20 m and locally reaches 50 m. These constitute the most productive portion of the aquifer, which is semiconfined in the central sector of the plain and free in the area of the Terreforti hills.

The conceptual model of the Pleistocene deposits envisages, starting from the surface, sandy silts followed by sandy and gravel lenses that alternate with clayey silts and finally lenses of gravels and conglomerates of greater thickness. From a hydrogeological point of view this creates variable conditions of vertical and horizontal permeability that give rise to three superposed aquifer levels with different conditions of confinement. Going from east to west, a decrease of the thickness and frequency of the most coarse-grained deposits and an increase of the fine-grained deposits are observed (Ferrara and Marchese, 1978).

AQUIFER CHARACTERISATION

The larger thickness of the aquifer corresponds with

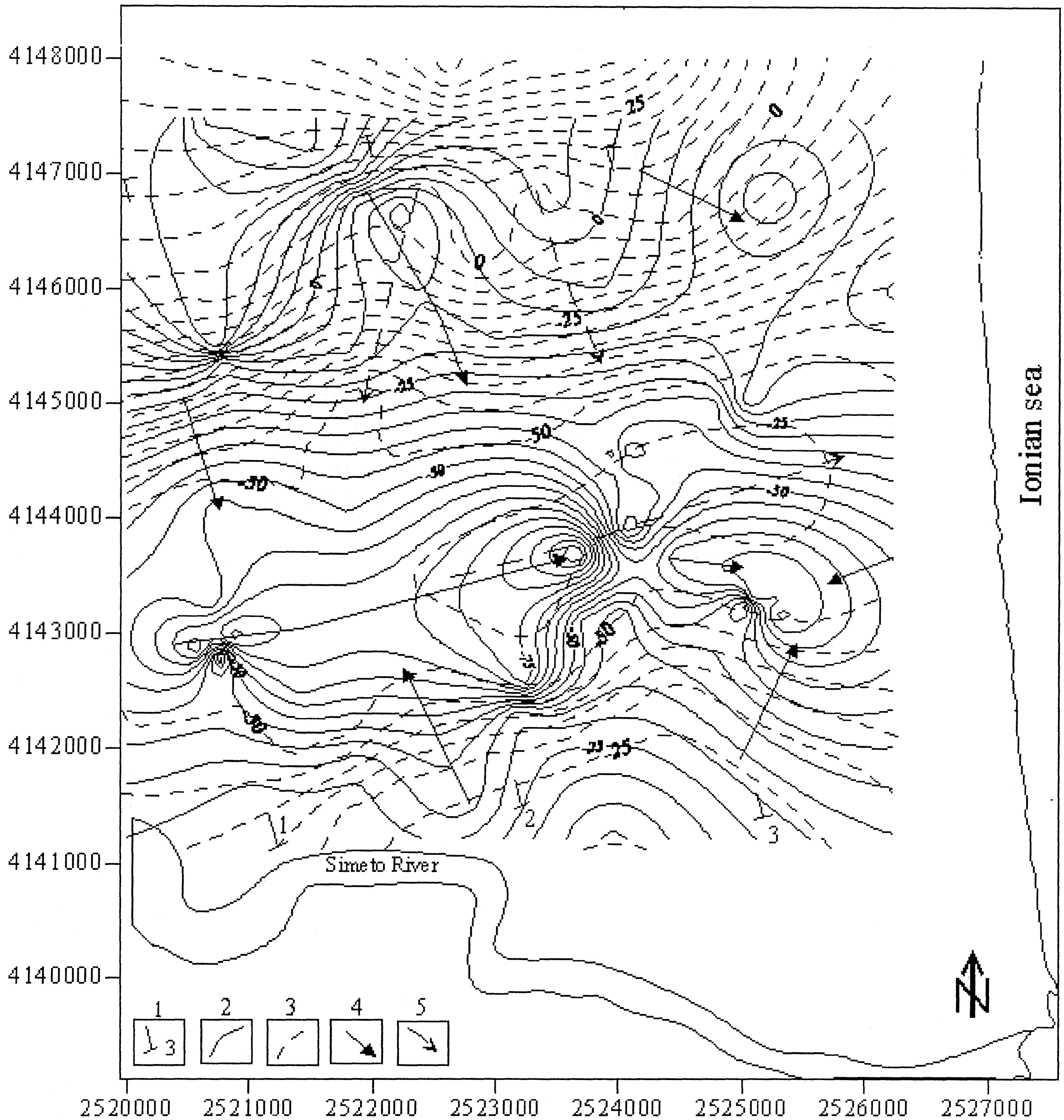

Fig. 3. Morphology of the Pleistocene clayey-marly substrate. 1) Section; 2) Data from wells; 3) Geophysical data; 4) Axis of the depression in the clayey substrate from geognostic data; 5) Axis of the depression in the clayey substrate from geoelectric data.

the site of the industrial area, where the highest density of productive wells of the entire study area are located. The yield of the wells is generally about 20 l/s, and reaches maximum amounts of 40 l/s. Among these, 16 wells belonging to the Industrial Development Agency (ASI) have depths of 60-70 m and together yield about 385 m^3/h (Ferrara, 1998). Other wells are not used due to the excessive chloride content in the waters. In the hilly zone of the Terreforti, the depths of the wells do not exceed 50 m and water productivity is generally around 10 l/s.

