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The role of integrated high resolution stratigraphic and geophysic surveys for groundwater modelling

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Abstract

This work sets out a methodology of integrated geological, hydrogeological and geophysical surveys for the characterization of contaminated sites. The flow model of the shallow aquifer in the Brindisi area (recognized to be at significant environmental risk by the Italian government) and the impact of an antrophic structure on the groundwater flow have been evaluated. The stratigraphic and hydrogeological targets used for the calibration phase of the flow model provide a means of assessing calibration quality. The good calibration of the model point out the key role of a detailed knowledge of the physical-stratigraphycal attributes of the area to be studied and field data collection. Geoelectrical tomography focus the attention on an area resulted of particular interest by the flow model obtained. This method permit to reconstruct in detail the lateral and vertical lithological variations in the geological formations improving the spatial resolution of the data and consequently the scale of observation. Besides, anomaly resistivity values have been correlated with pollution. Chemical analysis have confirmed this correlation.

1 Introduction

According to Bridge et al. (2005), “aquifer characterization should ideally involve the following steps: (1) analysis of borehole logs, cores, and hydraulic testing data to determine the sedimentological nature and origin of the strata, and their hydraulic properties; (2) stratigraphic correlation of boreholes logs and cores in order to assess the lateral continuity of distinctive sediment types (facies) between boreholes; (3) use of geophysical profiles to assess the orientation and structural continuity of sequences of strata, and to recognize distinctive geophysical patterns that can be related to distinctive sedimentary facies; (4) modelling of the geometry and distribution of sedimentary facies in the volume between boreholes, and (5) distribution of properties such as porosity and permeability as a function of sedimentary facies. Unfortunately, hydrogeologists rarely incorporate information on the sedimentology of the aquifers, and shallow geophysical methods are routinely used for aquifer characterization”. Notwithstanding this, previous works have shown the importance of the integration of different stratigraphic and geophysics survey types for contaminant predictions (Binley et al., 2002a, b; Close et al., 2004; Schulmeister et al., 2004; Winde and Van Der Walt, 2004; Jeong, 2001; Sandberg et al., 2002; Deiana et al., 2006). Fine-scale hydrostratigraphic features often play a critical role in controlling groundwater flow and contaminant transport (Schulmeister et al., 2003).

The purpose of this study is to point out a methodology of integrated geological, hydrogeological and geophysical surveys for the characterization of contaminated sites (De Sousa, 2001; Petts et al., 1997; Rivett et al., 2002; Swaigen, 1995). The site of Brindisi (recognized as being at environmental risk by Italian Law L.426 of 9 December 1998; Fig. 1) has been chosen for testing this methodological approach. Besides, the area object of this study is entirely crossed by a road conveyor belt equipped for the transport of the coal (“Asse Attrezzato”). The impact of this structure has been evaluated through the comparison of the flow model considering the presence and the absence of the road conveyor belt and through geoelectrical surveys.

2 Geological, morphological and hydrogeological setting

The studied area is delimited to the north by the port of Brindisi, to the south by the “Cerano” power station, to the east by the Adriatic sea and to the west by the highway S.S.613 connecting Lecce to Brindisi (Salento, Italy; Fig. 1). The area therefore lies on the eastern edge of the Brindisi – Taranto plain. The area of interest, part of the Apulian foreland, is an emerged area of the Apulian Plate, consisting of a thick basement of carbonatic rocks. These Mesozoic limestones are covered by lower-middle Pleistocene deposits, resulting from the sedimentary cycle of the Bradanic foredeep. These deposits are covered in succession by terraced bioclastic marine deposits in transgression (linked to the variations in sea level caused by the primarily glacio-eustatic phenomena that occurred in the Middle-Upper Pleistocene period), Holocene continental deposits and recent continental deposits. This part of the foreland has been partially affected by the Apenninic orogeny, with fractures, faults and large folds. The morphology of the area under study is characterised by a broad plain, slightly sloping towards the sea, in many places marked by natural and/or man-made channels which form the drainage network. The altitude is between 30 and 40 m above sea level, decreasing towards the "Fiume Grande" and the coastal zone. On the Adriatic coast near the "Cerano" power station, there is a vertical cliff that reaches a maximum height of 15 m. Moving northwards from this area, the cliff decreases in height, leading to depressions below sea level (e.g. the "Salina Vecchia"). The current shoreline runs perpendicular to the drainage channels, with some steep cliffs in rapid retreat due to erosion. In other cases, the Holocene rise in sea levels led to the lower courses of the deepest rivers being submerged, forming inlets such as the "Canale Pigonati", "Seno di Levante" and "Seno di Ponente", which form the natural port of Brindisi. The drainage system in the area is well developed. It is characterized by numerous shallow incisions that in many cases run directly into the sea (e.g. "Fiume Grande", "Foggia Rau", "Fiume Piccolo", "Canale Palmarini – Patri", "Canale Cillarese"). The watersheds are hard to identify. Numerous smaller channels drain into modest depressions which are subject to flooding even after light precipitation. Near the mouth of the "Canale di Scarico" water course is a broad marshy area. The overall picture is of an area whose environment has been strongly conditioned by human activity. Especially over the last few decades, the hydrographical and morphological order has been modified not only by the imposition of a system of drainage channels but also by the frequent filling-in of depressions for the purposes of agriculture and/or to render them suitable for industrial or residential construction.

