AQUIFER CONFIGURATION AND POSSIBLE CAUSES OF SALINATION IN THE MURAVERA PLAIN (SE SARDINIA, ITALY)

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ABSTRACT

In the early 1970's an aquifer with high salt content was recognised in the coastal belt of the Muravera plain. Because of capillary rise and intense evaporation, this situation has resulted in a progressive salination of the soils and the irremediable loss of land traditionally under cultivation for citrus fruits.
The study, involving hydrogeological investigations and chemical analyses, conductivity and temperature logging, geognostic investigations and geophysical prospection, has allowed to characterise the aquifers in the plain in geometrical and hydrodynamic terms. Based on the findings, some hypotheses are advanced as to the causes of salt water intrusion.

SETTING OF THE STUDY AREA

The area concerned extends over the delta plain on the right bank of the Flumendosa river, a few kilometres from the sea, near the built up area of Muravera (Sarrabus, S.E. Sardinia).
In latter years a great deal of stratigraphical, petrographical and tectonic studies has been conducted in the Sarrabus region. The most ancient formation, the *San Vito Sandstone,* is composed of a thick, weakly metamorphosed sequence of sandstone, quarzites and shales. These are overlain by metavolcanites, known as the *Grey and White Porphyries.* The volcanic formations are followed by metasandstones and metaconglomerates, the *Punta Serpeddì Formation*, silicified limestones, the *Tuviois Formation* and lastly by metasediments of Silurian-Devonian and likely Carboniferous age, the *Serra S'Illixi Group*.
The foothills encompassing the plain are composed entirely of clastic sediments (talus) that further down-slope mingle with the ancient alluvium bordering the water courses. The river valley floor and the entire plain are made up of recent and actual alluvium (Fig. 1).
For several years now, the coastal aquifers in the Muravera plain, and in particular the areas on the right bank of the Flumendosa river below the town of Muravera, have been affected by widespread saltwater intrusion. The has also resulted in the accumulation of salt in the upper soil horizons, with the irremediable loss of land traditionally used for farming.

For the time being, water supply in the whole area is secured by the increasingly large number of wells in the plain, most of them dug. Uncontrolled groundwater withdrawals, especially in the summer when the demand soars, has upset the fresh-saltwater equilibrium regime, and consequently the saltwater is progressively encroaching inland.

EARLIER STUDIES

The first studies concerning groundwater contamination in the Muravera plain date to the early 1970's (Aru,1970), and pointed to the alarming phenomenon of gradual salination of the soils. The causes were attributed to capillary rise and to the intense evaporation of the salty groundwater that flows just beneath ground level.
Studies were resumed in the 1980's by the Institute of Applied Geology at the Faculty of Engineering, Cagliari University. Both hydrogeological and geophysical research techniques were adopted to follow the temporal and spatial evolutionary trend of saltwater intrusion in the groundwater (Barbieri et al., 1983).
For this purpose, a network consisting of about thirty wells dotted more or less regularly over the plain and extending over some 3.2 km^2 was set up for monitoring the shallow aquifer. Water levels were measured periodically and samples taken for chemical analysis. Based on the findings of these investigations it was possible to determine the extent and intensity of saltwater intrusion and to advance the hypothesis that it was the over-exploitation of groundwater during the summer months that was chiefly responsible for the phenomenon (Barbieri & Barrocu, 1984).
In the years 1983-1985 a geophysical investigation was conducted resorting to vertical electrical soundings for resistivity and chargeability for the purpose of delineating the freshwater-saltwater interface (Barbieri et al., 1986).
Further investigations in the period 1989-1993 allowed to determine the evolutionary trend of saltwater intrusion, and pointed to a significant deterioration in groundwater quality over time, as a consequence of the progressive advance inland of the area affected by saltwater encroachment (Ardau & Barbieri, 1994).
Studies in the Muravera coastal plain were resumed once again in 1993-1995, with conductivity and temperature logging, geognostic investigations and geophysical prospection and have continued up to the present time.