The piezometric surface has been reconstructed through water level measurements since 1997. The main directions of groundwater flow in the plain, follow the main depressions of the impermeable substrate oriented W-E. In correspondence with the hills, the orientations are NW-SE and NNW-SSE, flowing together in the ancient valley of the Simeto river (Figure 6).

The average annual withdrawal of groundwater in the entire plain is estimated at 22.5 x 10^6 m^3 (Ferrara, 1998); whose major proportion is extracted within the industrial area, this has created a strong depression in the piezometric surface currently lying below the sea level (Figure 6). This can be attributed to the progressive increase in groundwater extraction as shown by measurements of the water level carried out in the wells of the industrial area between 1962 and 1967 (Figure 7).

Pumping tests made in some wells that traverse the entire aquifer have yielded permeability values ranging from 5 x 10^{-2} m/s to 10^{-4} m/s and transmissibility values between 1 x 10^{-3} m^2/s and 5 x 10^{-3} m^2/s.

HYDROCHEMICAL STUDY

Extraction of groundwater in the area of the plain can be estimated at 22.5 x 10^6 m^3/yr, which is much higher than the direct infiltration rate from precipitation of approximately 7.2 x 10^6 m^3/yr, (Ferrara, 1999). Even when considering that most of the aquifer recharge takes place through the stream underflow and reinfiltration of the irrigation waters, the aquifer system must be considered over exploited, as shown by the progressive drop of the piezometric levels and the variations in water quality.

The depression of the piezometric surface in the industrial area, causes an increasing salinity due to saltwater intrusion from the Ionian sea.

Samples of water taken from 33 wells in December 1997 in the industrial area and near the mouth of the Simeto river have shown elevated values of conductivity (up to 11.000 μS/cm) (Figure 8a), which are mostly due to the mixing with brine, as demonstrated by the Cl^- content of up to 5400 mg/l (Figure 8b). In contrast, lower values of conductivity (< 2000 μS/cm) and of the Cl^- content (< 250 mg/l) have been observed in the sector lying close to the Terreforti hills, due to the influx of fresh water from uphill and the much less intense extraction of groundwater. The highest sulphate contents (> 1500 mg/l) (Figure 8c) are observed near the Simeto river and the coastal belt, whereas the nitrate contents (> 150 mg/l) (Figure 8d) varies in function of the inhomogeneous density and typology of agricultural and industrial activity.

Monitoring of 6 wells in the industrial area has allowed to recognize an increase in the conductivity values of 23% during the period 1997-2000 (Figure 9) and at the same time an increase in the content of some of the main ions (Na, Mg and Ca) in the waters that varies from one well to another (Figure 10). In the case of sodium, the increase is not constant but varies from one year to the other; the same is observed for iron, whose maximum value is 10,2 mg/l, while

