

GEOCHEMICAL AND GEOPHYSICAL STUDY OF SALT INTRUSION IN THE SOUTH-WESTERN COAST OF SICILY

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ABSTRACT

In this paper we present an hydrogeological study which was carried out in the coastal overexploited aquifer located in South-Western Sicily. The aquifer, constituted by calcarenite and sands, overlaying low-permeability sandy clays, has been investigated using geochemical and geophysical methodologies. A chemical and physical characterization of the waters allowed to detect the marine intrusion wedge in the coastal aquifer. Moreover the geoelectrical survey, suitably calibrated on stratigraphic data, allowed to reconstruct the calcarenite layer and the underlying impermeable bed. Furthermore a TDEM survey clarified some of the features of the intrusion phenomenon. Four observation wells have been drilled and equipped with SMS telemetry system to monitor both the piezometric level and the freshwater/saltwater transition zone.

Key words: coastal aquifer, TDEM survey, salt-water intrusion, monitoring network

INTRODUCTION

The coastal aquifer located between the towns of Mazara del Vallo and Marsala was studied in this paper. Due to the excessive withdrawals, a change of the groundwater flows took place, breaking natural equilibrium, increasing salt-water intrusion phenomena and causing the disappearance of particular humid littoral areas, locally called "*margi*".

The studies and the surveys are aimed at:

- Defining the hydrogeological characteristics of the aquifer by means of surface surveys and at a detailed census of a lot of wells of the same area;
- Searching, positioning and checking the wells with the greater water withdrawals;
- Investigating the freshwater/saltwater transition zone by means of measurements and borehole logs of electrolytic conductivity as well as electromagnetic surveys (TEM) in order to reconstruct the actual conditions of the intrusive phenomenon;
- Calculating a hydrologic balance in order to estimate the mean volumes of the water resource,

recharging every year, which is able to resist the dramatic evolution of the intrusive phenomena.

The aquifer at issue is made up of calcarenitic and sandy deposits and of terraced deposits, both of them of the quaternary age. They are located in the coastal zone between the built-up areas of Marsala and Mazara del Vallo and between the broad streams Mazarò and Marsala.

During the well census, measurements of the depth of the water table were carried out and a few water samples were taken to measure the electrolytic conductivity in situ and make chemical-physical analysis.

These data, increased and supported by geophysical surveys, allowed to detect the piezometric surface and differentiate groundwater with respect to the degree of salinity, as well as to control eventual conditions of precarious equilibrium between withdrawal and natural recharge.

GEOGRAPHICAL OUTLINE AND MORPHOLOGICAL CHARACTERISTICS OF THE AREA

The area at issue is located along a part of the southwestern coast of the Sicily island, between the urban areas of Marsala and Mazara del Vallo, in the rural district of Trapani. The area is located in the Marsala-Mazara plane and is delimited by the Sossio river (or Marsala large stream) in the West, by outcropping low permeability formations in the North-eastern and by Arena-Delia river in the East. The area is about 150 km² wide and is characterized by salt-water intrusion phenomena.

The zone includes some humid areas, which nowadays are partially or completely dried up, locally called *margi* (namely, *Margio* Pilo, Nespollilla, Spanò and Capo Feto). The *margi* are very sensitive ecosystem of a great environmental importance; from the hydrogeological point of view, they are the outcropping of the piezometric surface.

In this area there are only two streams, the Marsala and the Mazarò ones, respectively located in the north-western and south-eastern areas.

The northern boundary of the studied area is characterized by very inclined slopes, generally with a northern vergence, laid down two wide fluvial valleys (Torrente Iudeo and Fiumara di Marsala).

GEOLOGICAL OUTLINE

The geology of the area is characterized by quaternary marine deposits made up of calcareous sands and gravels, with much fossil bits (mainly lamellibranchiate and gastropods), partially cemented (calcarenitic-calci-ruditic levels of the Calcarenite di Marsala), sometimes passing to thinner levels.

These deposits were subjected to marine abrasions and successively covered by small thickness (down to 10 m) of sands and calcarenites, which accumulated during several oscillations of the sea level. These oscillations in turn, in the latest 100.000 years, caused the submergence of the older calcarenites at different times. The "marine terraces" are about 170 m a.s.l. D'Angelo and Vernuccio (1996) define eight orders of terraces, recognizable by a series of morphological steps and by the abrasion platforms as well as the presence of paleosols (one of the terraces nowadays is submerged).

