SEA WATER INTRUSION IN THE COASTAL AQUIFERS OF SOUTH-EASTERN SICILY (ITALY)

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Abstract

The south-eastern coastal area of Sicily is constituted by Quaternary continental deposits and sandy-calcarenitic marine sediments overlying a thick sequence of Miocene marls and Oligocene-Miocene carbonate formations. The Quaternary cover constitute a shallow aquifer with anisotropic permeability due to lithologic variability. The Oligocene-Miocene fractured and karstified carbonate formations form a deep aquifer characterized by high permeability, confined by an Upper Miocene-Pliocene sequence. Due to its high productivity, it represents the most important source of water supply in the area. Since the early 1980s, to satisfy the increased water demand of enlarging agricultural areas and expanding summer homes and tourist resorts, new wells were drilled to greater depths, intercepting the deep aquifer with more consistent groundwater resources. This situation has caused an intensive exploitation of ground water resources with the consequence of salt-water intrusion both in the shallow and the deep aquifers. A survey during October 1996, consisting of measurements of the water level and electrical conductivity in a network of 298 wells located in the stretch of coast between Scoglitti and Pozzallo, and the determination of the principal hydrochemical parameters, has enabled to verify the conditions of salt-water intrusion in both aquifers.

Keywords: Shallow and deep aquifers, aquifer exploitation, hydrochemical water composition, salt-water intrusion, south-eastern Sicily.

Introduction

The studies carried out since the early 1970s along the south-eastern coastal belt of Sicily have shown a progressive increase in the exploitation of groundwater for agricultural and civil purposes. Until the early 1970s, groundwater resources in the shallow aquifer, constituted by continental deposits and Quaternary

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marine sediments, were sufficient to satisfy the demands of agriculture and population centers scattered over the region.

During the following years, the expansion of agricultural areas with the substitution of traditional open-field cultivation by greenhouse cultivation and the construction of residential and tourist resorts has resulted in an intensive exploitation of the shallow coastal aquifer and, consequently, in a reduction of groundwater availability. Towards the end of the 1980s, to satisfy the increased water demand new wells were drilled to greater depths with the purpose of intercepting more consistent groundwater resources.

Groundwater withdrawal, mainly during the summer season, for irrigation in agricultural areas and for drinking purposes, has led to a deterioration of the water quality, caused by salinization of both aquifers and by the supply of chemical substances widely used in agriculture. This has mainly affected the more vulnerable shallow aquifer.

A survey conducted during October 1996, consisting of measurements of the water level and electrical conductivity in a network of 298 wells located in the stretch of coast between Scoglitti and Pozzallo and the determination of the main hydrochemical parameters, has allowed to verify the existence of salt-water intrusion by means of the comparison of conductivity and chloride contour line maps of the two aquifers.

Geological context

From a geological point of view, the coastal area represents the extreme south-eastern margin of the Hyblean Foreland (Figure 1), which has been the site of intense extensional tectonics during the Alpine orogenic phase (Ogniben, 1969; Caire, 1970; Tapponier, 1976; Di Grande and Grasso, 1977; Ghisetti and Vezzani, 1980). According to many authors studying the Hyblean area (Rigo and Cortesini, 1959; Pieri, 1967; Mascle, 1974; Grasso *et al.*, 1979) this area has been affected by normal faults trending NE-SW (Scicli system) and NNE-SSW (Marina di Ragusa system), mainly in three principal phases during the Lower Miocene, the Middle to Upper Pliocene and the Plio-Pleistocene (Carbone *et al.*, 1982). Activity at these fault systems has led to the formation of horsts and grabens oriented NE-SW, such as the Santa Croce Camerina and Pozzallo horsts.

The stratigraphic succession of the area (Grasso, 1997) is chiefly composed of Tertiary and Quaternary sediments. The oldest formations are represented by an early Miocene alternation of calcisiltites and marly limestones that pass into calcarenites and packstones of the Ragusa Formation, whose full thickness surpasses 500 m (Schmidt and Trovò, 1962). These are conformably overlain by marls and clayey marls of the middle to late Miocene Tellaro Formation, with a thickness varying from a few tens of meters to 170 m near the Ippari river (Rigo and Cortesini, 1959). Small outcrops of gypsum and calcareous marls of Pliocene age (Trubi Formation) are present in the valley of the Ippari river and the subsurface presence of these rocks has been revealed by various boreholes drilled for water research.

The most recent units are represented by fossiliferous Pleistocene calcarenites and sands (Grasso *et al.*, 1979; Grasso, 1997), whose thickness does not exceed 30 m, and by marine terraces of various orders along the entire coastal belt, which testify several eustatic variations that have occurred during the

Pleistocene. Among the most recent deposits there are alluvial terraces, Tyrrhenian terraces, swamp deposits, recent alluvial deposits, coastal dunes and coastal sands. These deposits crop out in the entire area with a thickness ranging from a few meters to 25 m.