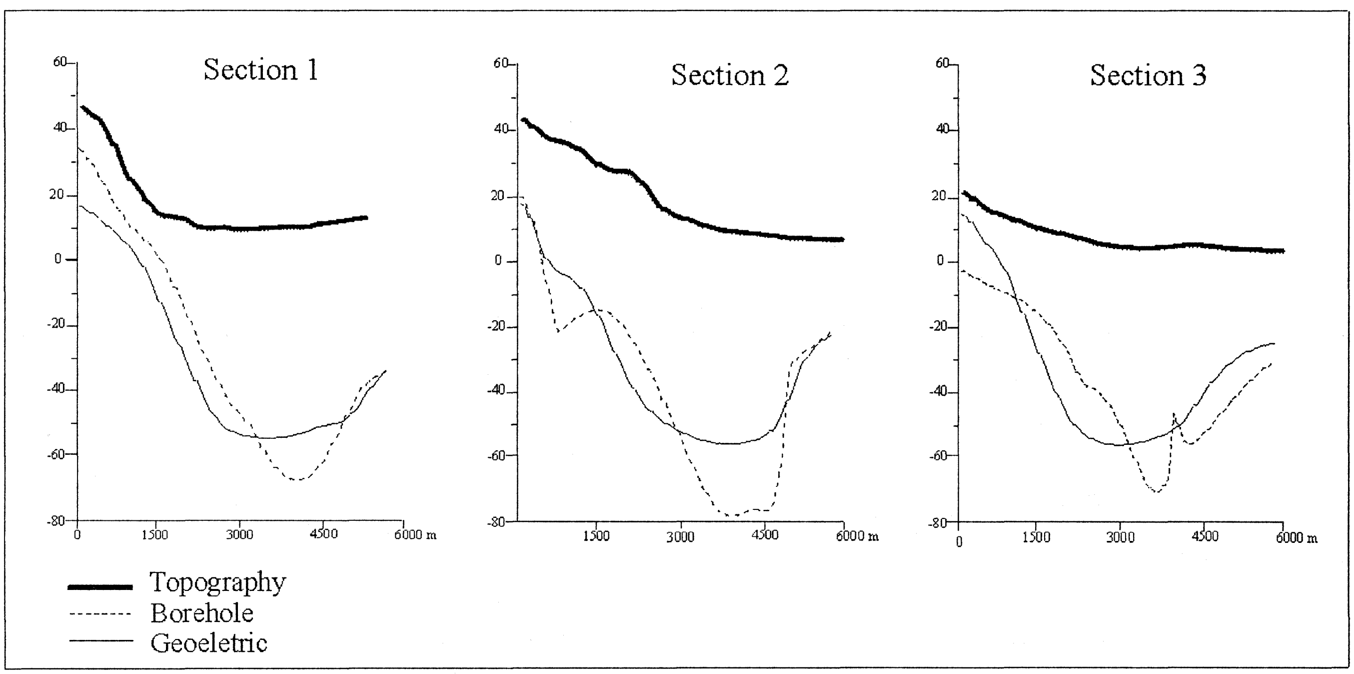

Fig. 4. Sections through the Pleistocene clayey-marly substrate (see Figure 3 for location of trace).