The small beaches along the coastal line are made up of recent deposits; then there are black terrains, of lacustrine origin, that characterize the humid areas (*margi*) with a moderate thickness, sometimes up to 1 m.

Alluvial deposits outcrop in the upper part of the large stream Mazarò and along the Sossio-Marsala large stream; they are characterized by the presence of silt, sands and polygenetic gravels.

The calcarenitic deposits lie in discordance on post-orogeny terrains, mainly terrigenous, which have considerable thickness (up to 500 m and till 1500 m).

As regards tectonics, the most evident effects are concerned with the pre-quaternary bedrock, outcropping in the north-eastern part, with a fold system having their axes in the NE-SW direction. The calcarenitic deposits, in a horizontal attitude, were only involved in a post-Sicilian swell.

A particular note is dedicated to some karst sinkholes, creating some pans, located between "Calcareniti di Marsala" and marine terraces. These depressions constitute very important hydrogeological structures as they drain a lot of shallow waters.

HYDROGEOLOGICAL OUTLINE

The aquifer is generally made up of yellow calcarenites overlying gray little cementated calcarenites, mixed with clays. The calcarenitic complex lies on a clay/marly bedrock, which is the definite permeability boundary of the aquifer.

The subsurface water flow is mainly due to the natural porosity of the rocks and consequently to preferred circulation along bedding joints and fracture/fissure system. Karst manifestations increase the subsurface water flow, too.

The calcarenitic aquifer has got varying thickness according to the bedrock pattern. Many geophysical surveys at different times proved the particular structure of the bedrock aquifer, made up of depressions alternated to "structural highs", strongly conditioning the groundwater flow. Although bedrock geometry is not well defined, TEM surveys, here presented, contribute to the knowledge of the geometry of both, the aquifer and the intrusion wedge. The results of geophysical surveys integrated with data coming from stratigraphic columns indicate that the thickness of the calcarenitic aquifer varies from a few meters up to 60-70 m.

Along the coastal line, where the most recent marine terraces outcrop, at least two groundwater levels in communication with each other, but with different recharges, were defined by means of the monitored hydrogeological parameters. In fact, terraced calcarenitic and sandy deposits include thin-bedded intercalations of loam/clay grained materials, with a low permeability. These discontinuous levels define thresholds and boundaries of permeability, separating the surface portions where the direct absorption of the rains takes place from the lower aquifer levels.

Different permeability horizons are also inside the "Calcarenite di Marsala". They may condition the subsurface water flows as well as create different types of aquifers (multi-groundwater, semi-confined). These assumptions are corroborated by the existence of artesian aquifers, not yet defined in the space because of the lack of sufficient information on lithology variations.

Hydropotable wells of the surrounding towns (Marsala, Petrosino and Mazara del Vallo) were deepened till the underlying impermeable formations and so they are completely inside the aquifer. On the contrary, most agricultural and domestic wells in the coastal platform only soak into the upper part of the aquifer: in fact, they are less deep and get a water column less than 1 m. Only some of the wells, mechanically drilled recently, get a water column down to 5 m, without getting to the impermeable bedrock of the aquifer. Consequently, they use the shallower groundwater of the aquifer system.

Some of the past hydrogeological studies, carried out in the area at issue from the end of the fifties, allowed to define the critical conditions of the groundwater due to the piezometric drawdown. In fact, in the last fifty years, 30 meters drawdowns were registered as well as a drastic reduction of the withdrawal rates. These data show the precarious hydro dynamic equilibrium