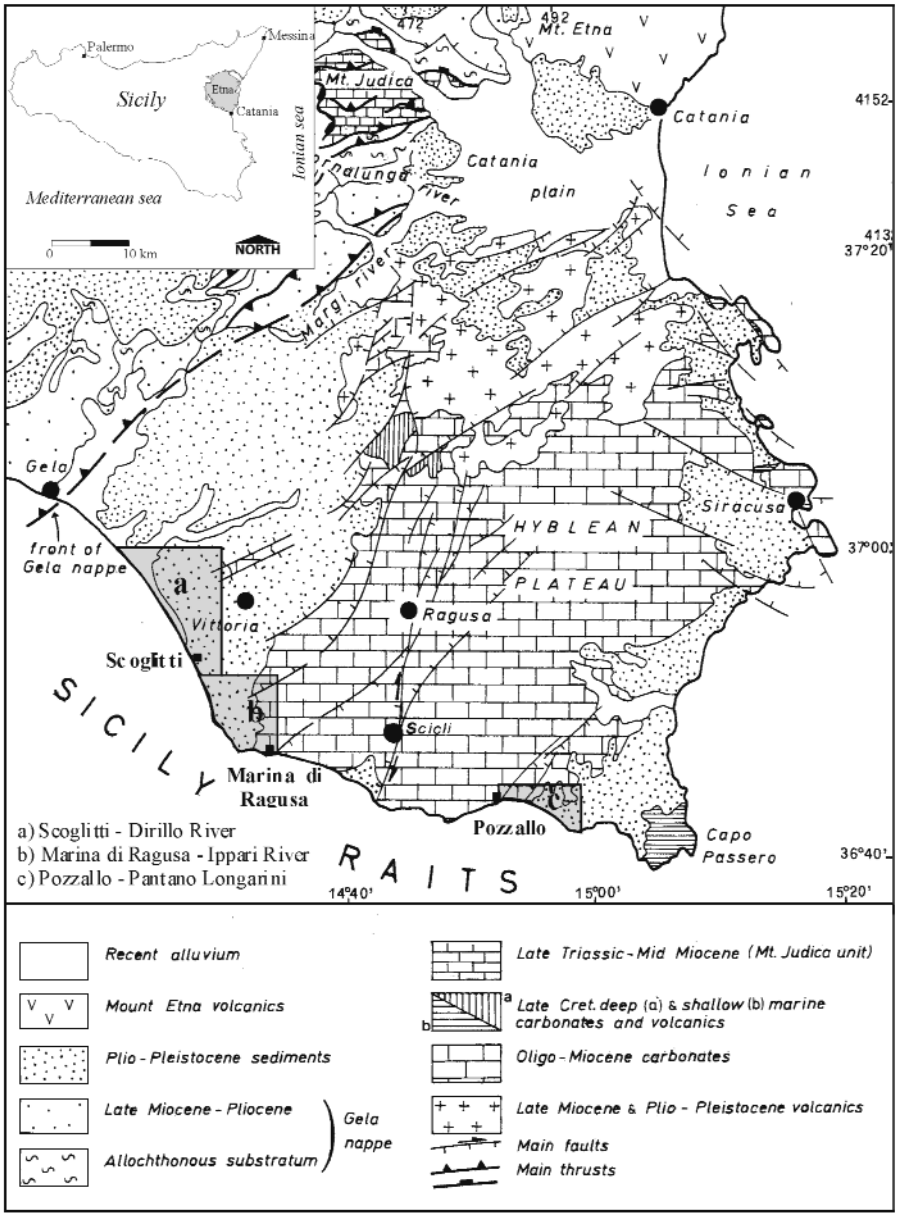

Figure 1. Schematic geological map of SE Sicily showing the location of the study areas (modified from Grasso and Ben-Avraham, 1992).

Hydrogeological characteristics of coastal aquifers

In relation to the permeability properties of the various units of the stratigraphic succession different aquifers can be recognized in the study area.

A shallow aquifer, prevailingly constituted by the Pleistocene sands and calcarenites and by the marine and continental deposits, is a water table aquifer, which rests upon impervious clayey marls of the Tellaro Formation and, locally, upon poorly permeable calcareous marls of the Trubi Formation. This aquifer is characterized by high anisotropy, due to the presence of unconsolidated permeable sediments with intermediate aquitards represented by pelitic or consolidated levels; this entails discontinuous water circulation and often a modest water yield. Nevertheless, the aquifer has played an important role in the economic development of the area through the 1980s, constituting the main water source that could be easily exploited by means of dug wells 20-30 m deep, due to its shallow depth. However, extensive extraction has led to a deterioration of groundwater, both by seawater intrusion and by agricultural and urban pollution.

A deep aquifer, constituted by the carbonate sediments of the Ragusa Formation with elevated permeability due to fracturing and karstification (Barbagallo and Ferrara, 1985), is a confined aquifer by the marly-clayey Tellaro Formation and the Trubi Formation. Due to its high productivity it represents the most important source of water supply of the entire area, serving tourist facilities and residential areas and being used for agricultural purposes (Ferrara and Pappalardo, 2003). This aquifer is intensely exploited by a large number of drilled wells whose depths range from 50 to 200 m, with groundwater discharge at individual wells of up to 20-30 L/s.

The intake area of both aquifers is represented by nearby hills where the carbonate formations are widely exposed in outcrop. The ground water flow directions, oriented mainly NE-SW, are controlled by tectonics.

Monitoring of 298 wells in the entire area was carried out in October 1996 by means of measurements of the level and electrical conductivity, determining the main chemical parameters in about 20 % of the wells. The results of this study have revealed overexploitation and a more or less accentuated qualitative degradation of the aquifers along the whole coastal belt, mainly due to the excessive presence of certain ions indicative of marine intrusion.

Three areas in the coastal belt have been studied in particular detail due to the presence of a higher number of wells with high discharge, extensive greenhouse cultivations and a higher density of residential and touristic areas. Proceeding from NW to SE, the three sectors lie between the village of Scoglitti and the Dirillo river valley, between the village of Marina di Ragusa and the Ippari river valley and between the village of Pozzallo and Pantano Longarini (Figure 1).

Scoglitti –Dirillo River sector

In this sector of the coastal belt mid-Pleistocene marine terraced deposits are widely represented, occurring in several orders at elevations varying from 20 to more than 100 m above sea level. These are abrasion platforms with rare and limited coarse-grained, yellowish-browh calcarenite deposits (panchina), overlying

sandy and silty clayey sediments heterotopic with the lower Pleistocene calcarenites. All together these deposits constitute the shallow aquifer, resting on marly and marly-calcareous sediments of the lower Pliocene (Trubi) and of the Messinian (upper member of the Tellaro Formation). These sediments latter crop out in limited areas near Scoglitti, in coincidence with a NNW-SSE oriented fault system. The carbonate rocks of the Ragusa Formation, which constitute the deep aquifer, are not exposed in this sector, but are encountered in deep wells in the southern portion of the sector (Figure 2).