HYDROGEOLOGICAL AND HYDROCHEMICAL INVESTIGATIONS

The water level measurements and results of chemical analyses were used to map piezometric surface as well as chlorine isohypes.
The piezometric surface contour maps showed the water table to vary strongly during the hydrological year. During late autumn, winter and spring, when the crops do not need irrigating and little water is pumped from the wells in the plain, the isohypses exhibit a very regular pattern. Conversely, during the summer and early autumn, when the demand for irrigation water rises significantly and the farmers abstract huge quantities of groundwater from the wells, the contour lines become highly irregular and distorted.
This gives rise to extensive water table depression, particular in the area between Foxi Padrionnas e Bau Obilu ("*foxi*" are former arms of the river no longer connected thereto), where the irrigated crops are concentrated.
From analysis of the hydrometer recordings, one installed at sea to record fluctuations in tide, the other in the Foxi Padrionnas, about 3 km from the coast, it emerged that the variations

in sea level coincided with the variations in the level of water measured at Foxi Padrionnas, with half-wavelengths of roughly 6 hours (rise and fall of tide) in both cases and time lags of about 3 hours between the maxima and minima measured at sea and those measured at the river mouth. This goes to show the direct influence that the sea and the tides exert on the regime of the foxi, even in those points furthest from the coast.

Examination of the chlorine contour maps clearly shows that the shallow aquifer is severely contaminated by saltwater in the south-eastern part of the study area. What is more, saltwater intrusion in the same well varies with time and has been observed to gradually increase over the years, generally showing peaks in late summer. The shape of the chlorine isohypses also indicates that the saltwater intrusion has a specifically irreversible nature, insofar as even abundant runoff during the winter months does not suffice to flush the salt out and high concentrations of salt persist the contaminated groundwater.

Water samples were collected in the dug and drilled wells, and at sea in an area facing the study site. The Cl^-, Br^-, e Sr^{2+} contents were determined, presuming that these ions, good indicators of seawater encroachment in many hydrogeological situations, could furnish some explanation as to the cause of seawater encroachment in the area.

The rBr-to-rCl e rSr-to-rCl ion ratios have been calculated and compared with those typical of present day seawater for which they remain essentially constant. Analysis of groundwater sampled from the shallow aquifer revealed substantially constant rBr-to-Cl and rSr-to-Cl ratios, close to those measured for seawater. The same can be said for the rSr-to-rCl ratio of the deep aquifer while the rBr-to-rCl exhibits a different trend.

CONDUCTIVITY AND TEMPERATURE LOGS

Salinity and temperature were repeatedly logged in both the dug and drilled wells in the monitoring network, with a view to identifying the freshwater-saltwater interface and the presence, if any, of water coming from different aquifers.

In the shallow wells, excavated down to depths of no more than 5-6 m below ground level, no variations in conductivity were observed with depth and this was true for both the fresh-water wells upstream and the salty ones downstream. As for the drilled wells, only the ones upstream containing fresh-water yielded constant conductivity (around 400 μS/cm), while log data for the ones further downstream indicated that brackish water was present at the surface, but especially that salinity increased with depth (Fig. 2).

Beneath the layer of allothermic soil (at roughly 6 m below ground level), mean temperatures of 16-17°C were measured in the dug wells, 18°C in the drilled ones.

GEOGNOSTIC INVESTIGATION

The soundings were performed moving from up- to downstream perpendicular to the coastline at roughly 1 km spacing, the last sounding being done at about 300 m from the sea. Penetration depth ranged from 30 to 33 m (Fig. 2). Because of operational difficulties, it proved impossible to drill to greater depths and none of the soundings penetrated down to the Palaeozoic schist basement In spite of the fact that it was not possible to extract even discontinuous cores during drilling, the cuttings were carefully sampled at each lithological variation so as to reconstruct as accurately as possible the stratigraphic column of all the exploratory boreholes.

During perforation of the boreholes, groundwater was sampled and conductivity and temperature measured in situ. The drillings performed during the course of this investigation confirmed the statigraphic variability of the alluvial cover, indicated by findings of earlier investigations.

The geognostic investigation pointed to the presence of a thick layer of clay at a depth of 15 m separating two sandy layers of various grain size in which groundwater flows abundant. However the salinity differs significantly, the upper groundwater strata being brackish while the deeper strata are decisively salty.