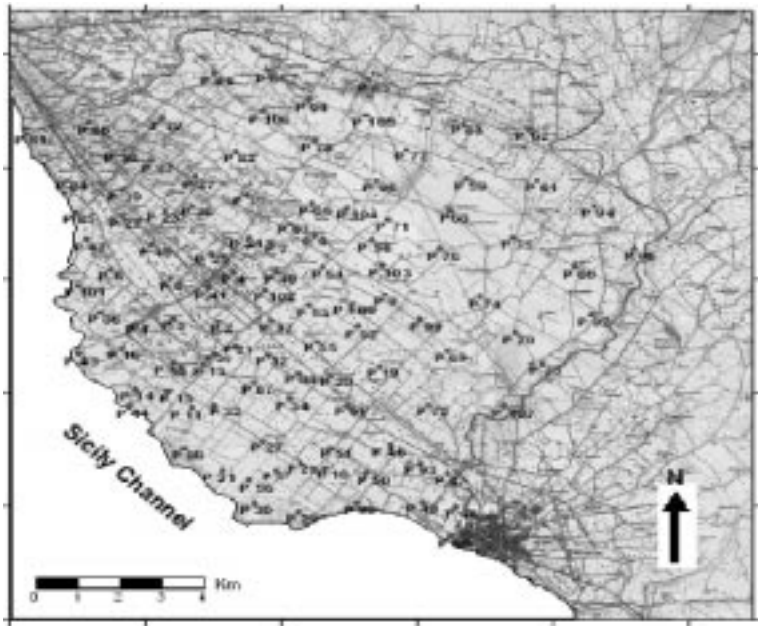


Figure 1. Location of the wells selected for census.

rium of the aquifer where, since seventies, drastic salt-water intrusion phenomena have taken place. The derichment of the water resource increased and will still increase the intrusive phenomenon, which already appeared with a considerable worsening of the quality of the groundwater.

Piezometric conditions of the aquifer were reconstructed by means of measurements of the levels, carried out in the wells of the area. In particular, two field measurements were carried out: the first in the August 1998, concerning 53 wells used both for irrigation and for potable uses; the second one was carried out between February and April 2001 on 107 wells, only for agriculture use (figure 1). The census and the survey concerned the monitoring of depth of the groundwater, electrolytic conductivity, temperature and pH. A most detailed monitoring (chemical-physical analysis) was carried out for hydropotable wells. The elaboration of the data of both sets of field measurements gave similar results, but showing a gradual increasing of the intrusive phenomena.

The piezometric surface was reconstructed by using the data of the second set of field measurements, which showed a more critical hydrogeological situation. The geometry of the piezometric surface (figure 2) allowed detecting a band, approximately parallel to the coastal line, where flow lines have opposite directions (ground-water divide).

GEOPHYSICAL SURVEYS BY MEANS OF TEM

Acquisition and processing of data

Among various geophysical methods, the TDEM technique seems to be the most suitable for the indicated purposes. In fact, TDEM has a better lateral resolution and is more efficient than Vertical Electrical Soundings when the shallow soils are very conductive, but it is usually unable in delineating the resistive geological conditions. In the area no deep wells are present and therefore no information on the deep aquifers and bedrock are available.

The TDEM survey

The TDEM surveys were carried out with the coincident loop configuration, using different sizes in order to increase the penetration depth (Nabighian and MacNae, 1991). A TEM-FAST 48 system, powered by built-in batteries and 12.5 m and 25 m loop sizes were used. It is highly portable geophysical system that can be applied for solution of a very wide range of problems, including environmental investigations, hydrogeological researches, archaeological and mineral prospecting. In particular this instrument is convenient and high efficient tool for prospecting, control and monitoring of ground water, leakage and pollution.