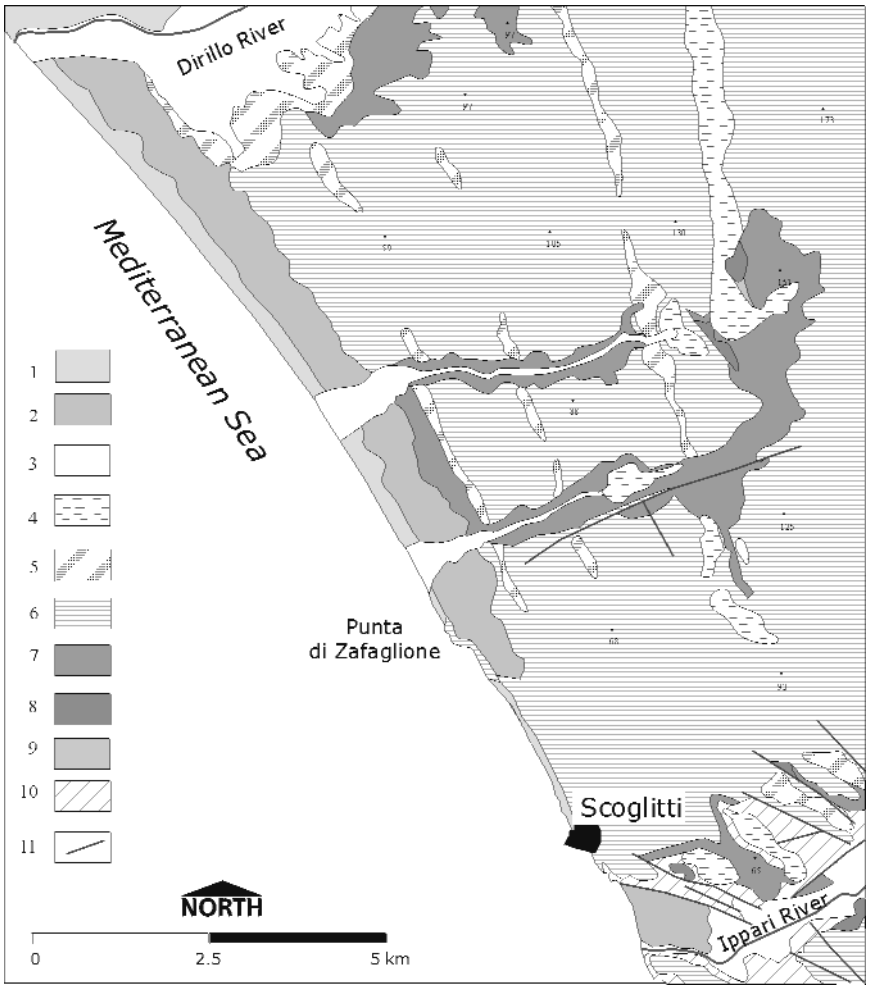

Figure 2. Geological map of the Scoglitti-Dirillo River sector: 1) Coastal sands; 2) Coastal dunes; 3) Recent alluvial deposits; 4) Swamp deposits (Upper Pleistocene); 5) Alluvial terraces (Middle Pleistocene-Holocene); 6) Marine terraces (Middle - Upper Pleistocene); 7) Calcarenites (Lower Pleistocene); 8) Trubi (Lower Pliocene); 9) Gypsum (Messinian); 10) Tellaro Formation (Middle - Upper Miocene); 11) Normal fault.

The thickness of the shallow aquifer does nowhere exceed 50 m. In higher areas, it lies in hydraulic connection with the underlying calcareous aquifer, from which it is fed mainly via fault systems that exalt its permeability. It is an unconfined or semiconfined aquifer whose water table lies at minor depth and therefore is highly vulnerable. Thus, it is very sensible to the climatic conditions and shows a strong lowering of the piezometric surface during the dry months, mainly in years of drought, which notably reduce its productivity.

The deep aquifer, confined below a thick cover of marly-clayey sediments, have an elevated hydraulic charge and a higher productivity, mainly in the tectonically disturbed areas.

From the measurements of the water level made in 142 wells, both dug and drilled, with depths varying from a few tens of meters to more than 100 m, it is seen that the potentiometric surface of the shallow aquifer (Figure 3a) is fairly regular, with a groundwater flow direction orthogonal to the coast. In contrast, the deep aquifer (Figure 3b) shows accentuated depressions to the north of Scoglitti and near the mouth of the Dirillo river, with levels well below the mean sea level (about 45 m), due to the continuous water extraction at some wells.

The same wells were chosen, during the same period, for measurements of the electric conductivity of groundwater, which has consistently shown values above 2,000 µS/cm in the shallow aquifer, particularly to the north and east of Scoglitti (Figure 3c). In the deep aquifer (Figure 3d), the values show ample variations from 1,000 µS/cm to more than 11,000 µS/cm, of which the latter were taken near Scoglitti, where the strong depression in the potentiometric surface is observed. Near the mouth of the Dirillo river, the values exceed 5,000 µS/cm, probably due to the mixing with sea water.

Chloride contents are always strongly elevated (> 2000 mg/L) and mirrors the conductivity values in the deep aquifer (Figure 3f), while the highest values in the shallow aquifer (Figure 3e) are observed along the Dirillo river.

From the Piper diagram (Figure 4) it is evident that most water samples from both aquifers belong to the sulphate-chloride earth alkaline facies, with a strong alkaline tendency, which indicates an obvious interaction between the two aquifers. Furthermore, many points lie near the limit with the alkaline sulphate-chloride type.

