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SALT WATER INTRUSION IN THE COASTAL PLAINS OF VERSILIA AND ELBA ISLAND (TUSCANY)

SUMMARY

The salt contamination level of the aquifers and the effects of intensive summer pumping have been investigated on the Versilia coastal plain and on three minor plains of Elba Island.

Water table contour maps and isoconductive maps are presented. Chemical and conductivity analyses of ground-water samples have shown that the electrical conductivity is strictly controlled by the salt content; therefore, the isoconductive contours provide a good pattern of the marine water intrusion in fresh waters.

Along the coastal strip of the Versilia, the ground water conductivity increases as a result of the intensive summer pumping of the aquifer. The highest value in salinity is however reached in the intermediate belt of the plain, where the water table is permanently maintained below sea level by the drainage pumping of areas occupied in the past centuries by lagoons or marshes.

On Elba Island the overdraft conditions of the coastal aquifers, resulting from the increased demand of water, expecially during summer, have caused a permanent salt water intrusion in many areas. Consequently, the salinity of the drinking water from many public wells is above acceptable limits.

1. INTRODUCTION

Versilia, the Tuscan coastal plain that extends from Viareggio to the mouth of the Magra River, and the Island of Elba are popular summer resorts. In Versilia approximately 240,000 tourists join the 127,000 permanent residents for the months of July and August. The number of tourists visiting the Island of Elba has increased 700% in the past fifteen years; in August of 1981,

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in addition to the 29,000 permanent residents, there was a daily average of 25,000 tourists.

The sizeable increase in the population of these areas results in increased demand for water, and more pumping of ground water, which is the primary source in both places. Since the water sources are coastal aquifers, extensive pumping exposes them to the risk of contamination by sea water.

The problem of contamination of ground water studied in a large part of Versilia (15 km of coast and approximately 45 km^2 of coastal plain) and in three coastal plains of the Island of Elba (Marina di Campo, approximately 5 km^2, Portoferraio, approximately 3 km^2, Mola, 1.7 km^2).

2. METHOD OF STUDY

The study was divided into the following steps:

a) Location and description of wells.

b) Reconstruction of the lithostratigraphic succession of incoherent sediments containing aquifers.

c) Chemical analysis of samples of well water and comparison of their electrical conductivity.

d) Seasonal measurements of the static water table in the wells and of the electrical conductivity of their water.

a) Between January and April 1982 the water wells in Versilia were surveyed to establish an evenly distributed net of stations. Of the many wells present, 202 were chosen, with an average density of 4.5 wells per km^2. Most of the wells are shallow (less than 10 m), and are either hand dug or of the Norton type.

For each well the topographic elevation, the elevation of the mouth of the well, its depth, use, and, when possible, the rock type encountered during its digging were recorded. Topographic elevations were determined within 10-15 cm, using maps with scales of 1:2,000 or 1:5,000.

On the Island of Elba 344 wells were catalogued and the first measurement of their water levels was done in May 1981. The greater density with respect to Versilia is justified by the more rapid changes in short distances found on the smaller coastal plains, both in the characteristics of the aquifers and in the salinity of the water. Topographic elevations were determined using published maps with scales of 1:2,000 for Portoferraio, 1:5,000 for Mola, and 1:10,000 for Marina di Campo.

b) For the Versilia 64 well logs are available, only 9 of which record depths greater than 70 m. These data allow a good reconstruction of the local stratigraphic colum.

Of the three Elba coastal plains, Marina di Campo is the only one with sufficient stratigraphical data: 21 well logs and an electrical resistivity survey. Three well logs are available for the Mola area, and one for Portoferraio. However, many owners of hand dug wells gave us information on the stratigraphy encountered.

c) The electrical conductivity of water depends on the concentration of ions present. In general, for the waters of a certain chemical type, the conductivity is directly proportional to the total concentration of the ions.

In order to determine quickly, even if approximately, the degree of ground water contamination by sea water, we first attempted to establish whether the degree of electrical conductivity of well water provided a sufficient measurement of sodium chloride content. We analysed 11 samples from Versilia and 11 from Elba for their content of the seven foudamental components (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^-, SO_4^{2-}, Cl^-). In samples from 7 other wells on Elba only the concentrations of Ca^{2+} and Mg^{2+} were determined.

The results of the analyses indicate that the waters, under natural conditions, are of the alkaline-earth bicarbonate type. The water from the plain of Mola is alkaline-earth sulfate, probably because of the presence of sulfides that have been oxidized to sulfates in the subsoil: the area was, until a few decades ago, a swamp. Contamination of well waters by sea water results in an increase in the concentration of Na^+ and Cl^-, shifting them into the alkaline chloride type waters.

The graph of electrical conductivity versus concentration of Cl^- (Fig. 1) indicates that above 1,000 micro Siemens the conductivity is almost directly proportional to the concentration of Cl^-. The same relations applies between

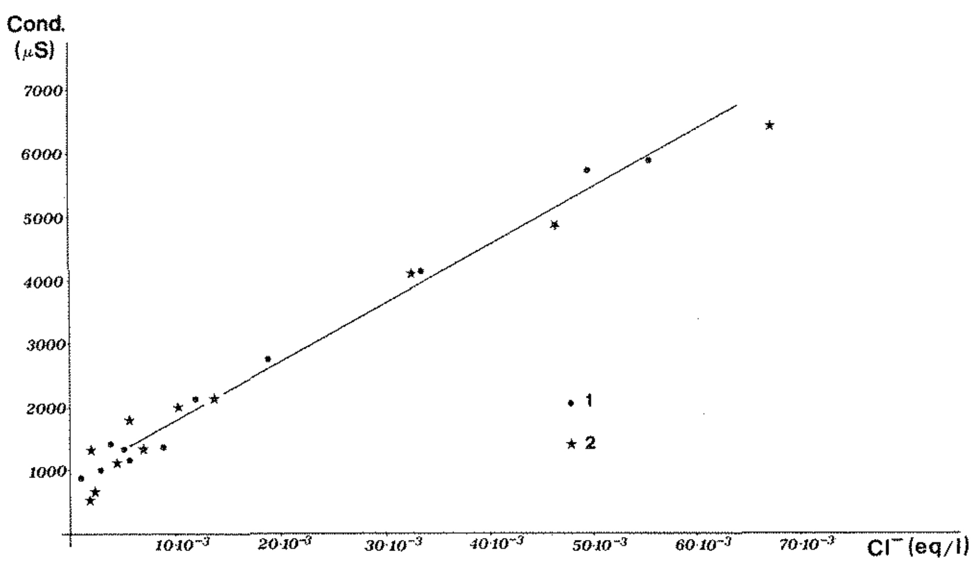

Fig. 1 - Electrical conductivity (microSiemens = 10^{-6} mohs) - Cl^- concentration (equivalents per liter). Dots: Versilia water samples. Stars: Elba water samples.