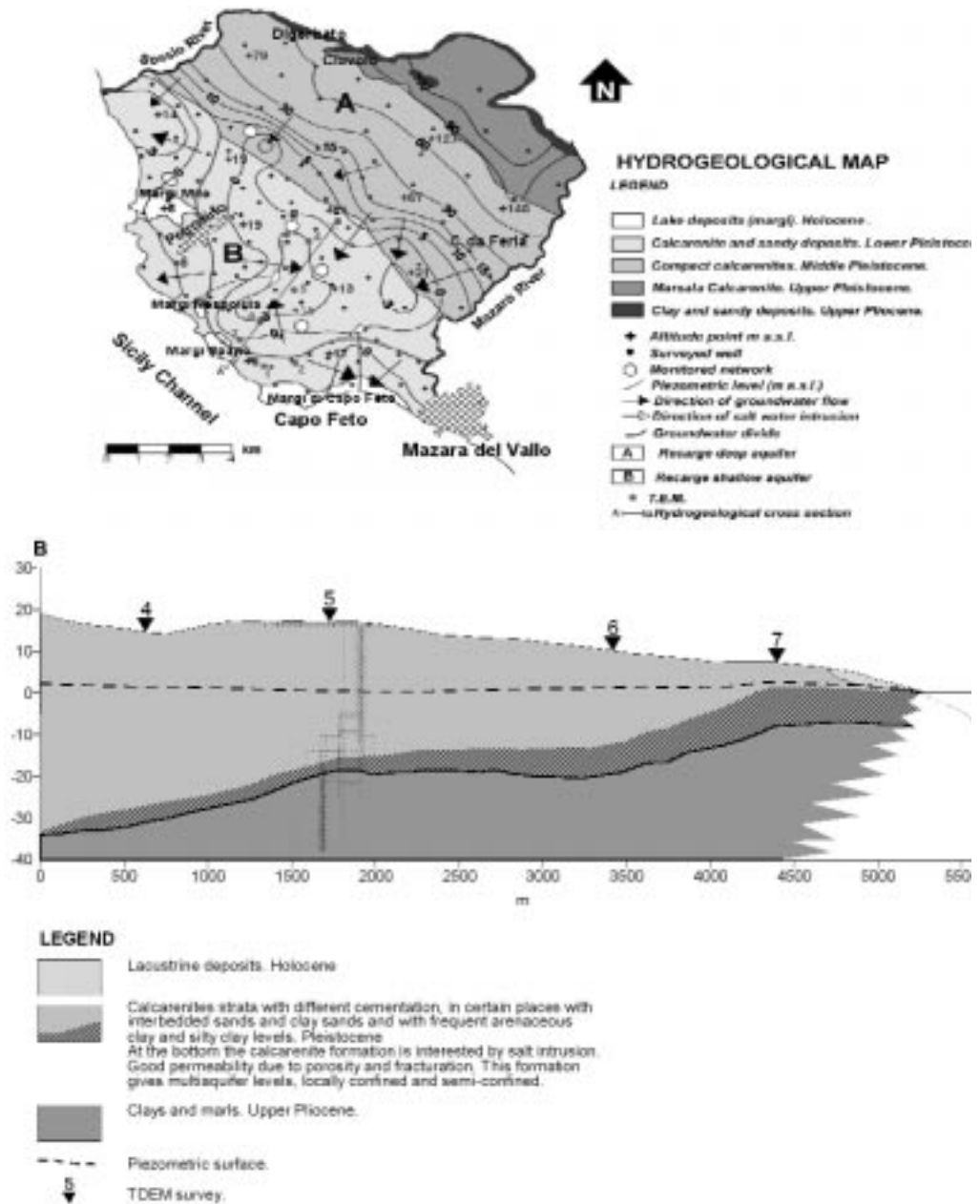


Figure 2. Hydrogeological map of the area (top) and hydrogeological cross-section (bottom) along the direction from A to B (see the map)

TEM-FAST 48 operates with a notebook computer and generates short pulses of electromagnetic field in the earth and registers its response, which depends on the electric section of underground formations.

The system is equipped with base software, which provides control, viewing of measurement results in

digital form as well as apparent resistivity curves and some characteristics of the noise existing during measurements.

Seven TEM-FAST soundings have been carried out in the investigated area. The experimental data have been collected using a square wave with null phase and