3 Stratigraphy

The geological study was organized in surveys of the surface, surveys of the subsoil via direct observation of borehole cores, identification of existing wells in the area, collection of all the stratigraphical data (about 600, Fig. 1) drawn from borehole cores and supplied by local agencies, from private research and publications in scientific journals (Radina, 1968; Tedeschi, 1969). The above-mentioned data have been processed and homogenised taking account of new geological knowledge of the area (Ricchetti et al., 1988; Gentile et al., 1996; Coppa, 2001). All the data have been inserted in database managed using specific software (arcview). In this phase also the hydrological and geo-technical data (piezometric levels, flow, permeability of the various formations, physical and granulometric characteristics) available from private research and scientific publications (Cherubini et al., 1987) have been processed.

The data thus acquired and processed allowed us to verify the horizontal extension in the subsoil of the formations, to evaluate the thicknesses of the lithostratigraphic formations, to draw numerous two-dimensional cross sections of parts of the area under examination (Fig. 2) and to identify areas for which data are still lacking.

Furthermore, the identification of the existing wells provided an initial overall picture of the distribution and the density of the points of extraction from the deep aquifer, highlighting the possible overexploitation to which this may be subject. From the geological surveys conducted by us, integrated with the data on the subsoil, the lithostratigraphic succession, from the surface downwards, was recognized (Fig. 3).

The topsoil is of a brown colour, tending to beige at greater depths, generally composed of sands and silts, generally with low organic content. The thickness of the topsoil varies between 0.3 m and about 6 m. It lies over almost all the area under examination (Fig. 4); it is lacking only where eluvial Deposits appear on the surface. In some places, for example near the industrial zone of Brindisi and the port, the topsoil has been completely removed and replaced with infill material. The infill material is made up of rubble and coarse sand of various kinds, sometimes mixed with an abundant silty-clayey matrix.

Marsh Deposits (Recent-Holocene) are characterized by peat with considerable non-decomposed organic content, with varying percentages of sandy mud and clay. The organic content decreases with depth, while the clayey fraction and the plasticity increases. The clayey fraction varies from 23% to 54% while the percentage accounted for by the sandy fraction (2%–25%) is less significant. These deposits are found especially in a marshy basin lying in the alluvial plain of the "Canale di Scarico", the terminal stretch of the "Fiume Grande". The process of erosion and accumulation of the meanders of the "Fiume Grande" has, over time, extensively modified the original topographical surface, widening the flood plain of the river so as to form a broad marshy area. Marsh deposits can also be found in the proximity of the mouth of the "Fiume Piccolo". The thickness of the peat varies, reaching a maximum of about 25 m. The height of the peat bed is between 3 m above sea level and 25.8 m below sea level; the thickest parts lie directly on the subapennine Clays. The degree of saturation of these deposits is always very close to 100%.

Lagoon Deposits (Recent-Holocene) are composed of clayey and/or sandy-clayey silts and are grey, green and nut-brown in colour, containing laminitic and carbonaceous residues as well as calcareous concretions, randomly mixed, with patinas of oxidation. The granulometric composition is fairly evenly divided between the sandy, silty and clayey fractions. The percentage of carbonate is high. The degree of saturation is about 95%. The deposits are characterised by low permeability, favouring, in places, the formation of water bodies suspended above them in the infill material, and partially protecting the underlying shallow aquifer. The thickness varies between 60 cm and 9.6 m, but the most frequent values are between 1.50 m and 5 m.