conductivity and concentration of Na^+. At low electrical conductivity this relationship is not valid because, in many cases, the majority of ions are other than Na^+ and Cl^-.

On the basis of these results we concluded that measurements of the electrical conductivity of well water with values above 1,000 μS give good approximations of the degree of contamination of fresh water by sea water.

d) In each area studied, the water conductivity and the static level in the wells were measured in two different periods. The first, in April and May, took place when the water table had reached its highest annual level, and the second occurred at the end of the maximum summer pumping, at the beginning of September. To study the relationship between Versilia's water table and surface water we also measured the levels of streams in 47 spots.

In each area the measurements were taken within a period of one to three days. Repeated mesurements in some of the wells indicate that variations in the level of the water table are not significant over such an interval.

Electrical conductivity was measured in the field, using a portable conductivity meter, on samples taken from slightly below the water levels of the wells. Due to lack of equipment, we were unable to test for conductivity at various depths, which would have allowed us to locate the salt water-fresh water interface. The measurements of water levels and conductivity were made contemporaneously in September. The measurements done in the spring were not contemporaneous, but were both made during the period of maximum elevation of the water table (see hydrogeological maps).

The isoconductive and isophreatic lines of the four areas studied were combined on the hydrogeologic maps. Because of the large reduction in scale of our maps with respect to the original 1:10,000 maps, it was necessary to simplify them. We therefore divided the conductivity of the waters into three ranges, with limits at 1,000 and 2,000 μS. Lines corresponding to maximum and minimum values of isoconductivity were also drawn. One may observe that, in our case, water with conductivity above 2,000 μS is salty enough to be nonpotable, while water with conductivity between 1,000 and 2,000 μS has already been contaminated to some degree by sea water.

3. VERSILIA'S FREE AQUIFER

The Versilia region is a tectonic through, bounded to the east by the Apuan Alps, which has been in existence since Messinian Time. Figure 2 is a stratigraphic section normal to the coast near Fosso di Camaiore. There are both marine sands and continental gravels and peaty clays, whose interbedding is due to eustatic variation in sea level during the upper Pleistocene and Holocene. Marine sands and continental gravels make up the major aquifers. The unconfined aquifer is in the sands, and, inland, in sandy or gravelly muds and in the gravels of alluvial fans.

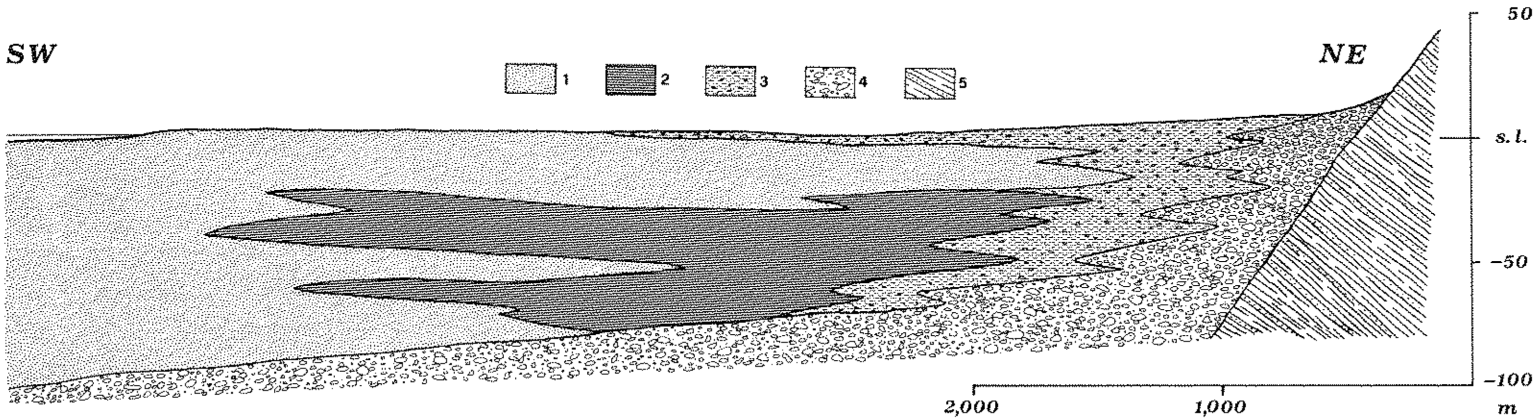

Fig. 2 - Geological cross section of Versilia plain, about 2 Km north of Viareggio. 1: marine sand; 2: peaty clay; 3: silt with clay and gravel; 4: gravel; 5: consolidated formations of Apuane Alps.

The hydraulic gradient of the unconfined aquifer (Figg. 3 and 4) (0.1% on the average) on the coastal plain is very low because of the high permeability of the marine sands. The piedmont strip, made up of alluvial fans, is the principal source of water for the aquifer, and has a hydraulic gradient that increases to over 1%.