GEOPHYSICAL INVESTIGATION

In order to construct a general model of the hydrogeological configuration of the entire plain, a geophysical survey with electric soundings was designed and executed. The soundings were performed along two alignments that cross the whole plain as far as the sea and were calibrated with the point hydrogeological and geognostic data collected along the same alignments.

For the electric logs, vertical electric soundings (VES) were performed using a Schlumberger instrument. A total of fifteen soundings were carried out , twelve along the same alignment perpendicular to the coastline (longitudinal profile), the other three perpendicular to the previous alignment (transversal profile).

The profile parallel to the coast was of little use in that it proved difficult to interpret, probably on account of lateral variations.

As the VES were performed close to the boreholes drilled for the geognostic investigation, it was possible to calibrate and interpret the electrically determined stratigraphical series using the lithostratigraphic and hydrogeological data gathered during perforation.

Similarly to borehole drilling, the electrical soundings did not succeed in locating either the aquifer bed, or the Palaezoic schist bedrock.

From analysis of the V.E.S. for the longitudinal profile, four electric layers were identified which differed in their resistivity (Ardau et al., 1999).

They are schematically described below, from the top down.

- a first layer of variable thickness from 4 to 10 m between V.E.S. 1 and 10, increasing to around 20 m between V.E.S. 14 and 15, with resistivity ranging from 10 to 50 Ω m in V.E.S. 1-10 up to120 Ωm in V.E.S. 15;
- a layer from 5 to 15 m thick between V.E.S.1 and 10 increasing to more than 30 m between V.E.S. 14 and 15, having resistivity of between 5 and 7 Ω m in V.E.S. 1-10 and of up to 40 Ω m in V.E.S 14 and 15;
- a 15-28 m thick layer with resistivity ranging from 10 to 20 Ωm;
- a layer whose lower limit could not be defined, having extremely low resistivity of between 2 and 3 Ω m.

Figure 3 shows the stratigraphic section reconstructed from V.E.S. 1-10 and 14-15 carried out along the longitudinal alignment to the plain.

CONCLUSIONS

The research programme, which concerned specifically a monitoring network comprising around thirty wells spread over the Muravera plain, included systematic hydrogeological surveys and chemical analyses, integrated with geognostic investigations and geoelectric surveys.

It was possible to identify two aquifers, one overlying the other, hosted in the thick Quaternary sandy-gravel and clayey-silt sedimentary cover (Fig. 3):

- a shallow, highly productive aquifer hosted in the sandy formation, lying just beneath the surface (1-2 m) generally phreatic and traditionally exploited by farmers abstracting groundwater from wide diameter wells no more than 4-6 m deep. This aquifer has been locally recognised by means of exploratory boreholes and geophysical prospection throughout the plain and has thickness decreasing from 15-20 m upstream to 4-5 m near the sea:

- a deep, artesian aquifer, composed of sand and gravel confined at the top by a clay layer that separates it from the overlying phreatic aquifer.

It was the systematic difference in temperature (1-2°C) and in hydraulic head (from 10-15 cm up to 60 cm between water from deep wells and water from nearby dug wells) that pointed to the existence of a deep aquifer about which little is known and which differs significantly from the shallow aquifer.

The presence of the aquifer was subsequently confirmed both by exploratory boreholes and electric soundings that perforated the impermeable formation and the aquifer itself, without however reaching the aquifer bed or the Palaeozoic schist basement.

Geophysical prospection revealed the continuous presence of a clay layer along the entire length of the longitudinal profile. with thickness varying from a maximum of over 30 m upstream, to a minimum of a around 10 m in the middle of the plain, increasing to 10-15 m near the sea.

The shallow aquifer is currently contaminated by brackish waters, and conductivity of up to 3000-6000 μS/cm with peaks of as much as 8000 μS/cm, has been measured in the whole area that extends from the sea up to the town of Muravera. The area between Foxi Bau Obilu and Padrionnas is particularly severely affected by salt water intrusion. The water level contour map for the summer and autumn months exhibit cones of depression where the water table falls to below sea level. However, the conductivity logs did not reveal the presence of a freshwater-saltwater interface

The groundwater in the deep aquifer also has high salinity but it has not been possible to clearly define the extent of contamination as few drilled wells exist in the area. However, in the same area where high salinity was recorded in the shallow aquifer, the conductivity logs showed the deep aquifer to be contaminated too, but chlorine content was far higher and conductivity increased sharply with depth up to as much 20000-25000 μS/cm.