Marina di Ragusa – Ippari River sector

In the northern portion of this sector the geological conditions are similar to those of the preceding sector, with a predominance of terraced deposits overlying calcarenite sediments, which constitute the shallow aquifer. In the southern portion there are widespread outcrops of carbonates of the Ragusa Formation, whose fracturing and karst phenomena allow for an elevated permeability, constituting the more interesting aquifer (Figure 5). Relative to the tectonic setting, this latter aquifer is present not only in outcrop but also below a thick cover of impermeable sediments, which confine it in the northern part of the sector. Groundwater flow, controlled by the NE-SW oriented fault system, is directed towards the coast, where some time ago, between Marina di Ragusa and Punta Braccetto, they gave origin to conspicuous submarine springs with varying discharge, which, however, was nearly always superior to 10 L/s (Aureli, 1992).

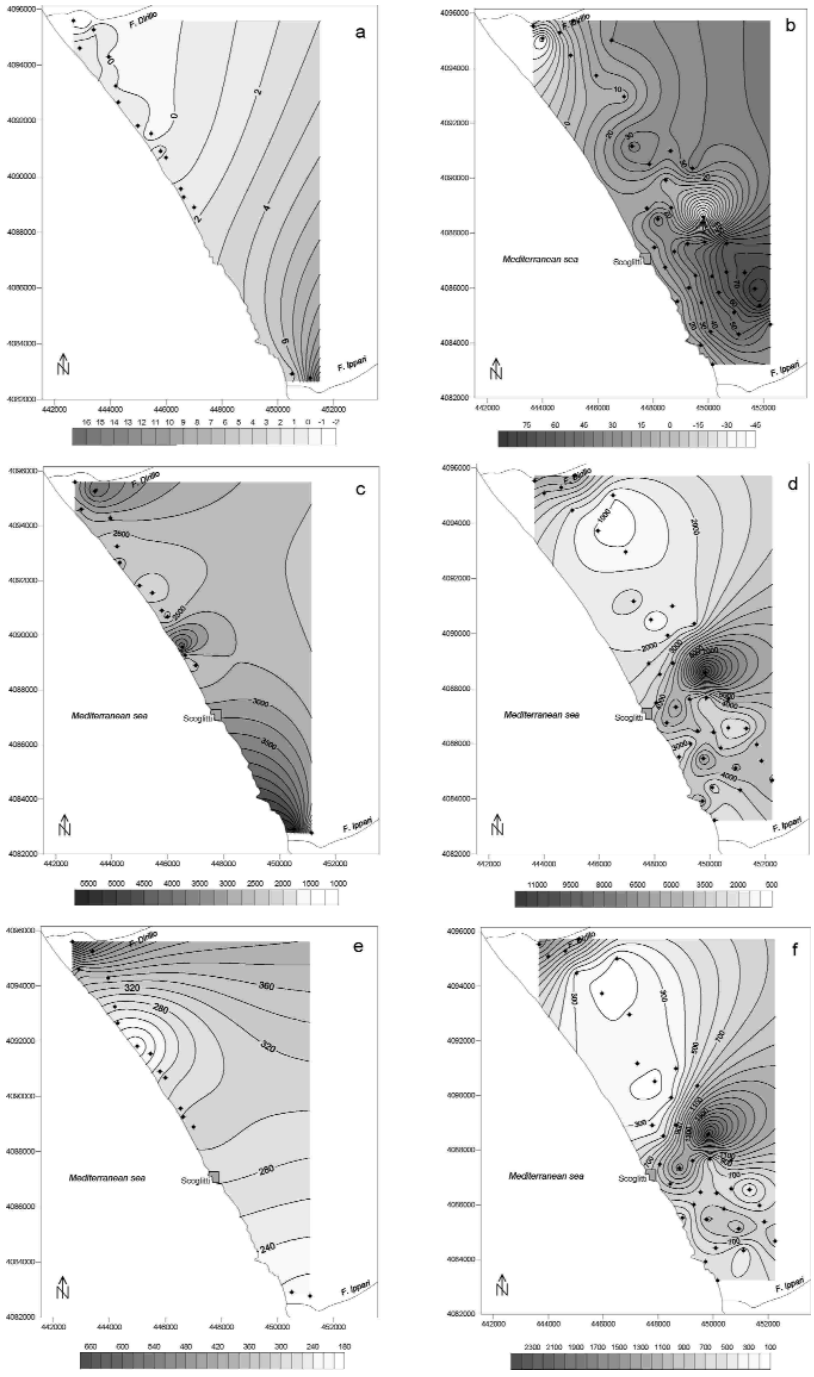

Figure 3. Potentiometric contour lines of the Scoglitti-Dirillo river sector: (a) Shallow aquifer and (b) deep aquifer; electrical conductivity contour lines (μS/cm) for the shallow aquifer (c) and deep aquifer (d); chloride contour lines (mg/L) for the shallow aquifer (e), and the deep aquifer (f).

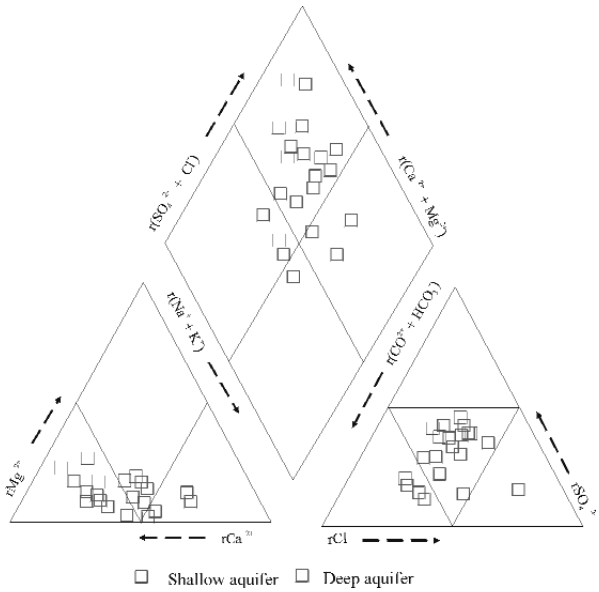

Figure 4. Chemical composition of groundwater in the Scoglitti-Dirillo River sector.