The isophreatic lines clearly indicate that in both seasons when measurements were made the water table was lowest in the central part of the plain, and in many areas was below sea level. In the past this zone was in large part occupied by lagoons or swamps (the soil contain peat), that have been reclaimed through the use of drainage ditches or other means. The water table is lowest in the Brentino area, where siliceous gravels are quarried. Here continuous pumping by the Consorzio di Bonifica has lowered the water table to more than 3 m below sea level. Along the outer strip of the Versilian coastal plain the water table is always above sea level, though summer pumping lowers it by an average of 0.5 m.

The highest electrical conductivity values occur where the water table is lowest. In the Brentino area the conductivity is 3,000 μS in May and 5,000 μS in September. 500 m south of Viareggio, a profile (Fig. 5) done by means of electrical soundings by Geotecneco [1], clearly shows that sea water slides under the lens of fresh water along the coast and rises in areas where the water table is depressed. Canals and ditches are other sources of salt water diffusion, which occurs during high tides and, to a greater extent, during storms. However, in areas further from the coast, canal water infiltrates and lowers the salinity of the aquifers.

By comparing the isophreatic maps done in the spring and in September, we may observe the general lowering of the water table caused by summer pumping and the consequent increase in salinity.

To avoid continuing deterioration in the quality of ground water, a more rational management of hydrologic resources is necessary. In particular, pumping near the coast should be limited to avoid raising the fresh water-salt water interface. Instead, the rich confined aquifers made up of gravel that underlie the sand and clay layer should be tapped. It would also be prudent to reduce the diffusion of salt water through the canal system, either by waterproofing the channels of by installing locks.

4. AQUIFERS ON THE ISLAND OF ELBA

In the central part of the island there are some small valleys debouching into the sea which are filled with thin sequences of Quaternary alluvial deposits. They consist, for the most part, of sandy muds, with lenses of gravel commonly in contact with bedrock. Only near the coast are marine sands found (Fig. 6). A great many shallow wells remove small amounts of water slightly permeable unconfined aquifers. The flow is generally greater in wells that penetrate either the gravels beneath or the fractured bedrock.

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[1] Geotecneco (1975) - Accertamenti ed indagini per la salvaguardia dall'inquinamento del Lago di Massaciuccoli e del suo territorio. Ministero Agricoltura e Foreste.

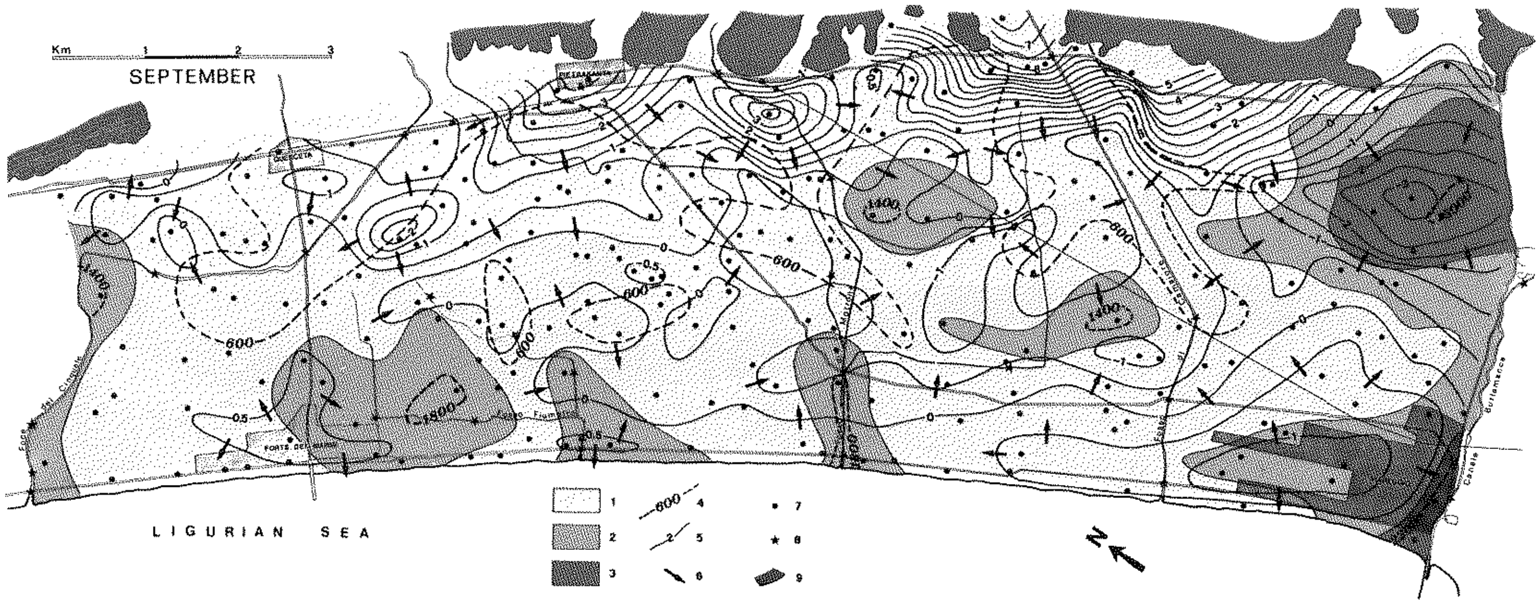

Fig. 3 – Versilia hydrogeological map. Ground water electrical conductivity and water table elevation: 3, 4 e 5 September 1982. 1: ground water electrical conductivity less than 1,000 microSiemens; 2: 1,000 to 2,000 μS; 3: above 2,000 μS; 4: isoconductive lines of maximum and minimum values (μS); 5: water table contours, interval 0,5 m; 6: flow lines; 7: measuring wells; 8: surface water measuring spots; 9: plain bounds.