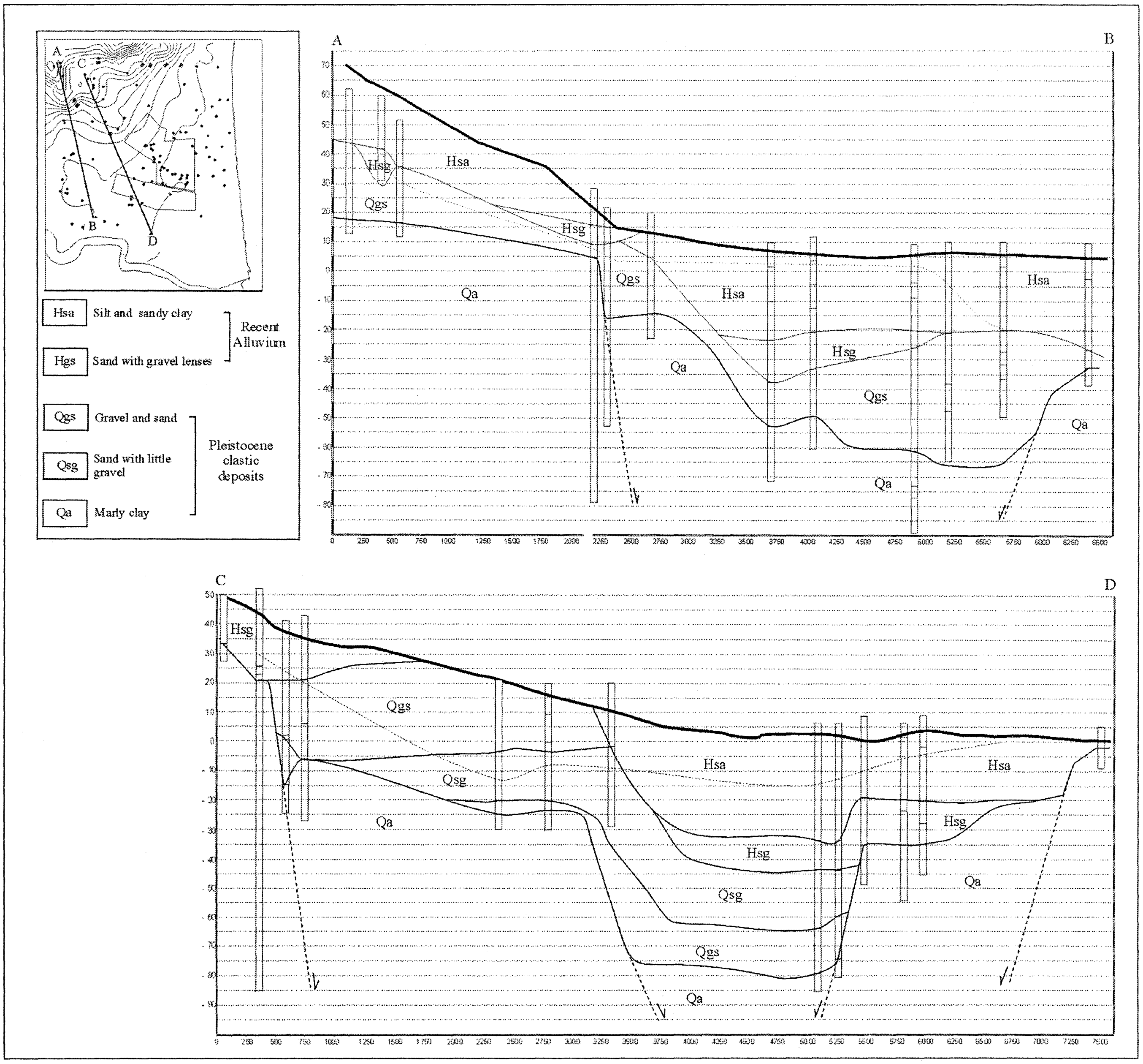

Fig. 5. Lithostratigraphic sections of the study area.

the magnesium content shows a constant increase, reaching a maximum of 0.83 mg/l. The high concentration in these elements might depend, among others, on the heavy pumping, which leads to the mobilization of deeper mineralized waters and to the attraction of polluted waste waters from the shallow zone of the aquifer in the industrial area. This is confirmed by the presence of cadmium and chromium in the waters of all wells (Figure 11).

CONCLUSION

Until the end of the 19th century, when extensive hydraulic drainage was begun in the Catania plain, this area has been free from extensive human settlements due to the unfavorable environmental conditions. In relatively recent time and particularly during the past twenty years there has been an expansion of agricultural activity and industrial activity into the plain, together with residential and touristic areas along the coast at the same time.

As a consequence of this development, there has been a strong increase in the demand for water, which has led to the extraction of ever greater quantities of groundwater from the clastic deposits of the plain, with a progressive lowering