The eluvial Deposits (Recent-Holocene) are formed by sands and clayey sands of eluvial origin, changing from brown-red to light-brown with depth. The deposits appear homogeneous, of low density and free of calcareous elements, except for the transition zone close to the underlying Terraced Deposits. The characteristic features of these deposits are: the prevalence of the sandy fraction, the absence of silts, the proportion of the clayey fraction (varying between 15% and 40%) and their mineralogical composition (almost free of carbonates). The saturation level is not high. The maximum thickness is about 6.2 m with mean values of 3 m. These deposits are not found across the whole of the area; where they are found, the bottom of this formation almost always lies about 10 m above sea level.

Alluvial Deposits (Recent-Holocene) are composed of sands and sands with silt predominantly light brown in colour, with abundant heterometric calcareous clasts. Stratigraphically, these deposits rest directly on the Terraced Deposits, though with a gradual transition; laterally, they border on marsh and lagoon Deposits. The thickness of alluvial Deposits varies between 40 cm and 8 m; the bottom of the layer varies between 0 and 20 m above sea level.

The Middle-Upper Pleistocene formation of the Terraced Deposits (Fig. 5) is lithologically composed of yellowish coarse-grained biocalcarenites with sandy layers or layers of organogenic limestones varying in thickness from a few centimetres to 15 cm; in places, near the contact with the subapennine Clays, layers of very compact and tenacious limestones, a few decimetres thick, are present. The sandy facies is composed mainly of quartz grains, feldspars and carbonatic material of detritic and bioclastic origin; mica crystals are present in a lesser proportion. The granulometry of the sandy facies in terms of gravel (0%–28%), sand (3%–84%) and silt (2%–75%) varies greatly depending on the stratigraphical level. The natural water content varies around an average value of 20.79% with the porosity index varying between 0.49 and 0.87. It may be assumed that this formation extends across the whole of the studied area. The transition to the underlying subapennine Clays is in some places direct and in others through the interposition of Brindisi sands. The thickness of the formation varies considerably, from a few decimetres to about 20 m, although the most frequent values are in the range of 5–6 m.

The provisional and informal term of Brindisi sands (Lower-Middle Pleistocene) is used to refer to sandy and silty-clayey deposits found in places between the Terraced Deposits and the subapennine Clays. The transition between the Terraced Deposits and this formation is characterized by an abrupt lithological variation (from diagenetic calcarenite to sands) (Fig. 5); this transition was observed in detail on the cliff near the “Cerano” power station. The erosional contact with the underlying subapennine Clays is also visible here. In terms of granulometry, moving downwards, the transition involves an enrichment of the silty-clayey fraction, interleaved with sandy layers a few millimetres or centimetres thick. In lithological terms, the Brindisi sands are composed of fine-grained sands whose colour shifts from grey to yellow-light brown moving upwards; this sand contains abundant diagenetic concretions. The lower part of this formation is made up of clayey-sandy silts of grey colour, with carbonaceous fragments. In mineralogical terms, the grains of the sandy fraction are mainly made up of carbonatic and quartzeous fragments. The clayey and sandy fractions comprise 35 to 38% of the lower part of the layer. The stratification is indistinct. The thickness of this formation varies from a few decimetres to 20 m. The mean thickness is about 13 m–14 m.

The subapennine Clays (Lower Pleistocene) formation is made of clays and grey-blue sandy clays, rich in fossils (Fig. 5). These deposits can be defined as sands with clay; nevertheless, there is considerable variation in the dimensions of the grains. The percentage of sand varies from 2% to 55%, that of silt about 10%; the average carbonate content is 31%, this value increases moving towards the underlying Gravina Calcarenite. Inside the formation, whose thickness is never less than several decametres, there are sandy layers of a grey-blue colour whose lateral and vertical extension is not easily measurable. The stratigraphical transition to the underlying Gravina Calcarenite has never been observed in outcrop. The natural content water ranges from 14.05% to 43.5% and the degree of saturation also varies considerably, from 71.84% to 100%. Laboratory analyses, conducted by the “Consorzio Basi” consortium in conformity with law 471/99 on the uncontaminated samples of the clayey layer, demonstrate the low permeability (between 10^{-10} and 10^{-11} m/s, average 1.81×10^{-10} m/s) of the formation. The thickness of this formation is varies greatly from a few metres to over 50 m. Specifically, the thickness increases moving from the “Cerano” power station (average 20 m), forming the southern limit of the investigated area, to the port of Brindisi, which forms the northern limit (average 45 m). Moving from west to east, the top of the Mesozoic limestones and the top of the overlying Pleistocene calcarenite tend to deepen, and the thickness of the subapennine Clays, which overlie the Pleistocene calcarenite, increases. The top of the subapennine Clays is above sea level in the zone near the "Cerano" power station, while elsewhere the top is found at a maximum of 29 m below sea level.