During the drilling campaign, the water at the bottom of the borehole, at a depth of 30-33 m below ground level was also sampled and analysis revealed extremely high electric conductivity of up to 40000-50000 μS/cm.

The geophysical surveys also pointed to high salinity in the deep groundwater. Two bands differing significantly in resistivity were detected at different depths and these would appear to correspond to the sharp increase in salinity observed in the conductivity logs obtained for the drilled wells.

Based on the findings of these investigations some hypotheses can be advanced as to the causes of saltwater intrusion in the groundwater of the Muravera plain. Unquestionably, indirect and predisposing causes for saltwater encroachment do exist and are to be sought in a reduction in natural groundwater replenishment, as the result of decreased precipitation in latter years, river engineering works on the Flumendosa but above all of the interception of surface runoff which collects in the reservoirs constructed upstream from the Muravera plain.

The direct and determinant cause of the progressive saltwater intrusion is to be attributed in the case of the shallow aquifer to uncontrolled groundwater overabstraction by farmers during the summer. This produces a lowering of the water table and the inversion of the hydraulic gradient, leading to seawater encroachment and worse still to the ingress of the high saline waters of the *foxi* and of the final stretch of the river Flumendosa, again very salty in the summer.

The hypothesis that seawater intrusion is responsible for the brackish waters in the shallow aquifer is borne out by the results of chemical analysis of water sampled from the dug wells that exhibited fairly constant rBr-to-rCl and rSr-to-rCl ratios, similar to those of seawater.

By contrast, the same argument does not hold for the high saline waters observed in the deep aquifer, which is little exploited. The most likely explanation for the high salinity observed is that it has been inherited from the marine environment that presumably prevailed in the Muravera plain during the Tyrrhenian transgression in the Quaternary.

This explanation is confirmed by the chemical determinations on water samples collected in the drilled wells that exhibit a substantially different rBr-to-rCl ratio from that of actual seawater.

REFERENCES

ARDAU F. (92/95). Studio dei fenomeni di salinazione delle acque sotterranee nella piana di Muravera (Sardegna sud-orientale). Tesi di dottorato. pp. 214.

ARDAU F., BALIA R., BARBIERI G., BARROCU G., GAVAUDÒ E., GHIGLIERI G., VERNIER A. (1999). Geophysical and hydrogeological studies in a coastal plain affected by salt water intrusion. Proc of SAGEEP 2000, Arlington, (in print).

ARDAU F., BARBIERI G. (1994). Evolution of salt water intrusion phenomena in the coastal plain of Muravera (South-eastern Sardinia). SWIM 13th Villasimius (Cagliari). pp. 305-312.

ARDAU F., BARBIERI G., PIRASTRU E., (1996). Applicazioni di tecniche radioisotopiche in idrogeologia. V Convegno Nazionale dei Giovani Ricercatori in Geologia Applicata. Cagliari [in stampa].

ARDAU F., BARBIERI G., BARROCU G. (1996). Idrogeologia della piana di Muravera (Sardegna sud-orientale), included in notes of new Geological Sheet 1:50.000 "*549–Muravera*".

ARU A. (1970). Nota illustrativa alla carta pedologica della Bassa Valle del Flumendosa, con particolare riferimento ai suoli salsi Muravera – Villaputzu (Cagliari). Centro Reg. Agr. Sperim. Cagliari. pp. 1-41.

BARBIERI G., BARROCU G., POLEDRINI C., URAS G.(1983). Salt intrusion phenomena in the South East coast of Sardinia – SWIM 8th Bari. Geologia Applicata ed Idrogeologia. Vol. 18, parte II. pp. 315 - 323.