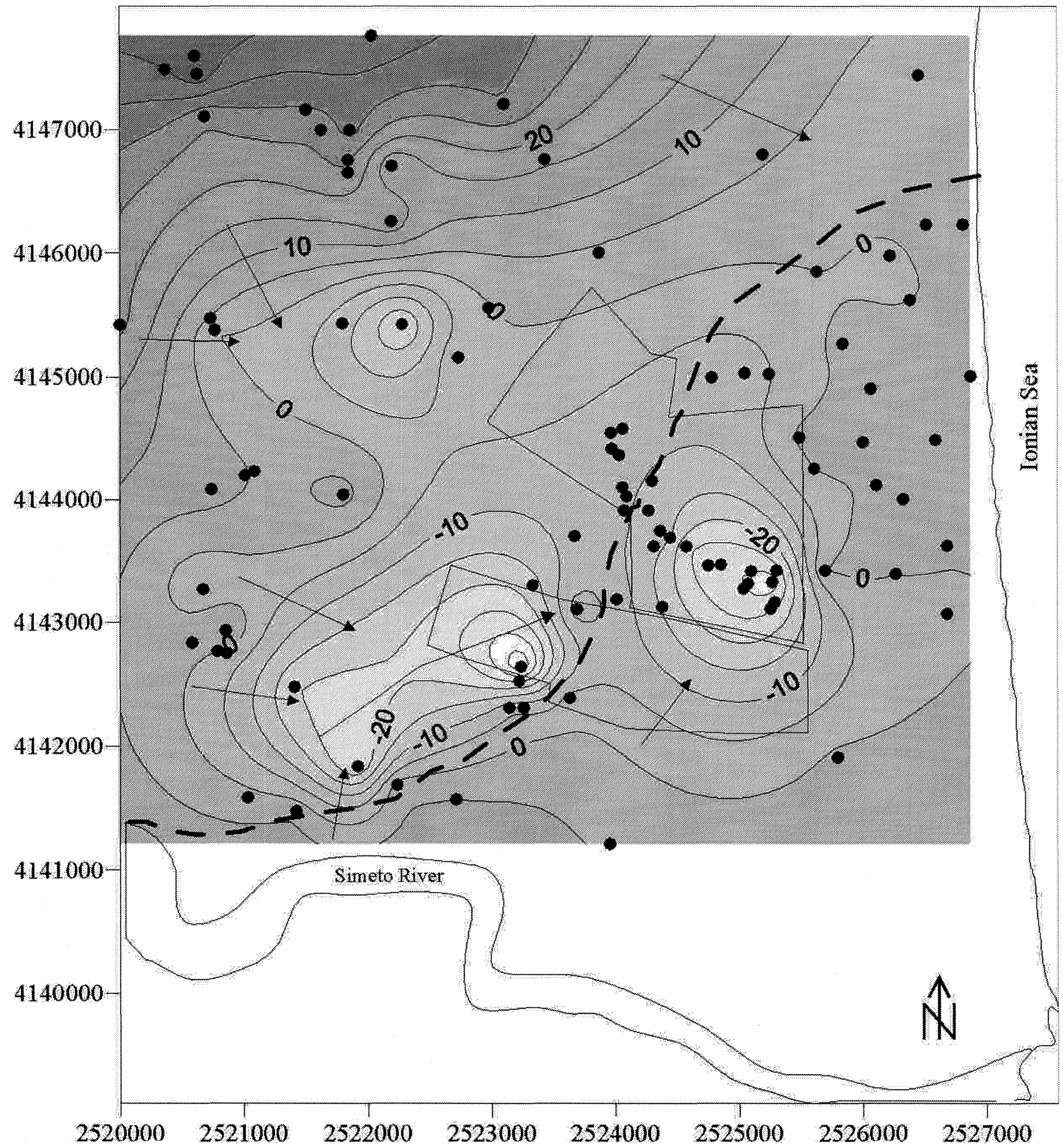

Fig. 6. Piezometric surface (1997). Arrows indicate groundwater flow directions; full circles indicate wells of measurements; dashed line indicate salt water intrusion.

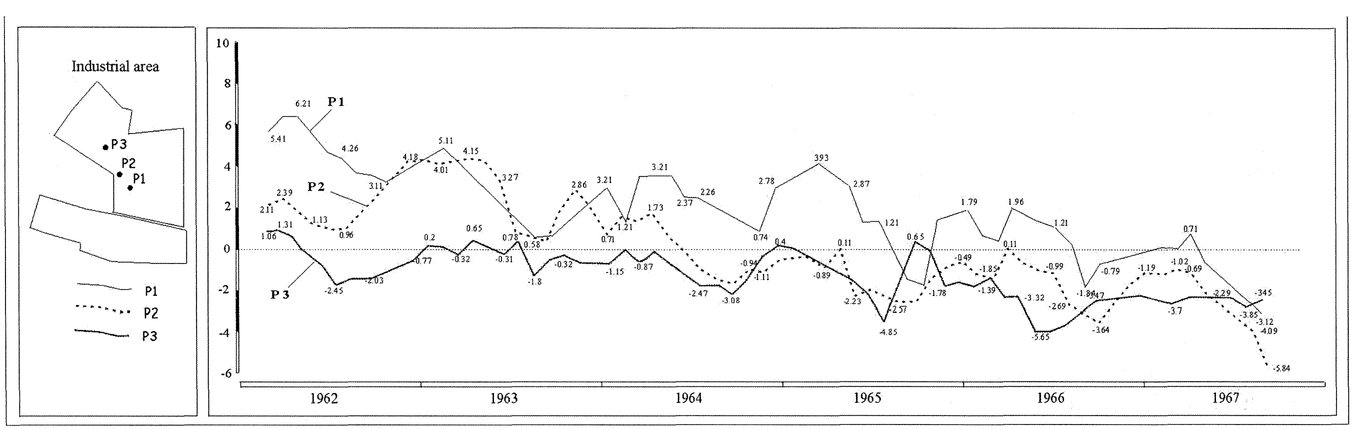

Fig. 7. Water level evolution observed in the wells of the industrial area.