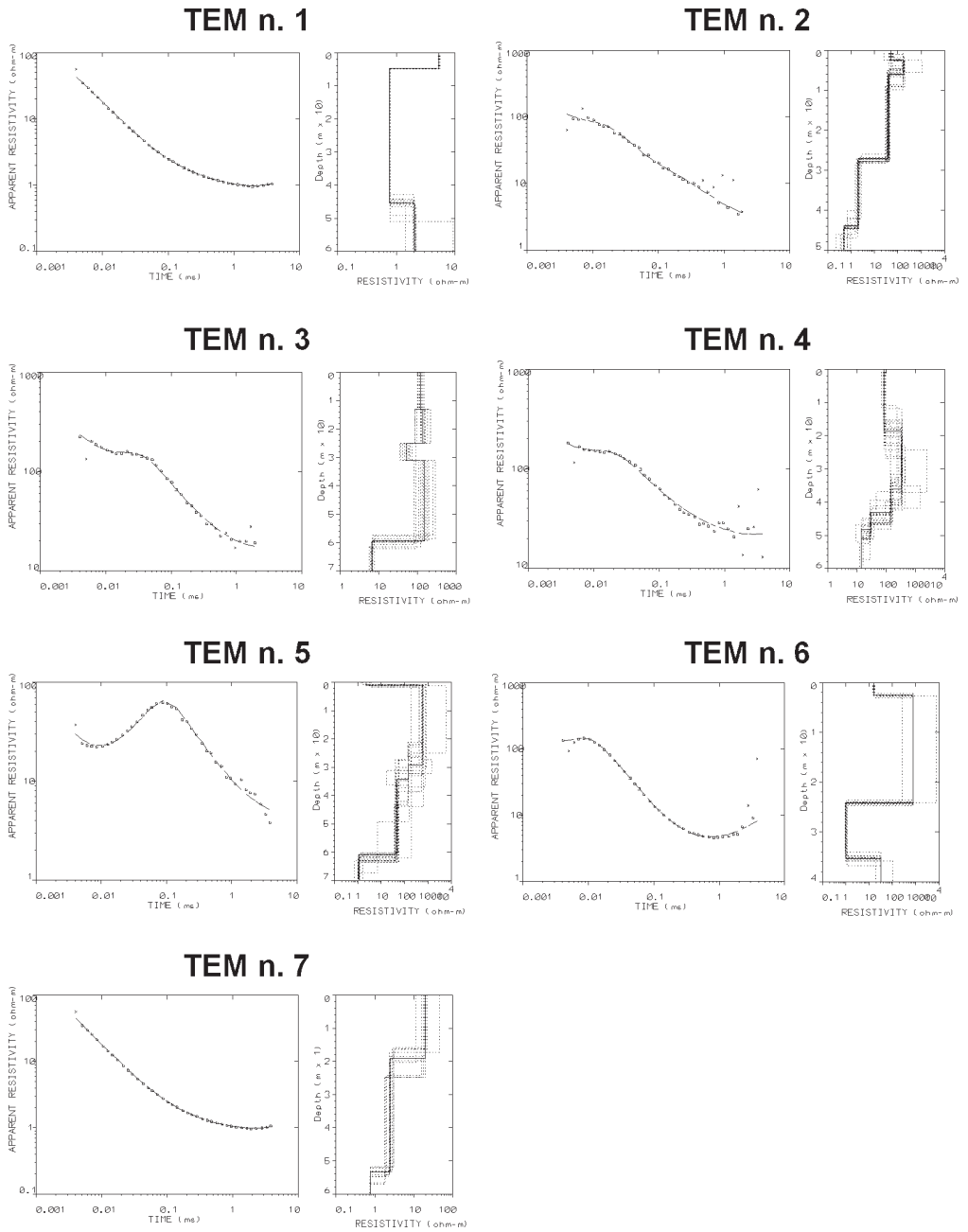


Figure 3. Data of the T.E.M. soundings and relative interpretation models.

an acquisition time window varying from 2048 ms to 4096 ms. The transmitting current intensity has been set to 3 A and 10 pulses of positive and negative polarities were stacked to attenuate noise.

Acquired data has been interpreted using advanced software package TEM-RESEARCHER for fast inver-

se problem solution. This software gives user possibility to do inversion even if induced polarization (IP) and super-paramagnetic (SPM) effect complicate experimental data. The interpretation has been carried out also using TEMIX ver. 3.0, which is an interactive, graphically oriented, forward and inverse modeling pro-

grams for interpreting TEM data in terms of a layered earth (1-D) model.

Interpretation data

The TEM soundings were located along preferred directions including some areas particularly involved by intrusive phenomena. Moreover, due to the high sensibility of the surveys to the noise produced by electromagnetic field sources (high-voltage lines, iron materials and so on), some areas, even if of particular hydrogeological importance, were not surveyed because of the presence of high and variable electromagnetic fields. Interpretation of the acquired TEM soundings (figure 3) confirmed typical hydrogeological characteristics of the investigated area.

The terrains of the zone are made up of an alternation of sandy-calcarenitic deposits with a variable thickness, from few meters in close proximity to the coastal line to a maximum of 60-70 m in the farther zones. These deposits overlie a clay-marl formation, which is the definite permeability boundary of the aquifer. The hydrogeological cross section in figure 2 shows the good correspondence of TEM with respect to the local geological conditions. In fact, the presence of a lot of wells in the investigated area as well as some geological surveys (some of them are the ones drilled for the creation of the piezometric network) is an element of calibration for the interpretation of the TEM soundings. Furthermore, the wells allow estimating the good quality of the methodology, when used for the reconstruction of the freshwater/saltwater transition zone.