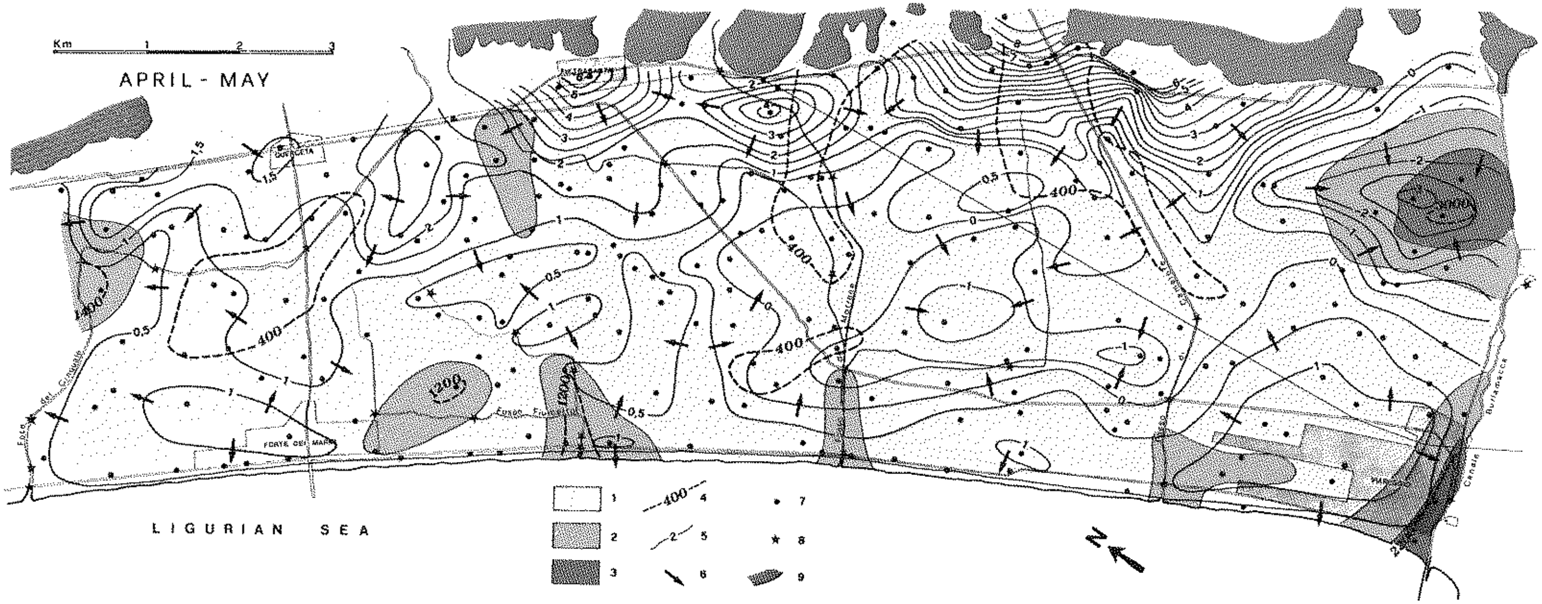

Fig. 4 - Versilia hydrogeological map. Ground water electrical conductivity: 5 e 6 May 1982. Water table elevation: 24 e 25 April 1982. Numbers see Fig. 3.

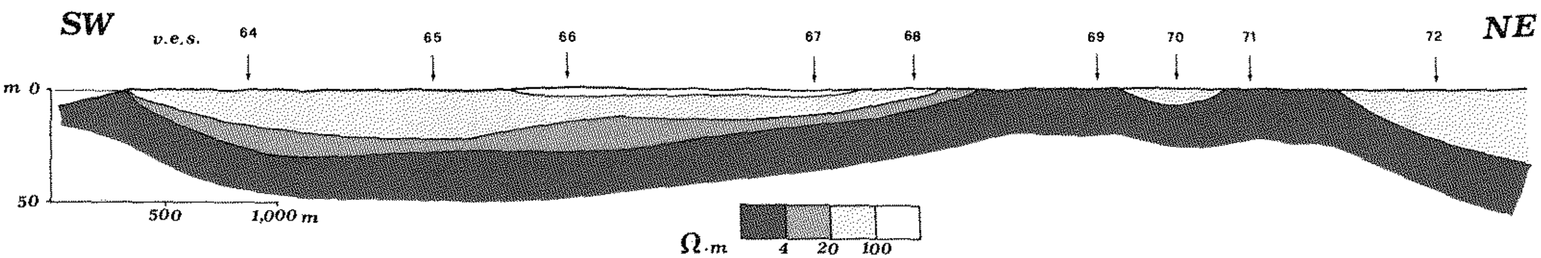

Fig. 5 - Electrical resistivity section of Versilia plain, 500 m south of Viareggio (from Geotecneco, 1975). Low resistivity values (less than 4 Ω m) correspond to the salt water intrusion.

4. 1. Marina di Campo

The water table's hydraulic gradient averages 1% because of the low permeability of the aquifer. Local, sometimes abrupt variations in the hydraulic gradient are due to variations in either the flow section (e.g. Galea valley) or in permeability (e.g. Fosso Alzi valley).

In September (Fig. 7) the water table is depressed below sea level over an area extending 1 km inland. Here the conductivity of the water is high, in many spots over 2,000 μS, which indicates that sea water has intruded into the aquifer. Other area, even far from the sea, that experience sizeable seasonal changes in the phreatic water level, also have high conductivity rates. Chemical analyses of samples from the unconfined aquifer 3 km from the coast in the upper Galea valley, where some wells pump water from the granodiorite bedrock, reveal a high concentration of sodium chloride. Sea water probably intrudes through fractures in the basement rocks. In the middle section of the Fosso Alzi valley the salinity of the water is relatively low, probably because the aquifer is supplied with fresh water by the stream. The map drawn in April (Fig. 8) shows the water to be less salty than in September, but in many areas its electrical conductivity still exceeds 1,500 μS.