The two aquifers are exploited through numerous wells of differing depth. Out of a total of 106 studied wells homogeneously distributed over the territory, 72 reach the shallow aquifer and the rest reach the deep aquifer. These wells have depths ranging from 10 to more than 100 m, with pumping rates varying from a minimum of 3 L/s to a maximum of 20 L/s. These are mainly used for agricultural and, to a lesser degree, domestic purposes. In a few cases water exploitation is continuous all over the year, since water is used for greenhouse cultivations, which represent the main source of income of the zone. During the summer season water consumption considerably rises, especially in the tourist and residential areas.

Monitoring was carried out with measurements of the piezometric level and of electrical conductivity in all 106 wells, 34 in the shallow aquifer and 14 in the deep aquifer. Water samples have been taken for laboratory analysis of the major ions.

In the shallow aquifer groundwater flow is directed towards the Ippari river valley in the northern sector and towards the Biddemi river in the southern sector, while in the central zone the flow direction is roughly orthogonal to the coastline, with limited variations determined by the morphology of the impermeable substratum (Figure 6a).

The deep aquifer shows two main drainage directions, one at a short distance from, and more or less parallel to, the Ippari river, while the other coincides with the course of the Biddemi river. This confirms the existence of tectonic structures affecting the entire stratigraphic succession. The piezometric surface in the central and southern sectors lies a few tens of meters above the mean sea level, and the flow direction is oriented towards the coast, with hydraulic gradient values ranging between 0.6 % and 3 %. In the northern sector a wide depression of the piezometric surface is observed, which is determined by the continuous pumping of some wells used for agricultural and touristic purposes (Figure 6b).

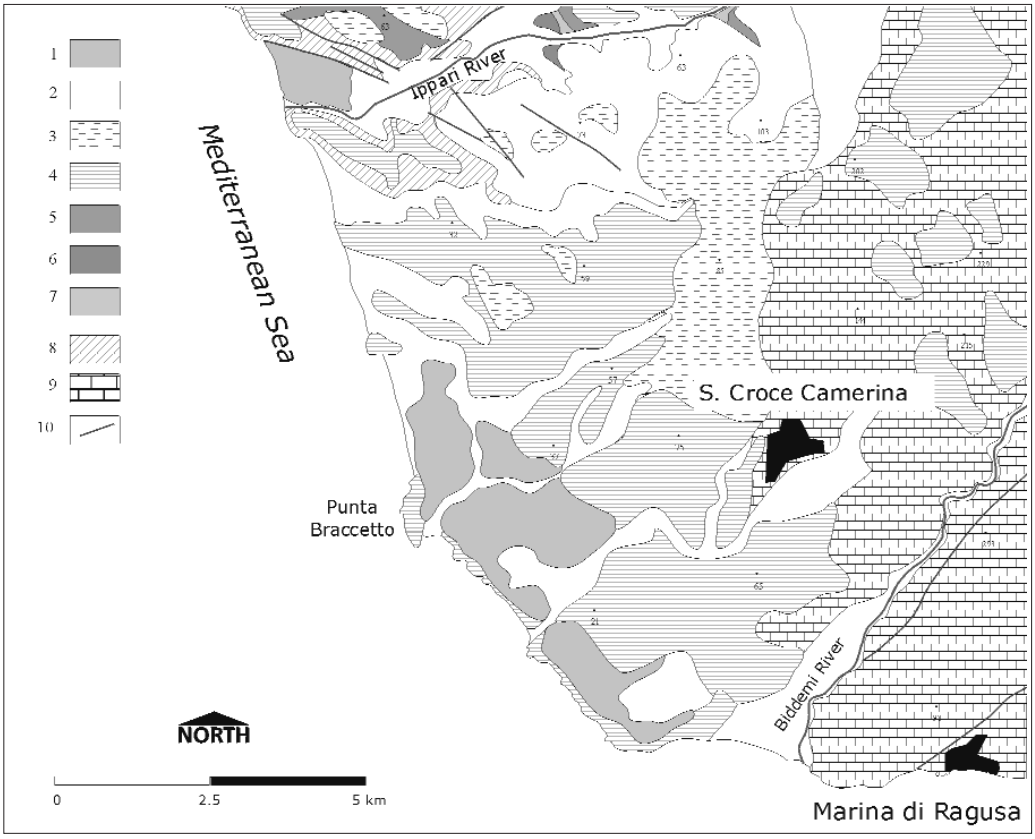

Figure 5. Geological map of the Marina di Ragusa-Ippari River sector: 1) Coastal dunes; 2) Recent alluvial deposits; 3) Swamp deposits (Upper Pleistocene); 4) Marine terraces (Middle-Upper Pleistocene); 5) Calcarenites (Upper Pleistocene); 6) Trubi (Lower Pliocene); 7) Gypsum (Messinian); 8) Tellaro Formation (Upper Miocene); 9) Ragusa Formation (Lower Miocene); 10) Normal fault (modified from Ferrara and Pappalardo, 2003).

Electrical conductivity in the shallow aquifer presents values always above 1,000 µS/cm and reaches values of more than 20,000 µS/cm near Punta Braccetto. In the deep aquifer values are fairly regular except in the northern zone, behind the coast, where a maximum value of 3,900 µS/cm is reached (figures 6c and 6d). The values of salinity (TDS) are always above 400 mg/L, with peaks of 7,100 mg/L at Punta Braccetto.

The high values of electrical conductivity and TDS in the areas nearer to the coast suggest a significant deterioration of the water quality due, in most cases, to seawater intrusion. This is confirmed by the distribution of chloride values, which are always above 100 mg/L in both aquifers and at times are as high as 1,000 mg/L (figures 6e and 6f). A fairly strong relationship between electrical conductibility and chloride is evident, while the highest sulfate values near the Ippari river indicate the influence of pollution caused by the use of fertilizers in agriculture.

On the base of the major ion contents, groundwaters in both aquifers can be classified as bicarbonate-earth alkaline and sulfate-chloride-earth alkaline, as shown in the Piper diagram (Figure 7).