Gravina Calcarenite (Lower Pleistocene) is the most ancient of the Pleistocene formations present in the area. Characterized by coarse-grained calcarenite of a yellowish colour with abundant fossils, it overlies, with discontinuous and discordant contact, the carbonatic cretaceous basement; the contact is clearly visible in several places in the Salento and was observed in the borehole cores in the area under study. From the chemical point of view these deposits are composed of normal calcite with low magnesium content. Present in smaller amounts are caolinite, illite, chlorite, smectite, gibbsite and goethite, scattered in the sediment, along with single grains of quartz and feldspars (Andriani and Walsh, 2002). The micritic matrix is almost entirely absent. The porosity ranges from 42.90% to 49.40%. The thickness of the formation varies considerably and reaches maximum values of more than 30 m.

Altamura Limestone (Upper Cretaceous) outcrops immediately to the west of the studied area, and is made up of alternating limestones and dolomitic limestones, both micritic, compact and tenacious, whitish, light grey or hazel in colour, in layers varying in thickness from a few centimetres to about 1 m. In places the layers appear densely laminar; flakes may be easily broken off pieces of the rock. The outcrops have a thickness of a few metres only, in places covered in topsoil. Greater thicknesses, (up to 30–40 m), are visible in the quarries located near the area under study, some of which are still in use while others are used as rubbish dumps. In many places the layers are fractured and disjointed. There are few macrofossils, characterized by fragments of rudists, with smaller amounts of coral and bivalves. The top of the carbonatic basement is also found at highly variable depths in nearby areas, indicating the presence of faults with slips of several decametres. In general, the top of this formation deepens moving from the “Murge” hills, where the described limestones outcrop, towards the sea, and from the south of the investigated zone (Cerano power station, where the top is 20 m below sea level) towards the north (Brindisi port, where the top is 90 m below sea level) (Fig. 6).

4 Hydrogeology

4.1 Introduction

From the hydrogeological data obtained by us and the data retrieved from the literature (Zorzi and Reina, 1957; Radina, 1968; Cotecchia, 1977; Cherubini et al., 1987; Ricchetti and Polemio, 1996), it is clear that the area under study contains two overlapping and hydraulically separate aquifers:

- the first (superficial) aquifer is formed by the Pleistocene marine Terraced Deposits overlying the Pleistocene clays, holding a phreatic groundwater body (Fig. 7);
- the second (deep) aquifer lies in the Mesozoic limestones, made up of fractured and karstic carbonatic cretaceous rocks, and in the overlying Pleistocene calcarenite. In these sediments circulate the waters of the deep groundwater body. This deep groundwater body floats on a base of sea water from continental invasion, in accordance with the principle of Ghyben-Herzber. Unlike the superficial groundwater, found only in certain places, the deep groundwater extends across the whole of the Apulia region. The deep aquifer, lying below the subapennine Clays, contains water under pressure and is therefore of the Artesian type. The deep groundwater is replenished by precipitation where the cretaceous formation outcrops, by underground outflows from the adjoining “Murge” hills, and by seepage from the shallow aquifer. The piezometric gradients are very modest, even at some distance from the coast. For the aim of this study it was not considered

necessary to perform hydrogeological investigations on the deep aquifer. The measurements performed served to determine the hydrogeological characteristics of the shallow aquifer, the one most likely to be affected by pollution.