BARBIERI G. and BARROCU G. (1984). Consequences of overexploiting coastal aquifers in areas of touristic development in South-Eastern Sardinia (Italy) - Proceedings of the Int. Conf. on Water Res. Plann. and Manag., Athens. pp. 1-12.

BARBIERI G., BARROCU G., RANIERI G. (1986). Hydrogeological and geophysical investigations for evaluating salt intrusion phenomena in Sardinia. SWIM 9th Delft. pp. 659-670.

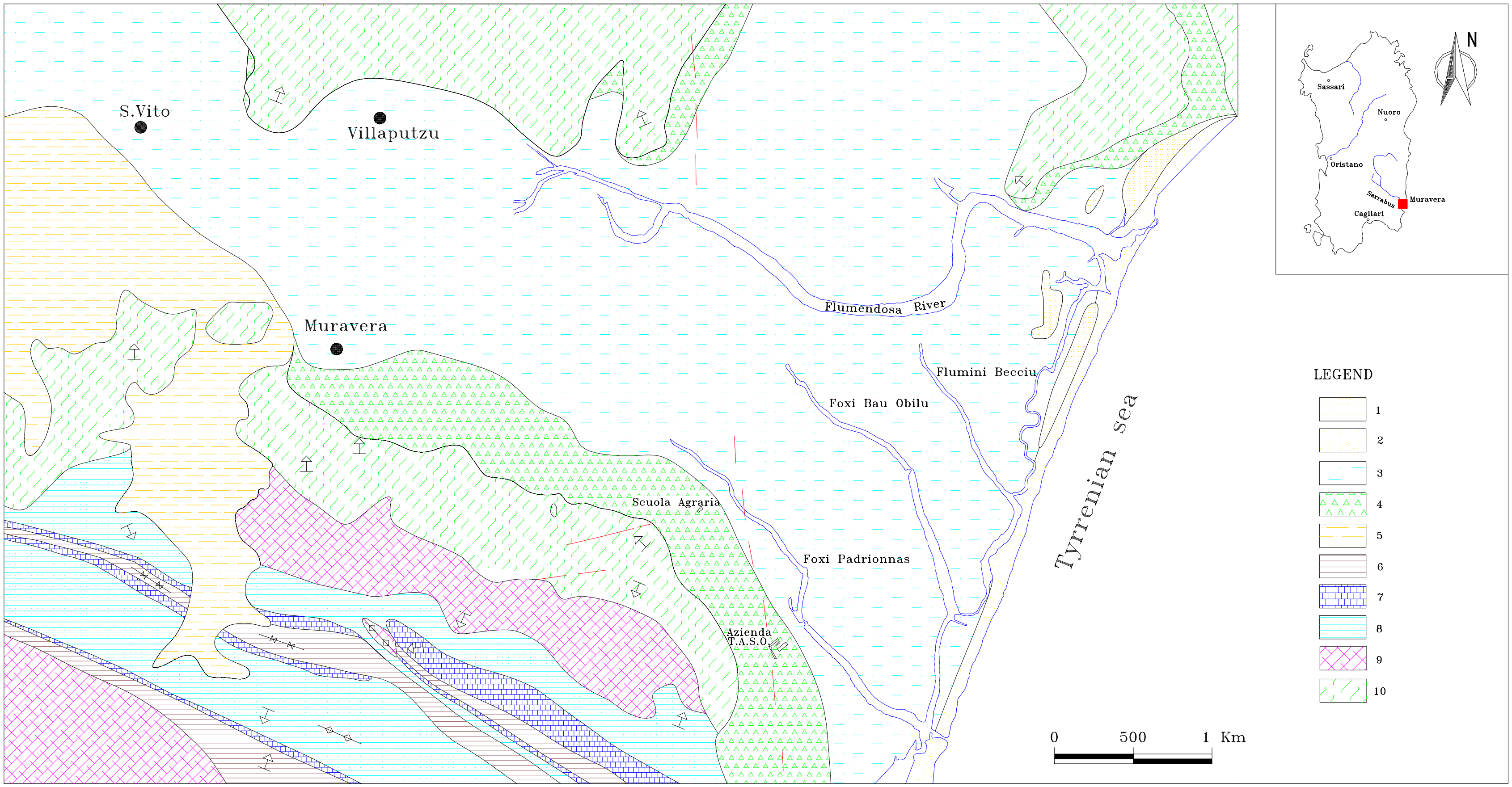

Figure 1 - Geological map of the Muravera plain - 1. beach deposits; 2. eolian deposits; 3. recent alluvium; 4. talus; 5. ancient alluvium; 6. Serra S'Ilixi formation; 7. Tuviois formation; 8. Punta Serpeddì formation; 9. Grey and White Porfhyries; 10. San Vito Sandstone