The hydrogeological cross section, reconstructed by means of few information obtained both from the direct surveys and wells and TEM soundings, shows a synclinal aquifer geometry. This geological structure, which

should be still supported by means of direct surveys, to carry out along the coastal line, evidences that the geometry of the basement of the aquifer plays a very important role in the intrusion phenomenon. In fact only a good freshwater recharge would contrast these dangerous effects; on the contrary, nowadays the recharge is so largely reduced that the humid zones are highly reduced or disappeared.

SALINITY DEGREE OF THE GROUNDWATER

To study the quantitative evolution of the intrusive phenomena, we used chlorine laboratory analyses on the waters of 20 wells, sampled between the end of July and the beginning of the August 1998. A second field measurement of the depth of the groundwater, the electrical conductivity and the chlorine-content was carried out between February and April 2001.

In order to obtain a good geochemical analysis on the quality of the water, we made all the data homogeneous according to the chlorine concentration, indicated "Cl-" later on. A good ratio between the electrical conductivity measured in the field (C) and the chlorine concentration obtained in laboratory was found with a reliability (R²) of 86 %:

The graph on the right shows that the previous correlation, in spite of the large difference, is also fairly in agreement with the salinity of the water of the Mediterranean sea.

In figure 5 is presented the distribution of the electrical conductivity of water sampled from wells in the different areas, which is related to different values of the water salinity.

The space distribution of the salt concentrations agrees quite well with the behavior of the flow lines presented in figure 2, suggesting the following integrated considerations.

$$ppm Cl = 141,52 \cdot C^{1,3305} \quad (1)$$

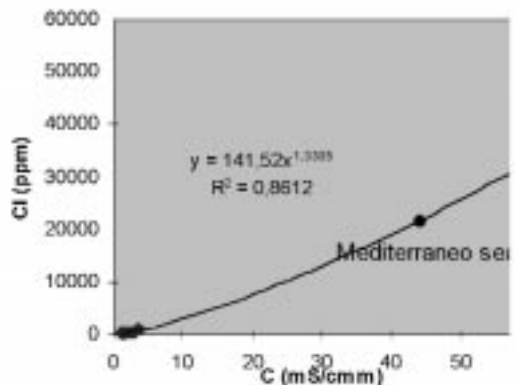
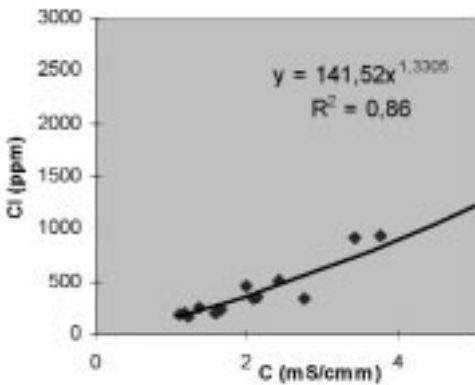


Figure 4. The equation (1) is shown by the above mentioned graphs. The graph on the left shows the correlation between the electrical conductivity measured on the field (C) and the chlorine concentration obtained in laboratory (Cl).