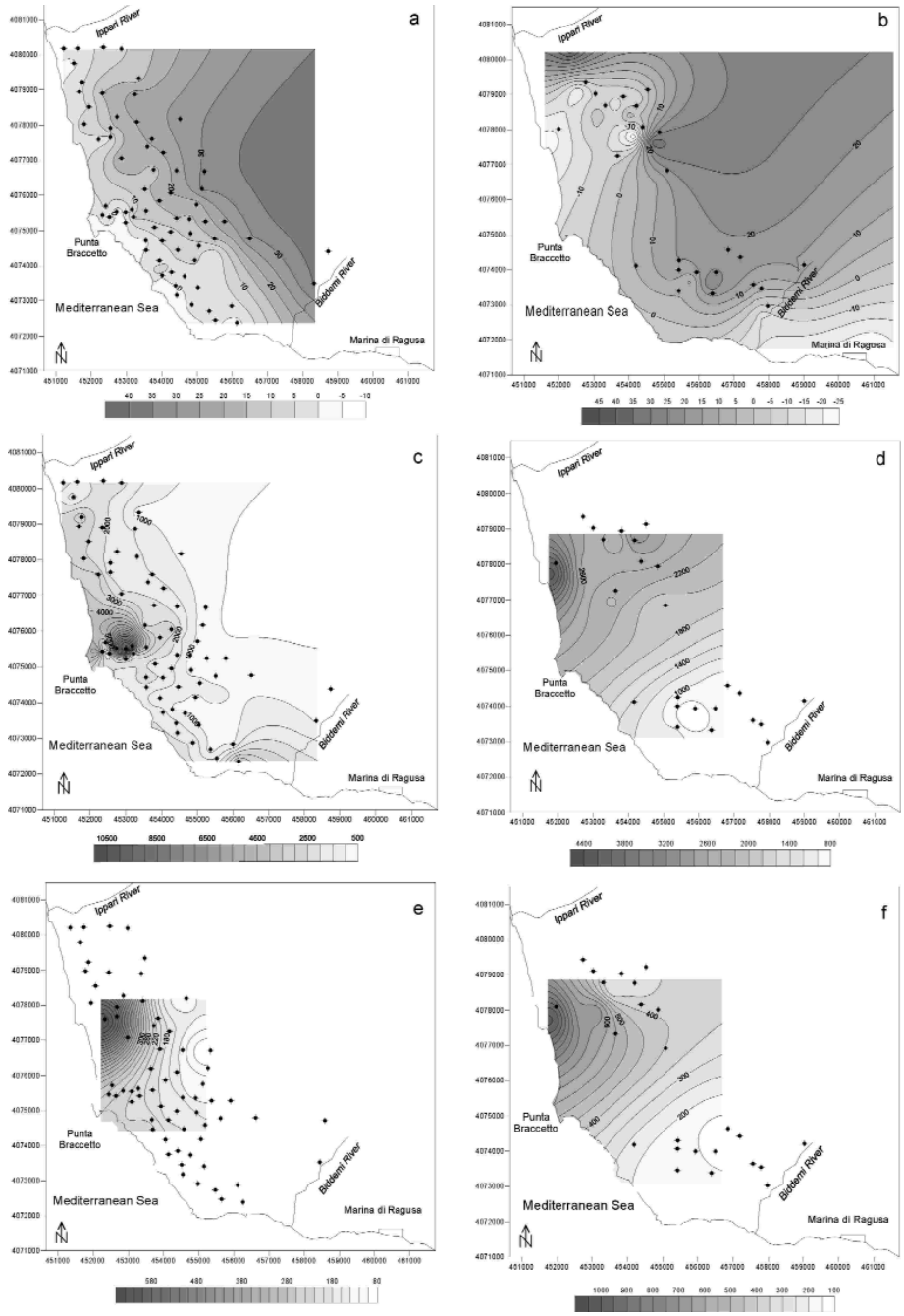

Figure 6. Potentiometric contour lines Marina di Ragusa-Ippori sector: (a) Shallow aquifer, (b) Deep aquifer; electrical conductivity contour lines (μS/cm) for the shallow aquifer (c), and the deep aquifer (d); chloride contour lines (mg/L) for the shallow aquifer (e), and the deep aquifer (f).

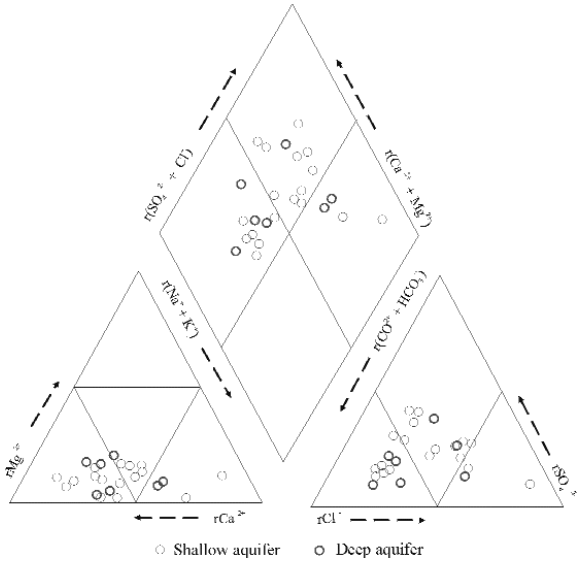

Figure 7. Piper diagram (Marina di Ragusa-Ippari River sector).

Pozzallo – Pantano Longarini sector

In the eastern portion of this sector there are widespread outcrops of recent clastic deposits and Pleistocene marine sediments, represented by coastal sands, present and recent alluvial deposits, marine terraces and biogenic calcarenites, which constitute a water table aquifer of limited capacity. These deposits generally rest upon Miocene clayey marls of the Tellaro Formation and locally upon Pliocene marls and marly limestones (Trubi), constituting the impervious substratum of the aquifer. It is fed by direct infiltration from rainfall and local interconnections with the underlying aquifer. This latter aquifer is constituted by the carbonate sediments of the Ragusa Formation, outcropping in the western portion of the sector in correspondence with horsts bounded by NNE-SSW trending fault systems. It is confined to the east by Pliocene and Miocene marly and marly-calcareous sediments, which represents an aquitard; to the west it is unconfined or semiconfined. Having an elevated permeability due to fracturing and karstification, this aquifer contains important groundwater resources (Figure 8).