4.2 Hydrogeological surveys

In order to characterize the superficial groundwater, hydrogeological investigations were performed in some boreholes located at regular intervals in the area under study. Measurements were taken for various parameters (temperature, pH, dissolved oxygen and salinity) at varying levels of the water column in each borehole. The instrument used was the Multiparametric Hydrolab MiniSonde 4. During the surveys the depth of the water table was also measured using a piezometric probe. 14 surveys (Table 1) were performed in boreholes located along the route of the "Asse Attrezzato" conveyor belt which divides the studied area from north to south. Another 4 surveys were conducted in boreholes situated in the Brindisi agricultural area, so as to uniformly cover the area. Briefly, the results of the investigations conducted enabled the following considerations to be made:

- in all the boreholes, temperature decreases with depth. This parameter is influenced by the external temperature; the recorded values vary between 20°C and 18°C, except for the borehole situated immediately to south of Cerano where values varied between 21.8°C and 19.8°C;

- pH values did not vary significantly between boreholes, or with depth; the average value was about 6.8;

- values for dissolved oxygen vary greatly both between boreholes and depending on depth in the same borehole. In general, as depth increases oxygen content decreases, due to the presence in the aquifer of two hydraulically connected layers with different permeability.

The aquifer is composed of marine Terraced Deposits, of medium-high permeability, and the underlying sandy-silty deposits (Brindisi sands), of medium-low permeability. Indeed, the data from the investigations conducted by the "Consorzio Basi" (2002) show that the permeability of the aquifer varies from a maximum of 4.9×10^{-4} m/s to a minimum of 4.51×10^{-9} m/s, with an average value of 2.33×10^{-5} m/s. Moreover, inside the Terraced Deposits, permeability values vary between 10^{-4} m/s and 10^{-6} m/s depending on the proportion of sands (which are present in discontinuous layers) in the matrix (Consorzio Basi, 2002). A sudden decrease in dissolved oxygen was recorded in the transition zone between these two Pleistocene formations. Further small variations were observed within the Terraced Deposits; these variations could derive from the lithological heterogeneity of these deposits;

- the salinity values appeared to depend on the distance of the boreholes from the sea. However, in every well, a similar trend was recorded of salinity increasing with depth, from fresh-water to values typical for the transition zone between fresh and salt water. The recorded data highlight the irregularity of saline intrusion from the coast inland.

When the geological data reported in stratigraphy section of this paper are taken into account, the following additional considerations on the characteristics of the shallow aquifer can be made:

- the superficial groundwater is of the phreatic type, with semi-confined conditions in the upper part of the deposit where this is overlain with sediments of low permeability (recent continental deposits);
- the water table of the shallow aquifer lies between 0.8 m and 7.4 m below the surface, with a mean value of about 3.5 m;
- the impermeable base of the groundwater is provided by the subapennine Clays (Lower Pleistocene), which are present across the whole of the area;

- the saturated part of the shallow aquifer has a thickness varying from a few decimetres to over 30 m;
- the motion of the groundwater is characterized by an undergroundwater flow towards the sea.

4.3 Groundwater flow

Ground Water Vistas 3.5 (GV) has been used to facilitate the use of complex three-dimensional Brindisi groundwater model through a calculus code (MODFLOW) that allows the modellers to create a model in a variety of way. In this paper GV allows the interface with Arc View Gis.

The studied area, 68.2 km^2 extended, has been divided in a finite difference grid by 60 rows and 40 columns to obtain 2400 quadrate cells (cells area: 40 000 m^2) as the best compromise between the accuracy of the model and the capacity of the system. Cells area designed using the row and column coordinates (dx. dy) while dz is the layer of cells. We have considered four layers: the first represented by the topography quota, the second by the bottom of Continental Deposits that is the top of the aquifer, the second (Terrace Deposits and Brindisi sands) constitute the aquifer and the third (the top of subapennine Clays) is the impervious bedrock. The quotas of the layers (Figs. 8 and 9) have been obtained with the stratigraphical data (about 600, Fig. 1) drawn from borehole cores and supplied by local agencies, from private research and publications in scientific journals Layer elevation, calculated with Arc View Gis, has been imported in GV. Boundary conditions fall into constant head boundary and general head boundary (GHB); GHB has been used along the edge of the model to allow groundwater to flow out of the model under a regional gradient. Each boundary condition has an associated starting and ending stress period number of one day which all boundary conditions are constant. For evaluating the impact of the industrial road/conveyor belt – the "Asse Attrezzato" on the environment we have chosen to represent it as a "flow barrier" for the first and second layers where the bottom of this structure is realized in a trench and is deeper than 3 m.