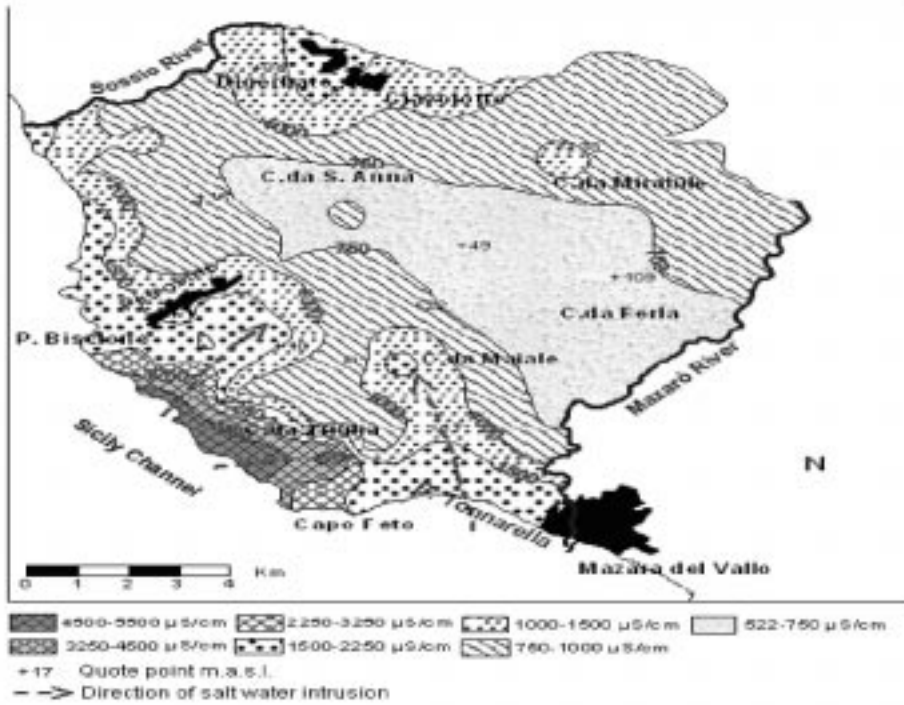


Figure 5. Map of the distribution of electrical conductivity of water sampled from wells.

The areas characterized by different types of waters are elongated roughly in NW-SE direction, and are about parallel with the coastal line, obviously showing an increase of the salinity towards the sea. In particular, a brackish-salt water belt along the preferred direction of the Petrosino village can be observed: it corresponds to a morphological high of the impermeable bedrock constituted by marls and clays. It is useful to notice that uplift of the impermeable bedrock produces a reduction of the thickness of the calcarenitic aquifer and probably also a decrease of the rates of the freshwater recharge (figure 6).

The second major direction of salt intrusion is located in the southern part, close to the city of Mazara del Vallo. This area is elongated inland towards an area (C.da Maiale) which is characterized by a high concentration of withdrawals.

HYDRODYNAMICS OF THE AQUIFER AND HYDROLOGIC BALANCE

In natural conditions the shallow groundwater tends to get to the sea, originating some humid areas, the so called *margi*. As regards the deep groundwater, a part of the subsurface flow was drained by the rivers, simple ravinements nowadays, and the rest recharged the shallow aquifer, contributing at the recharge of the

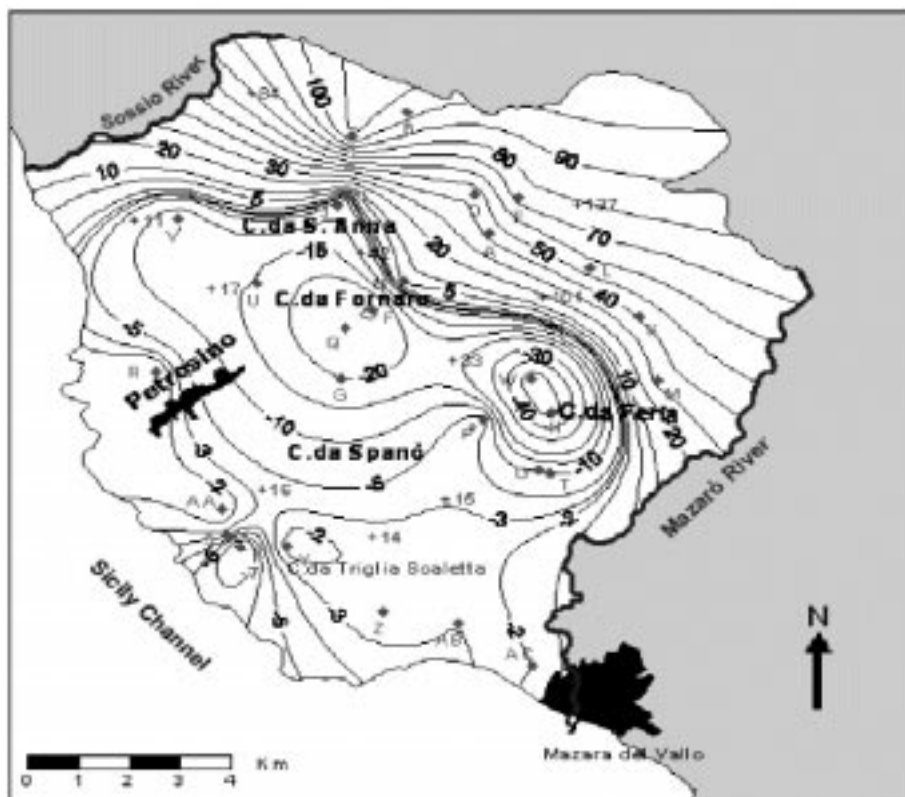
margi and avoiding the advance of the marine intrusion wedge. The presence of the *margi* created a particular equilibrium in the natural environment: the freshwater emerging in these areas resisted to the marine ingression and, in the same time, the extension of the *margi* was defined by the equilibrium between evaporation and underground recharge.