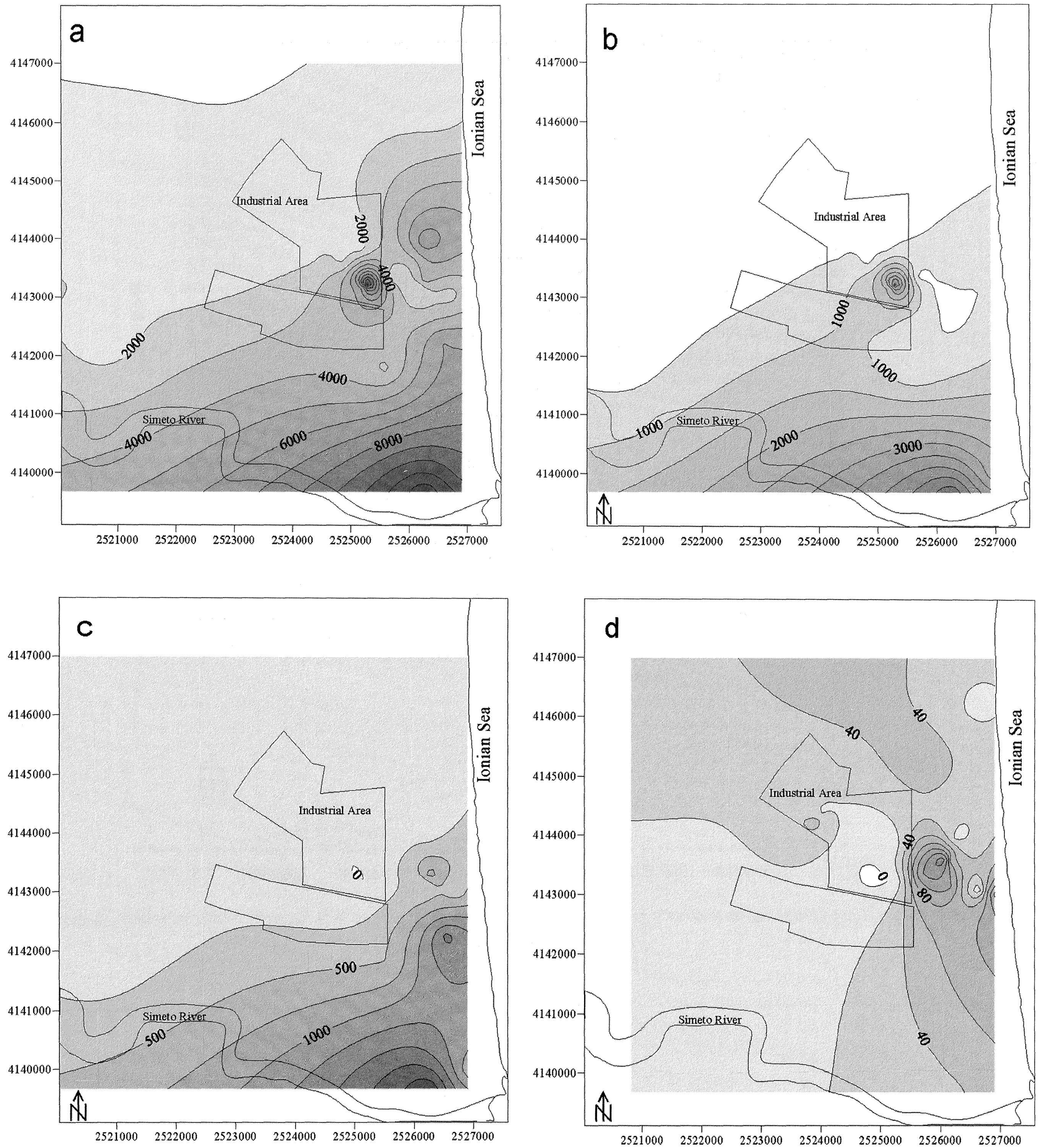

Fig. 8. Distribution of conductivity in μS/cm (a), chlorides (b), sulphates (c) and nitrate (d) in mg/l during 1997.

of the piezometric surface. At the same time, the water quality was substantially modified with a strong increase in salinity caused by marine ingression, and pollution by chemical products used in agriculture (fertilizers and pesticides) and industrial waste, which also contain heavy metals and are mainly concentrated in the northeast sector of the plain.