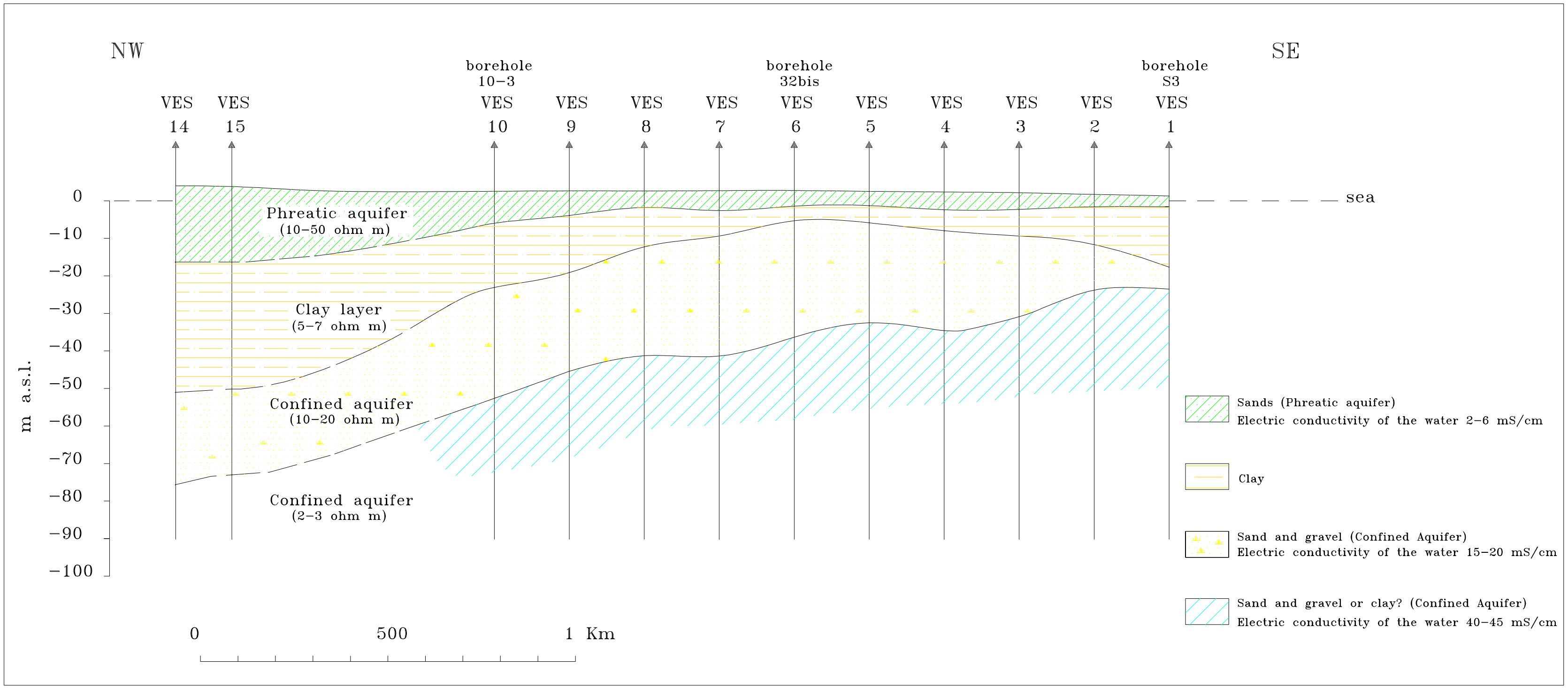

Figure 3 – Hydrogeological interpretation based on geognostic drillings and vertical electrical soundings