As we said in the chapter concerning the hydrogeology, in the investigated area there are at least two groundwater in communication with each other.

In the hydrogeological map (figure 1) two zones were defined: the first is indicated as "A", where the calcarenitic rocks forming the deep groundwater outcrops; the second, indicated as "B", where the above mentioned calcarenites are covered by a series of thin more recently deposits made up of sands and calcarenites are intercalated with thinner materials, is the location of the shallower groundwater.

In the B zone, the deep groundwater of the calcarenites is partially confined or semi-confined because of the presence of intercalations of impermeable sediments, limited in space and thickness.

The A zone is the recharging area for the deep groundwater of the calcarenites, while the B zone recharges a free shallow groundwater, partially in vertical communication with the deeper groundwater.



◆ Location well

+11 Quote point (m a.s.l.)

Figure 6. Map of the depth of the aquifer bedrock.

Months	P (mm)	ETP (mm)	ETR (mm)	R (mm)	I (mm)	Zone A l (l/s)	Zone B l (l/s)
Jan	60,5	21,3	21,3	7,8	31,4	802,9	898,1
Feb	58,8	27,3	27,3	6,3	25,2	714,2	798,9
Mar	46,5	38,4	38,4	1,6	6,5	165,5	185,1
Apr	39,8	58,1	58,1	0	0,00	0,00	0,00
May	18,3	91,3	50,0	0	0,00	0,00	0,00
Jun	6,0	122,5	6,0	0	0,00	0,00	0,00
Jul	3,0	149,0	3,0	0	0,00	0,00	0,00
Aug	6,8	145,2	6,8	0	0,00	0,00	0,00
Sep	37,0	116,4	37,0	0	0,00	0,00	0,00
Oct	65,6	78,1	65,6	0	0,00	0,00	0,00
Nov	62,4	50,1	50,1	0	0,00	0,00	0,00
Dec	78,6	32,8	32,8	1,6	6,5	165,2	184,8
b) Year R = 0.2	483,3	930,5	396,4	17,3	69,6	151,0	169,0
a) Year R = 0					86,9	188,8	211,2

R = total runoff, P = precipitation, ETP = potential evapotranspiration, ETR = real evapotranspiration, I = effective infiltration

Table 1. Hydrologic balance

From the computation of the hydrologic balance (table 1), we may note the deeper groundwater receives a mean yearly recharge of 150 to 190 l/s coming from its recharge area (A), 68.53 km² wide. The recharge of the shallow groundwater (B), on a surface 76.66

km² wide, was estimated at 170-210 l/s yearly on an average. Since the hydrotable wells withdraw about 325 l/s of water, it's clear that the aquifer is in a drastic condition of overexploitation.

CONCLUSION

The modification of the natural hydraulic process of the aquifer system of the Calcareniti di Marsala in the investigated area, has gradually taken place according to the increasing withdrawals.

The intensive exploiting of the deep groundwater by means of wells already began in the fifties. As far as exploiting points increased, because of the lack of a global management policy, a progressive reduction of the groundwater levels took place due to the groundwater reservoir (overexploitation). Therefore, the present conditions are characterized by lack of a groundwater reservoir due to a total pumping rate about equal to the renewable water resource, including both the calcarenitic groundwater and a great part of the shallow one.

One of the consequences of the breaking of the hydrodynamic natural equilibrium was the strong reduction of the flow towards the humid littoral areas (*margi*), originating almost their total disappearance. Simultaneously a drastic decrease of the freshwater discharge towards the sea and an increasing marine intrusion take place, with a consequent worsening of the quality of the groundwater.

Geophysical surveys by means of TEM sounding were particularly useful to detect the evolution of the intrusive phenomena. The reconstructed hydrogeological cross section shows aquifer susceptibility with respect to the marine intrusion, further aggravated by recharge reduction. Direct surveys to be carried out close to the coastal line will allow us to better define the aquifer bedrock depth and consequently to confirm the above interpretation.

Finally it should be stressed that the official bureaucratic project (from request to the grant) was not

easy and fast to be developed, even for such a critical and problem in the Sicilian coastal area. We hope that further researches and monitoring activities will be useful to the re-establishment of a correct groundwater management. In particular, we like very much to see again the *margi*, very important ancient ecosystems which are representative of a healthy environment.

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