4. 2. Portoferraio

The area can be divided geologically into two parts: the valley of the Fosso della Madonna, in which the unconfined aquifer is made up of muddy sands, and the plain of S. Giovanni, which consists largely of muds. The differing permeability of the two areas results in their having different hydraulic

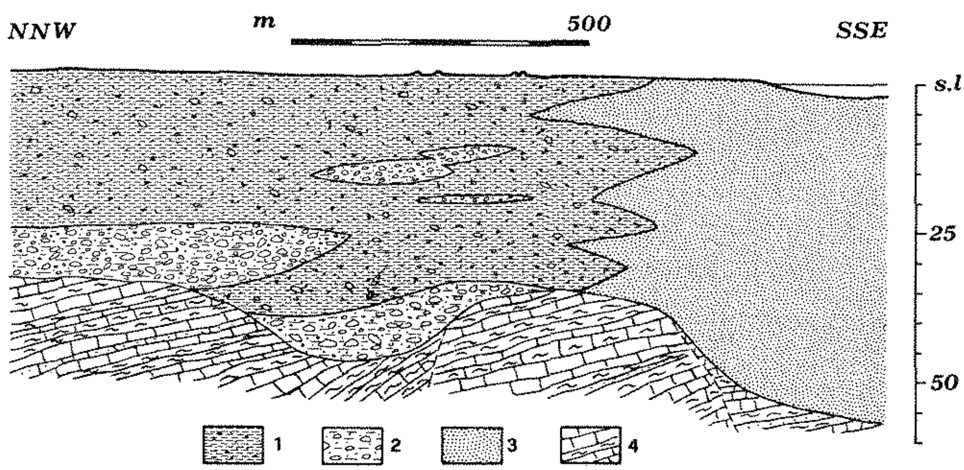

Fig. 6 - Geological section of Marina di Campo plain; 1: sandy silt; 2: gravel; 3: marine sands; 4: calcareous bedrock.

Fig. 7 – Marina di Campo hydrogeological map. Ground water electrical conductivity and water table elevation: 8 September 1981. 1: ground water electrical conductivity less than 1,000 μS; 2: 1,000 to 2,000 μS; 3: above 2,000 μS; 4: isoconductive lines of maximum and minimum values (μS); 5: water table contours, interval 5 m; 6: water table contours, interval 1 m; 7: measuring wells; 8: flow lines; 9: plain bounds.

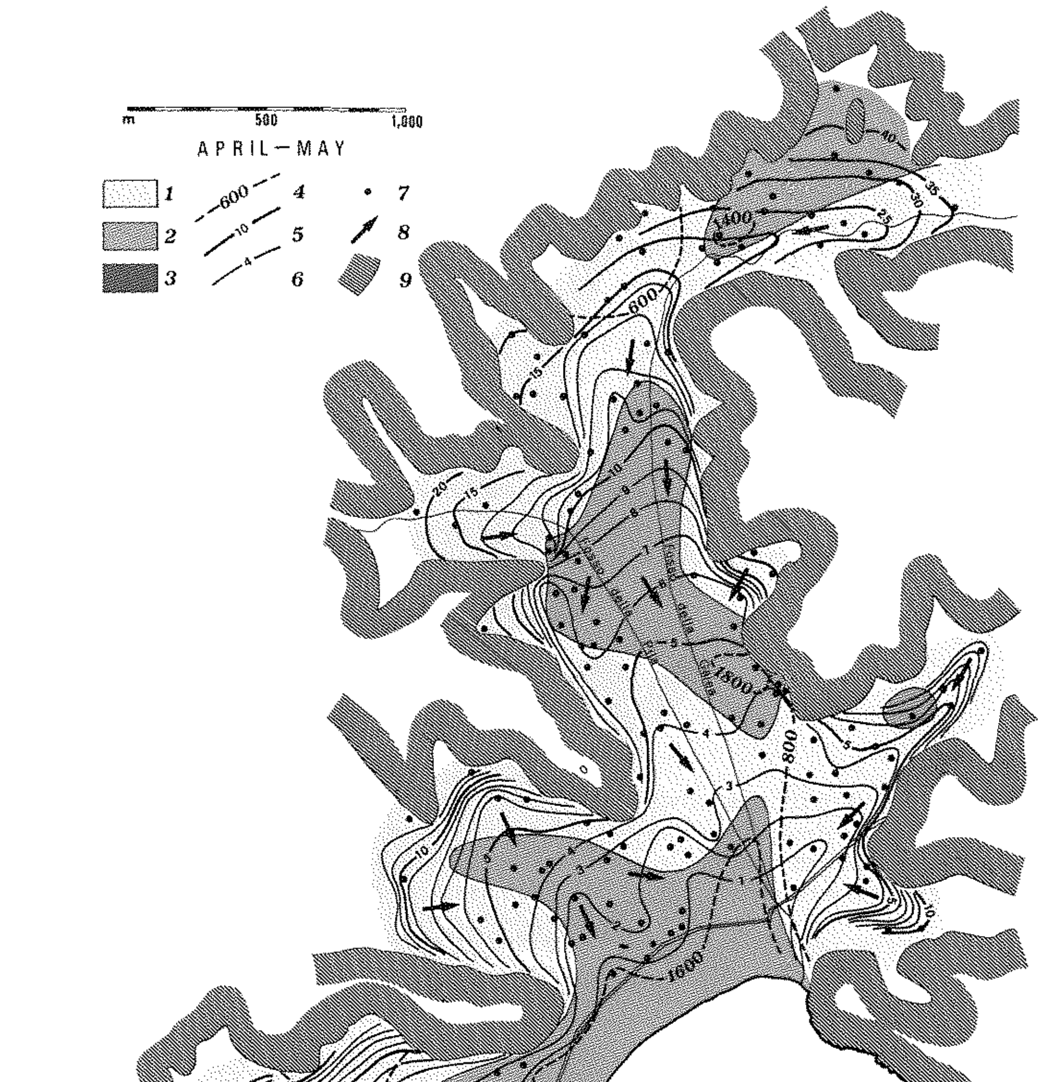

Fig. 8 - Marina di Campo hydrogeological map. Ground water electrical conductivity: 5 e 6 April 1982. Water table elevation: 25, 26 e 27 May 1981. Numbers see Fig. 7.