Pumping tests carried out in some drilled or dug wells in the shallow aquifer of the eastern large plain gave mean yields of 2-4 L/s and transmissivity values of 1.5 – 2.3 x 10^{-4} m^2/s. The yields of wells tapping the confined aquifer down to 200 m deep are up to some tens of L/s.

From measurements of the water level made in 23 dug and drilled wells in the shallow aquifer it is seen that the water table varies between 0.5 and 3.5 m below the surface in the coastal zone and averages about 10 m in the more internal areas (Figure 9a). Significant seasonal variations occur, with rapid response to rainfall. Groundwater flow directions, derived from the shapes of the water level contour lines, lie orthogonal to the coast line; the value of the hydraulic gradient is very low, in the order of 0.03 %. Due to the limited depth of the potentiometric surface and to the superficial morphology along the coastal belt, groundwater emerges, leading to the formation of extensive swamp areas.

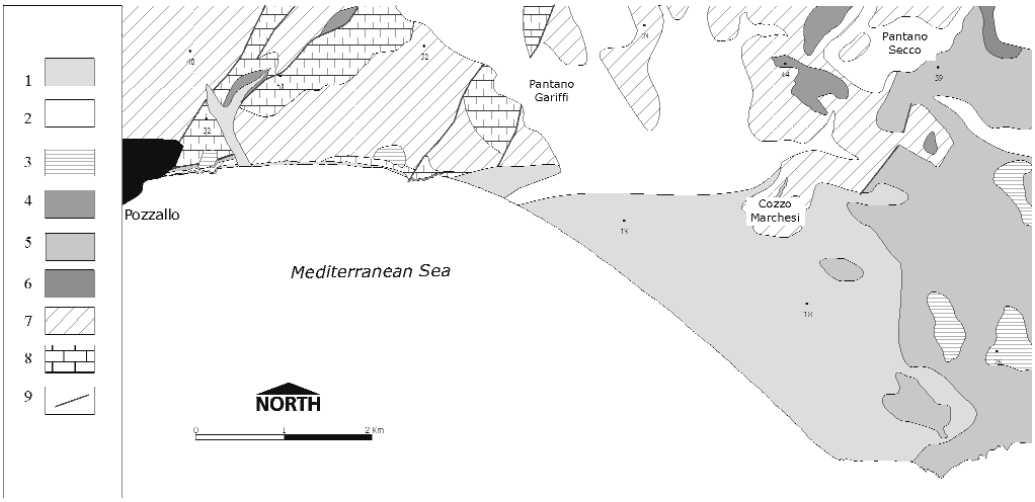

Figure 8. Geological map of Pozzallo-Pantano Longarini sector: 1) Costal sands; 2) Recent alluvial deposits; 3) Marine terraces (Middle - Upper Pleistocene); 4) Calcarenites (Upper Pleistocene); 5) Clays (Upper Pliocene); 6) Trubi (Lower Pliocene); 7) Tellaro Formation (Middle-Upper Miocene); 8) Ragusa Formation (Upper-Middle Miocene); 9) Normal fault.

In the confined aquifer the flow directions are similar to those of the previously described aquifer, but are clearly influenced by the structural setting. At the extreme west margin of the sector groundwater flow is favoured by the high permeability due to fracturing of the carbonate rocks, caused by the NNW-SSE trending fault system. The tectonic structures furthermore determine local interconnections between the two aquifers, adding to the exchange between surface and ground water.

The measurements made in 27 wells drilled to depths of up to 200 m have shown variations in the potentiometric map from 0 to 24 m above the sea level, especially in the eastern portion of the sector (Figure 9b).

Electrical conductivity values in groundwater are elevated both in the shallow and deep aquifers. In the former case, these values always exceed 1,000 µS/cm, with peaks of 12,400 µS/cm in the easternmost part of the sector (Figure 9c). These figures are indicative of mixing with salt waters due to marine intrusion, favoured by the higher permeability of the recent deposits. In the deep aquifer conductivity values are much higher: they consistently lie above 20,000 µS/cm and reach 28,300 µS/cm in the westernmost portion of the sector (Figure 9d). This indicates widespread seawater intrusion into both aquifers, confirmed by the chloride values that coincide with those of the electrical conductivity. In the shallow aquifer the chloride contents show variations from 100 to 2,300 mg/L (Figure 9e), with higher values occurring to the east, and between 200 and 3,800 mg/L in the deep aquifer (Figure 9f). In this latter case two main areas are identified, near Pozzallo and at Pantano Longarini, where marine intrusion appears more accentuated. Here the predominant hydrochemical facies is sulfate-chloride earth alkaline with a clear alkaline tendency (Figure 10).