This has led to major modifications in the hydrody-

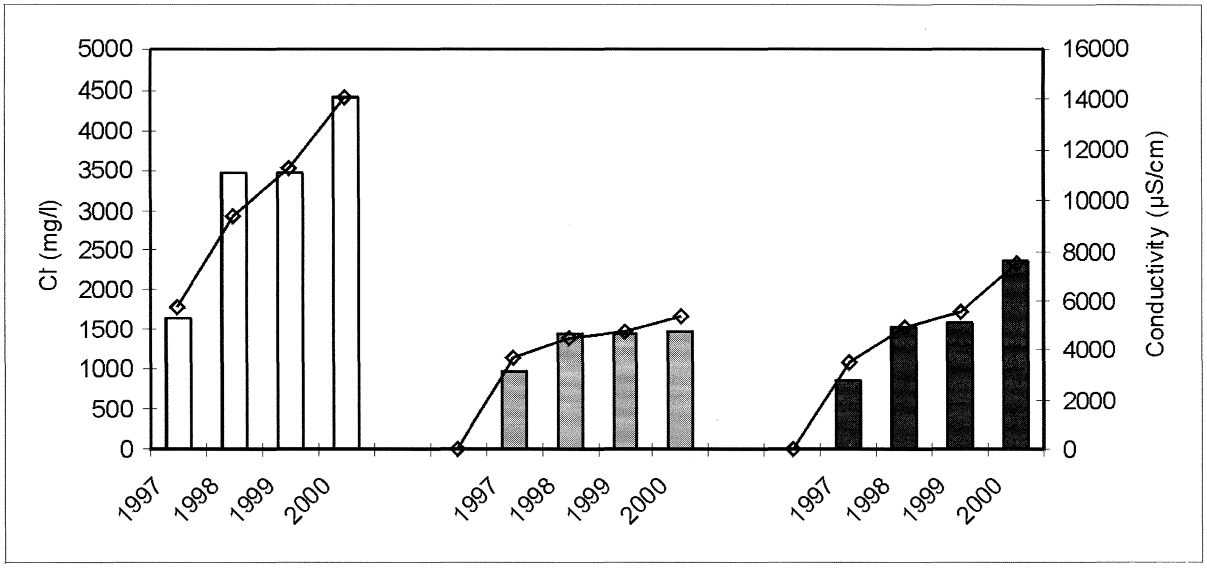

Fig. 9. Evolution of chloride concentration and conductivity values between 1997 and 2000 in the three wells of the industrial area.

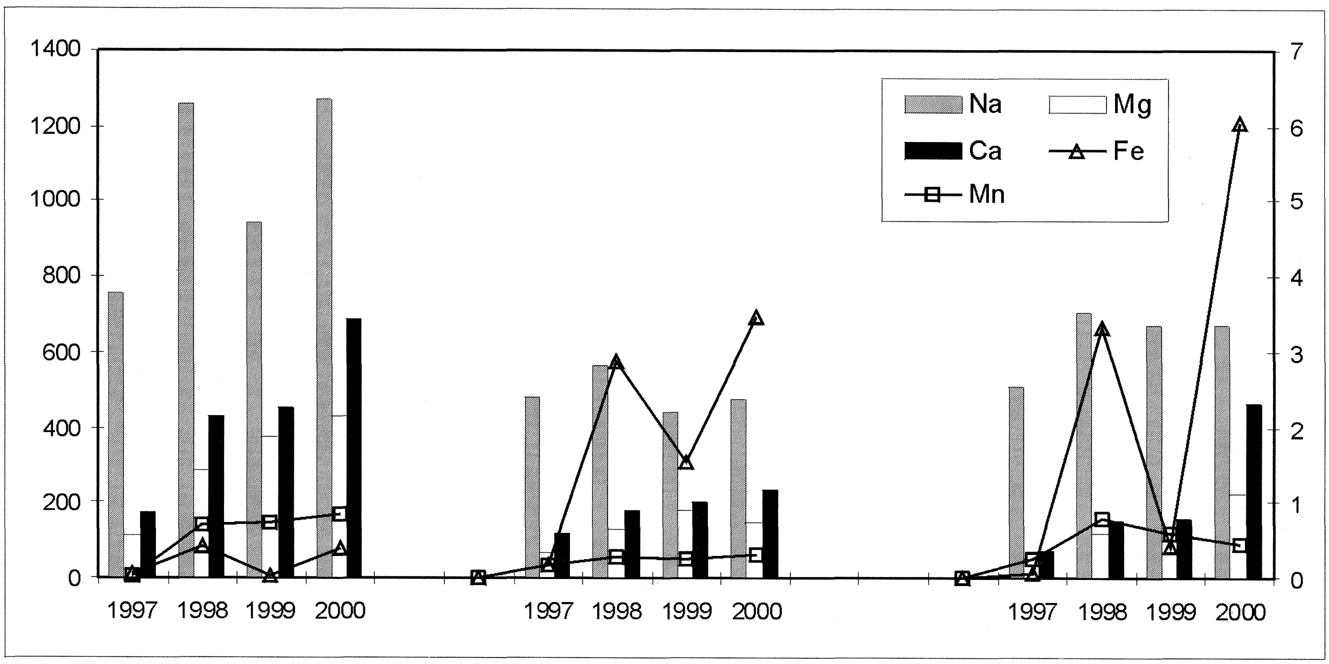

Fig. 10. Variations in the concentrations (mg/l) of Na, Ca, Mg, Fe, Mn from 1997 until 2000 in the wells of the industrial area.

namic regime and of the hydrochemical characteristics of the groundwater, whose quality is presently medium to low, rendering industrial and agricultural use of the water problematic.

The analysis of the stratigraphic and structural conditions of the sector most affected by these phenomena, carried out on the base of the data from numerous boreholes, wells, and geophysical prospecting, has allowed a detailed reconstruction of the geometry of the aquifer and its relationship with the impermeable clayey substratum.