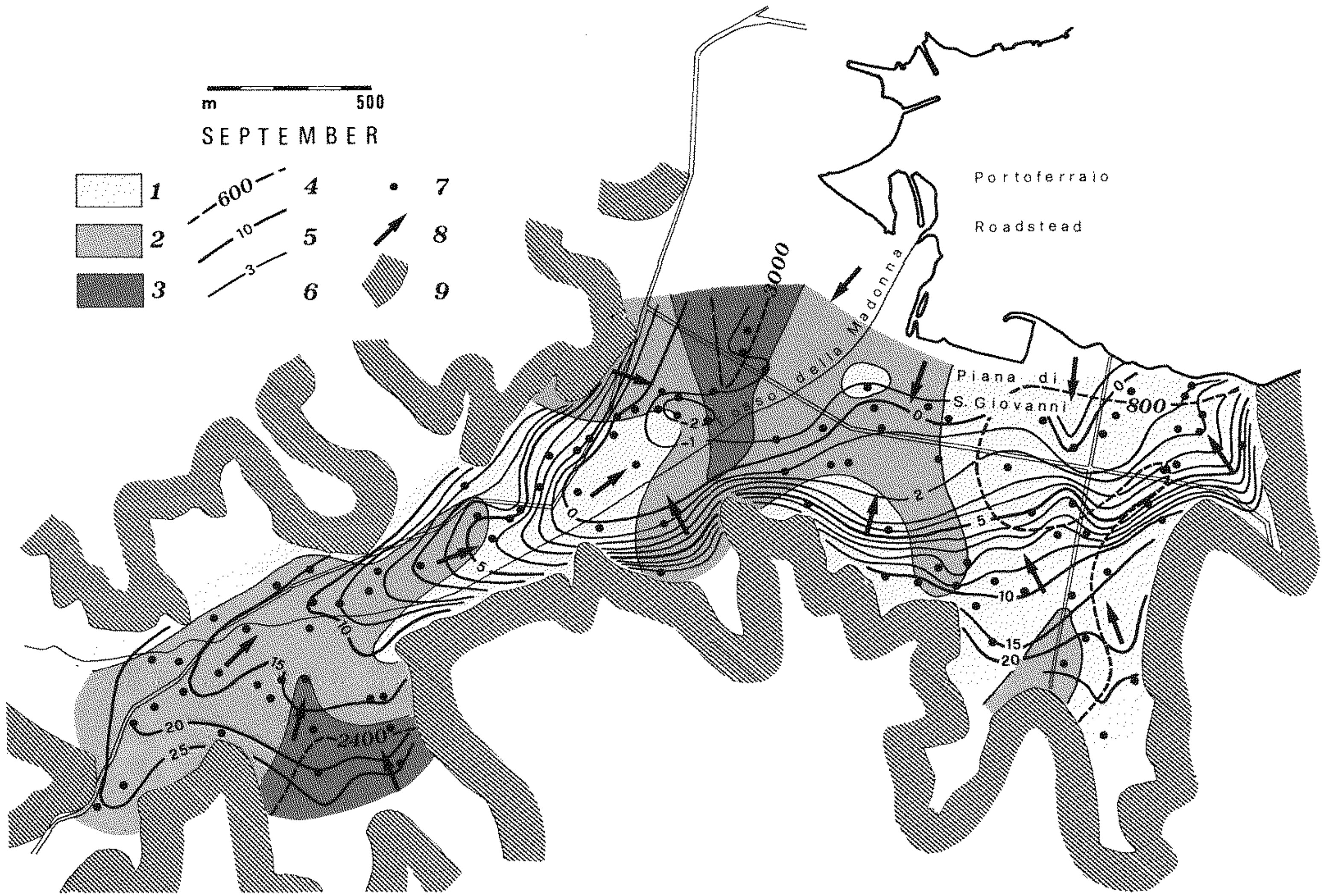

Fig. 9 – Portoferraio hydrogeological map. Ground water electrical conductivity and water table elevation: 9 September 1981. Number see Fig. 7.