Hydraulic properties (conductivity, porosity,...) extrapolated from collected well data, have been assigned for each cell in the model. Where the data was lacked GV allows us to specify calibration target within the model with a field-measured value that we attempt to match with model-computed values. “Strongly implicit procedure” iterative method (Harbaugh et al., 2000) has been used to solve flow equation for each time steps.

In Figs. 10 and 11 is clearly represented the influence of the road-conveyor belt on groundwater flow: the studied area is divided in two areas (east and west of the conveyor) characterized from a different hydraulic gradient. The comparison of the groundwater flow in presence and absence of the “Asse Attrezzato” is shown in Fig. 12: the direction of the flow is south-west toward north-east without the conveyor while divert from south-west toward north-west with the presence of the conveyor belt.

With the aim to obtain a good calibration of the model an accurate calibration phase has been effected using targets. Calibration target is a point in space and time where one of the model dependent variables has been measured. Calibration targets provide a means of assessing calibration quality because an error term, called a residual, is computed for each target location. In this case, the targets are the stratigraphic and hydraulic data deriving from borehole cores and the geological sections obtained by integrated of stratigraphic and geophysical data. The value of residuals, less than 10%, point out the good calibration of the model.

5 Geophysics

In the characterization of contaminated sites, the costs and environmental impact of drilling many boreholes make it desirable to develop less costly and less dangerous techniques. In the last decade, there has been great progress in computerized data acquisition systems for DC resistivity measurements that are now widely employed in environmental investigation and civil engineering (Olayinka and Yaramanci, 1999;

Chambers et al., 1999; Zhou and Dahlin, 2003). Many non-invasive geophysical methods have recently been applied to reduce the adverse impact of drilling on the environmental and to lower the costs of site characterization, monitoring and remediation (Barker, 1996; Godio and Naldi, 2003). Electrical resistivity tomography is one of the better geophysical technique to describe contaminated aquifer.

Geophysical prospecting was conducted inside the mostly industrialized part of the area (Fig. 13) and adjacent to the "Asse Attrezzato" (the industrial road/conveyor belt supplying the "Cerano" power station, whose floor lies below the water table), in order to better describe the site and to estimate the environmental impact resulted by the model of flow.

In the studied area eight electrical resistivity tomography (ERT) were carried out along profiles, showed in Figs. 14 and 15. For every profile two electrode arrays were used: Wenner-Schlumberger and Dipole-Dipole, using 48 electrodes with electrode-spacing 3 m. Apparent-resistivity data were collected using a Syscal-R1 Resistivity-meter (manufactured by the Iris instruments), in multielectrode configuration. To obtain 2-D resistivity models, the measured data were inverted using computers codes Res2Dinv (Loke, 2003). Res2Dinv identifies a two-dimensional subsurface resistivity distribution the response of which fits the measured apparent resistivity pseudo-section. Res2dinv calculates the apparent resistivity corresponding to a given subsurface resistivity distribution, using a finite difference approximation to compute the electrical field (Dey and Morrison, 1979; Loke, 1994); the program identifies the optimal resistivity which minimises the RMS of the differences between modelled and observed apparent resistivity in un iterative procedure. The ERT results were compared with geological and hydrogeological data existing in the studied area (boreholes S14 and S17). The electrical profiles were realized both east and west of Asse Attrezzato. The most significant ERT 2-D models are shown in Figs. 14 and 15. In the profiles P1, P4 and P5, the subsoil can be subdivided into the following four distinct electro-layers (moving downwards from the surface):

Electro-layer 1: the thickness of this layer varies between 1 and 2 m and its resistivity values between 10 and 20 Ω m. This layer is attributable to infill material at the surface;

Electro-layer 2: the resistivity of this layer varies between 50 and 200 Ω m, and its thickness from 6 to 8 m. In profile P1 the bottom of this electro-layer lies at a depth of approximately 7.5 m below the surface; towards the middle of the cross section relating to this profile, an area of discontinuity can be seen. In P4 and P5 the bottom of this layer lies at a depth of approximately 10.5 m. This layer is attributable to water-saturated calcarenite. These interpretations are supported by existing lithological and hydrogeological data;

Electro-layer 3: the thickness of this layer varies between 5 and 7 m; the bottom lies at a depth of between 12 m (P1) and 18 m (P4 and P5) and its resistivity values range from 8 to 20 Ω m. In P4 some horizontal discontinuity was observed, which is most easily seen in the cross section obtained using the Wenner-Schlumberger array. This electro-layer may geologically be associated with saturated Brindisi sands;

Electro-layer 4: the resistivity of this last electro-layer is characterized by values below 8 Ω m. This layer corresponds to the subapennine Clays. The resistivity values decrease with depth and this is certainly due, in the absence of vertical lithological variations, to the increasing salinity of the water content.