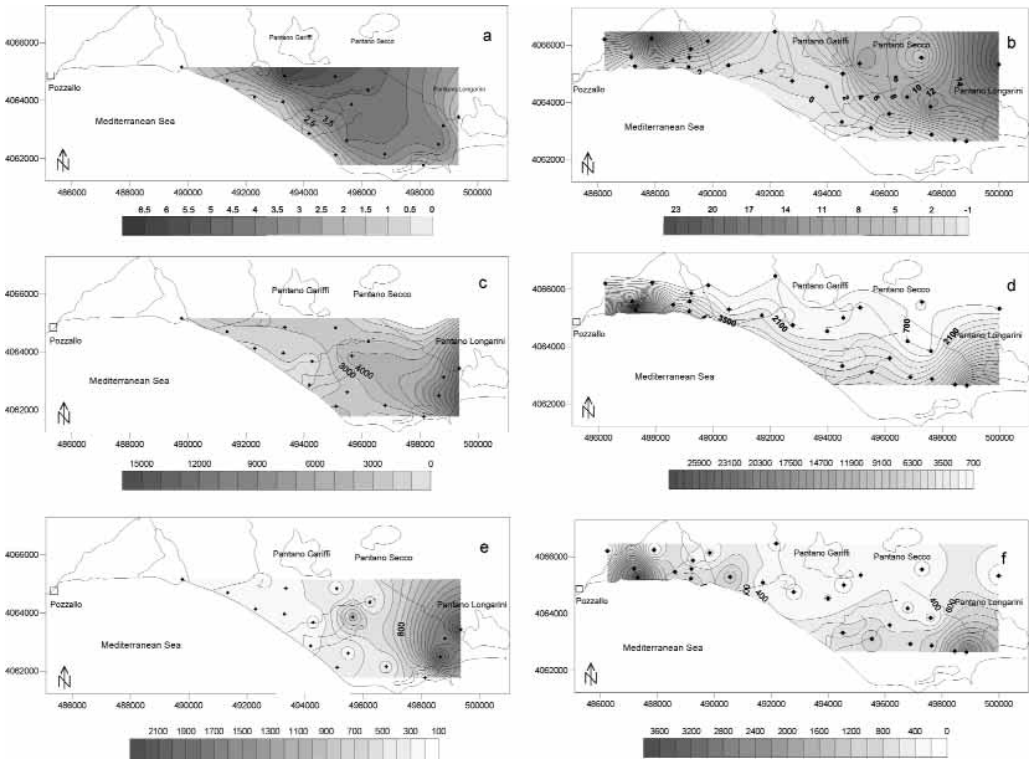

Figure 9. Potentiometric contour lines of the Pozzallo-Pantano Longarini: (a) Shallow aquifer, (b) Deep aquifer; Electrical conductivity contour lines (μS/cm): (c) Shallow aquifer, (d) Deep aquifer; Chloride contour lines (mg/L):(e) Shallow aquifer, (f) Deep aquifer.

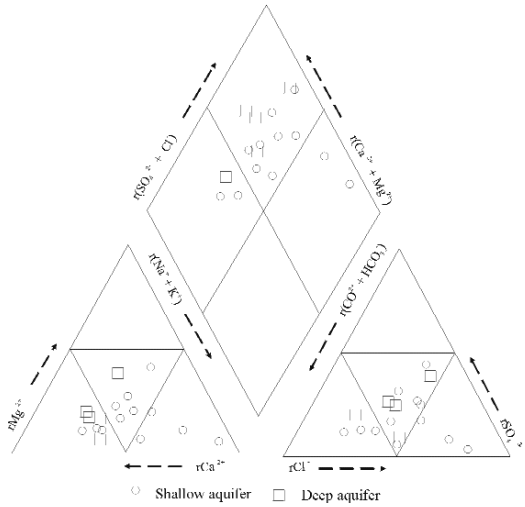

Figure 10. Piper diagram (Pozzallo-Pantano Longarini sector)

The two aquifers thus are seen to be affected in wide areas by intrusion of the saline wedge, which extends inland up to 3 km from the coast line in the more permeable areas and, in contrast, is limited to a few hundred meters or less where low-permeability deposits occur. This is determined by the withdrawals from the wells, which obviously are more numerous and show higher discharge in the areas where the aquifers are more productive.

Discussion and conclusion

The results of the hydrogeological study along the coastal belt between Scoglitti and Pozzallo clearly indicate that the aquifers are excessively exploited, with a consequent degradation of groundwater quality due to marine water intrusion. The aquifer system, constituted by a shallow water table aquifer and a deep confined or semi-confined aquifer, shows different water yields due to permeability and structural conditions. The shallow aquifer is intensely exploited, also for agricultural purposes, and its water quality is poor as demonstrated by high values of electrical conductivity. In the deeper aquifer, which shows a major yield and generally better water quality, exploitation is localized in some areas. The distribution of conductivity values indicates a local deterioration of water quality that increases from the coast towards the inland areas; these are on the average 2,000 μS/cm but locally reach up to 20,000 μS/cm. The highest values are observed near Scoglitti, at Punta Braccetto and to the west of Pozzallo. These conditions can be prevailingly attributed to sea water intrusion and, partially, to the influx of chemical substances used in agriculture and urban wastes.

Groundwater flows towards the coast, with flow directions being influenced mainly by the tectonic structures and, in part, by the morphology of the impervious substratum. The potentiometric surface bears evidence for a strong depression in the deep aquifer in different sectors of the study area (more than 70 m near Scoglitti), where many wells continuously withdraw important volumes of groundwater, differently from the shallow aquifer, whose water table is generally regular.

Chloride contents in the shallow aquifer reach maximum values of 2,000 mg/L in the Pozzallo-Pantano Longarini sector, contrasting with the other two sectors where the values do not exceed 660 mg/L. In the deep aquifer the electrical conductivity values are more than twice as high as in the shallow aquifer in all three sectors. This can probably be attributed to the predominant influence of the marine intrusion and infiltration of chemical products, which are abundantly used for agriculture.

The most common hydrochemical facies is sulfate-chloride earth alkaline, with an alkaline tendency.

From the resulting framework it appears that in the shallow aquifer, in the area between the Dirillo river and Marina di Ragusa, marine intrusion is limited to a belt about 1 km wide relative to the coast, with the exception of two zones where the intrusion is more extensive. In the deep aquifer the intrusion reaches more than 3 km in all places. In the Pozzallo sector marine intrusion has the same extent in both aquifers.

Provided that the uncontrolled exploitation of these aquifers continues, it is easy to foresee a complete salinization in the near future of both aquifers, especially in the deeper one, which represents the main available groundwater resource in the area. Even though the regional economic development depends

essentially on the available groundwater resources, it is fundamental that these aquifers maintain the appropriate quality necessary for the use that is made of them.

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