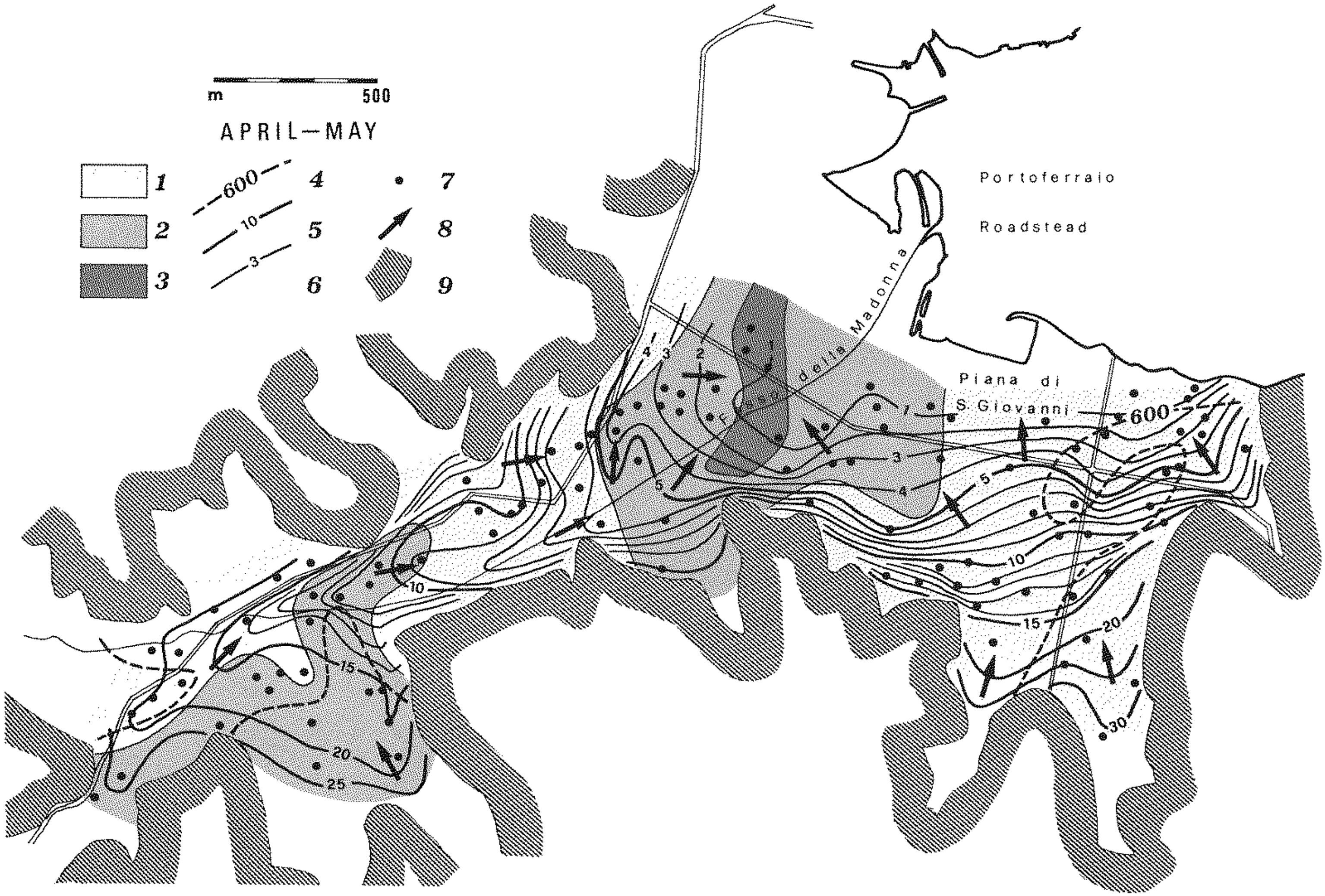

Fig. 10 – Portoferraio hydrogeological map. Ground water electrical conductivity: 7 April 1982. Water table elevation: 20,21 e 22 May 1981. Numbers see Fig. 7.

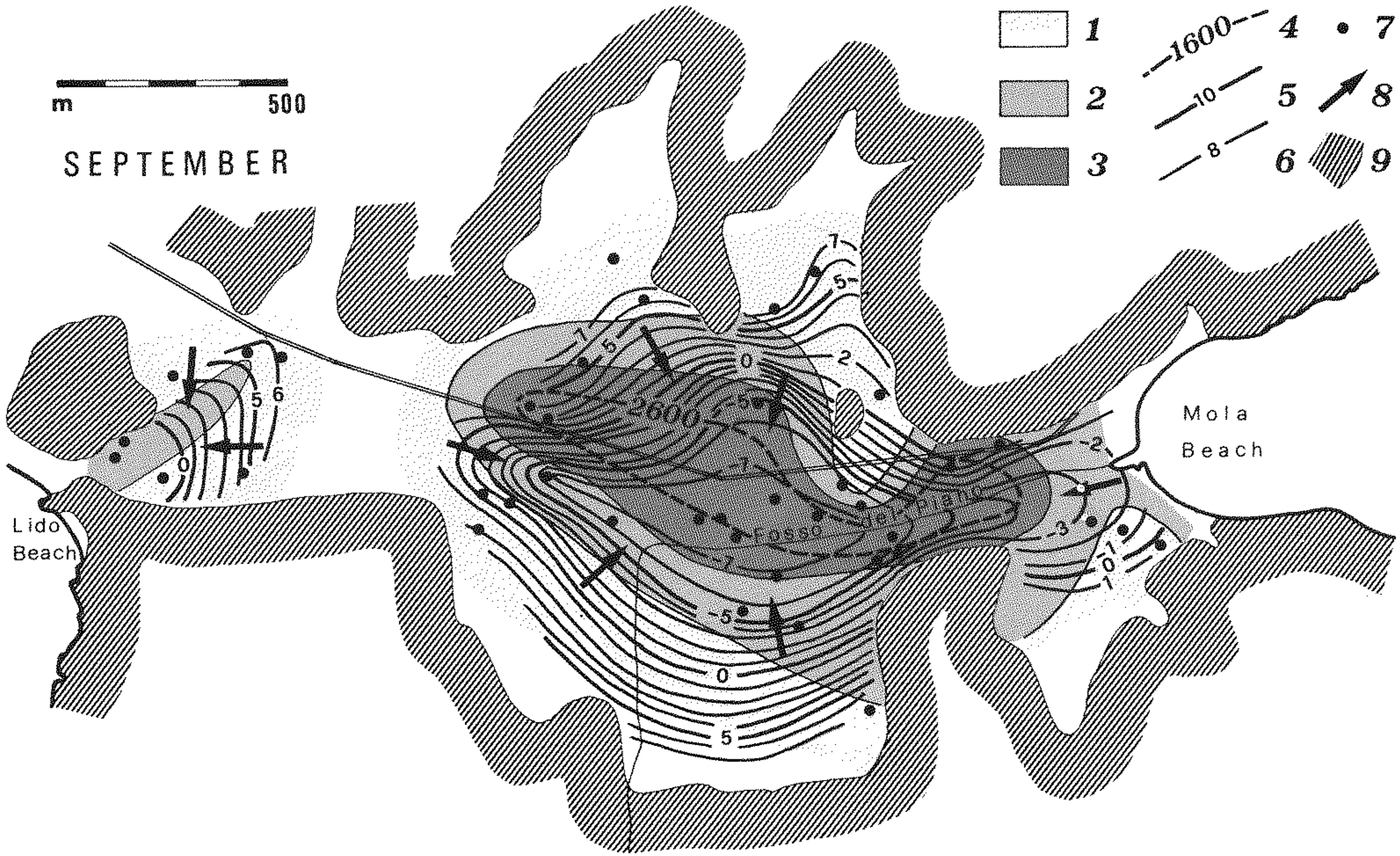

Fig. 11 - Mola hydrogeological map. Ground water electrical conductivity and water table elevation: 7 September 1981. Numbers see Fig. 7.