The succession of clastic deposits, represented by Pleistocene sands and gravels together with Recent sandy limes, constitutes a complex aquifer due to the great granulometric variations, which brings about partially unconfined and partially semiconfined conditions. As a result, there is a medium to high vulnerability in correspondence with the sandy-gravely deposits, tending towards low values where limey-sandy or limey-clayey sediments predominate, often present at the surface (Ferrara, 1999). The entire succession rests upon clayey-marly sediments of significant thickness (ENI-AGIP, 1972) affected by a system of directed faults oriented

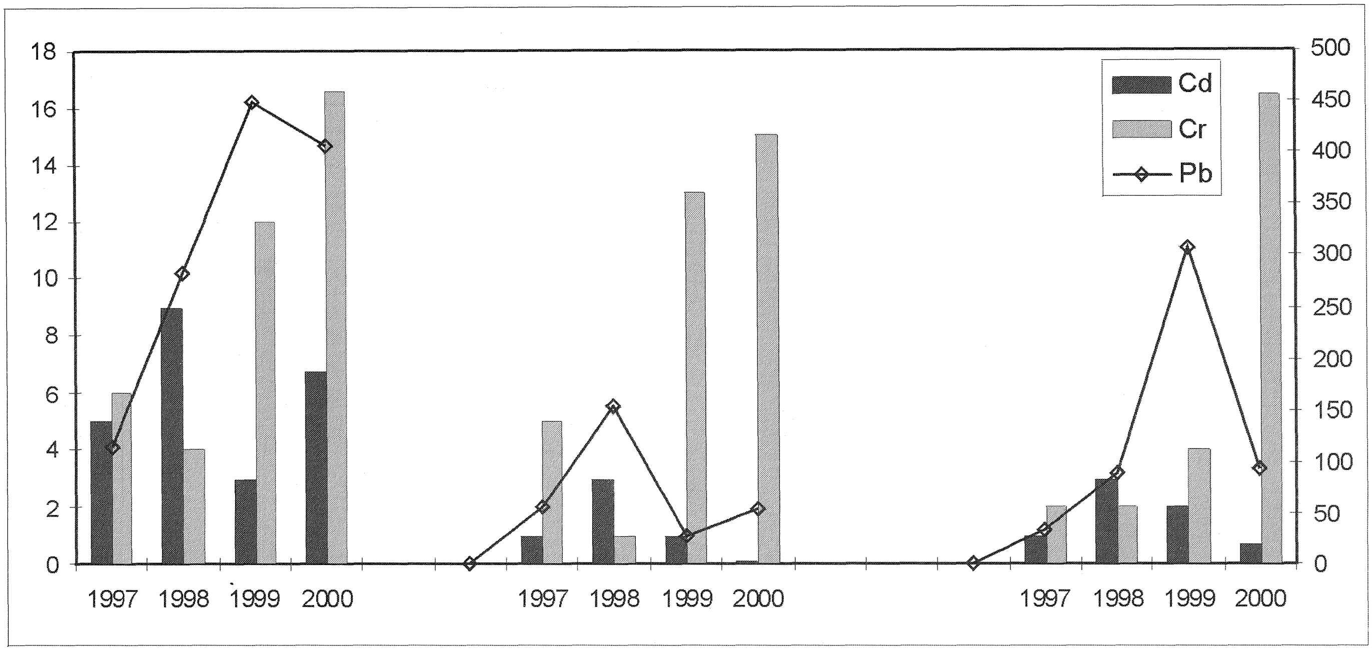

Fig. 11. Variations in concentrations (mg/l) of Cd, Cr, Pb from 1997 until 2000 in the wells of the industrial area.

mainly E-W, which has generated a depressed structure known as the "Simeto Graben" (Breusse and Huot, 1954). These tectonic conditions, which influence the geometry and hydrodynamics of the aquifer system, have been ascertained and studied in detail by means of the correlation of stratigraphic data from boreholes and electric resistivity surveys, showing the structures at high resolution and a minor depth (10-15 m) of the top of the clayey substratum (Figures 4 and 5).

The reconstruction of the piezometric surface by means of measurements of the water levels in wells and boreholes, indicate the existence of local cones of depression caused by the intense and continuous withdrawal mainly for industrial purposes. These have not only modified the previous hydrodynamic setting, but also led to the sea water intrusion into the aquifer. This is evidenced by the high values of electric conductivity (more than 10 000 μS/cm) and chlorides (exceeding 5000 mg/l), which have increased threefold in a period of about four years, from 1997 to 2000 (Figure 9), along with sulfates and nitrates. Such conditions are encountered mainly in correspondence with the industrial area and in proximity to the present mouth of the Simeto river, whose waters are highly saline over most of the year due to the low discharge rate of the river.

Besides the elevated salinity, the groundwater shows an increased concentration of heavy metals, such as cadmium, chromium and lead, since several years. These originate from industrial effluents discharged into the environment without any preliminary treatment, and are transported into the aquifer along the irrigation channels and river beds that traverse the northeastern sector of the plain, and discharge into abandoned wells used as drains.

Assuming that the degradation processes affecting the quality of the groundwater resources will continue to increase, it can be to envisage a future scenario in which it would be impossible to use these resources in a sustainable manner having disastrous consequences for the economy and development of the entire territory.

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