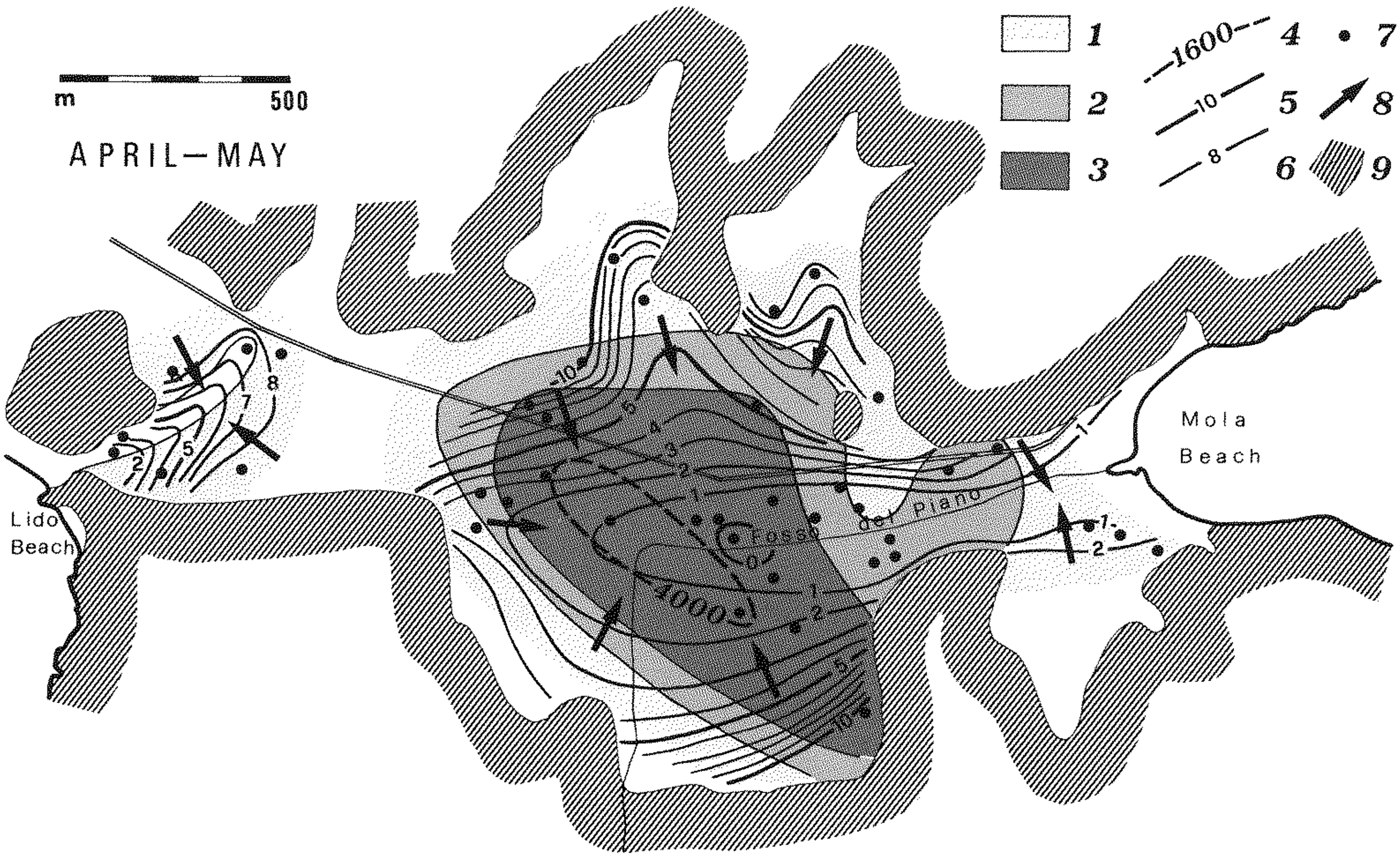

Fig. 12 - Mola hydrogeological map. Ground water electrical conductivity: 2 April 1982. Water table elevation: 14 May 1981. Numbers see Fig. 7.

gradients. The Valle della Madonna is intruded to a greater degree by sea water, and in September (Figg. 9 and 10) the lower part of the valley's water table is below sea level and the conductivity of its water is high. The salinity of the water in the upper part of the valley, where some wells draw from bedrock, is also high. In the area of S. Giovanni, on the other hand, the salinity of the water is low even in September.

4. 3. Mola

In this small dead valley, occupied until a few decades ago by a swamp, shallow wells pump water from a slightly permeable aquifer made up mostly of muds. Some of the municipal wells reach gravels at the foot of the valley, at a depth of about 35 m. The isophreatic lines for both seasons (Figg. 11 and 12) indicate a centripetal flow towards the area of maximum pumping. In September the water table is lowered as much as 8 m below sea level. Measurements of the water's salinity show that it is greatest where pumping is most intense, but, surprisingly, indicate that salinity is higher in May than in September. This is probably because when the May measurements were made the municipal pumps had been turned off: salty water, rising from the gravel aquifer, escaped through openings present in the upper part of the well casing and polluted the free aquifer.

4. 4. Conclusion

The unconfined aquifers of the plains on Elba are, in many areas, badly contaminated by salt water. Many municipal wells distribute water whose salinity is above acceptable limits, especially during the summer. Intrusion of sea water occurs both near the sea, where the water table has been lowered by pumping, and in areas far inland. In the latter case intrusion occurs through deeply buried gravels or through fractures in the bedrock. In spring the water is only slightly less saline than it is in September, reflecting the inability of the aquifers to flush themselves.

On the Island of Elba, as in Versilia, a more rational management of hydrologic resources is necessary, though the problem is more difficult because of the greater contamination of the aquifers and the paucity of hydrologic resources.

The seriousness of the situation could justify expensive preventive measures, such as impermeable barriers or recharging wells near the coast. However, it is probably more practical to seek alternate hydrologic resources; for example, wells in the limestones and jaspers that outcrop in the center of the island, or artificial reservoirs. It is also worth noting that there are plans for a submarine pipeline to transport water from the mainland that would solve many of the island's water problems.