The model related to profile P2 is characterized by lateral resistivity heterogeneity, particularly the profile P2 dipole-dipole. The ERT section shows the some Electro-layer 2 attributable to water-saturated calcarenite. Below 7 m, from the values of resistivity, it is not clear the correlation with the other electro-layers showed before. Particularly the ERT profile P2 dipole-dipole (more sensitive to horizontal resistivity variations) is characterized by more lateral resistivity heterogeneity. In the middle part of this profile is located a well-defined high resistivity anomaly (about 90 Ω m), labelled (A). On the basis of all data collected with geophysical, geological and hydrogeological surveys the anomaly (A) can be correlated at phenomena associated to an anomalous groundwater flow and/or possible pollution.

The results of the surveys effected at the north of the area point to differences between the resistivity values recorded on the east (profile P1), and west (profile P2) sides of the “Asse Attrezzato”. The ERT models pertaining to profiles on the eastern side (P1 and P5) and on the western side (P4), agree with the geological and hydrogeological data obtained from specific points (boreholes S14 and S17); these data were correlated together, enabling us to better describe the subsoil and to draw the geological cross sections shown in Fig. 16.

6 Results

This research has made it possible to characterize the shallow aquifer in the area of Brindisi and to evaluate the impact of the industrial road/conveyor belt – the “Asse Attrezzato” on the groundwater flow. The stratigraphical succession was reconstructed in the area using geological surveys, which highlighted the heterogeneity of the subsoil. A sandy and sandy-silty interval was identified; previously included in the subapennine Clays, we have provisionally associated this interval with the as yet not formally recognised Brindisi sands formation, whose lithological characteristics, extension in the subsoil and relationship to the under- and overlying formations are described for the first time in this work. The identification of this interval has particular importance since it is a basic part of the aquifer, the object of this study. In previous studies, the Brindisi sands were included in the subapennine Clays, the top of which was considered to represent the impermeable base of the aquifer. The distinct nature of the Brindisi sands with respect to the subapennine Clays – not only mineralogically, but above all in terms of its greater permeability – means that this formation is in fact part of the aquifer (constituting its lower level), which must therefore be thicker than had previously been assumed. Consequently, it is impossible to give a general value for the permeability of the aquifer, since the permeability of the Brindisi sands is lower than that of the Terraced Deposits.

In detail, the aquifer is of the phreatic type, with semiconfined conditions where its upper part is overlain with sediments of low permeability (recent continental deposits). The subapennine Clays (Lower Pleistocene), present across the whole of the area, constitute the impermeable base of the aquifer. The deposits that form the shallow aquifer are highly heterogeneous in terms of permeability. The greatest permeability is found in the calcarenite deposits (Terraced Deposits, Middle–Upper Pleistocene). As the fraction of silt increases, the permeability of the deposit decreases. The lower section of the aquifer, characterized by the presence of silty-sandy sediments (Brindisi sands, Lower-Middle Pleistocene), has lower permeability. This research point out the necessity to clarify the stratigraphy of Pleistocene sediments of Brindisi area, particularly for the identification of the properties of the Brindisi sands.

Ground Water Vistas 3.5 (GV) has been used to facilitate the use of complex three-dimensional Brindisi groundwater model with particular attention to the impact of the road/conveyor belt through a calculus code (MODFLOW) that allows the modellers to create a model in a variety of way. The study is based on the comparison of the flow model obtained considering the presence and the absence of the road conveyor belt. Indeed, it needs to be considered that the part of the "Asse Attrezzato" to which the surveys refer runs parallel to the "Canale di Scarico", towards which flow the waters of the shallow aquifer from both east and west. Thus the "Asse Attrezzato", whose floor lies below the water table, itself constitutes a barrier to the downflow towards the "Canale di Scarico" of at least the most superficial portion of the groundwater.

In an area near the "Asse Attrezzato" resulted of particular interest by the flow model, geoelectrical surveys have been conducted. The results of the geophysical investigations have enabled us to reconstruct in detail the lateral and vertical lithological variations in the geological formations near the "Asse Attrezzato". It was seen that the data thus obtained can be used to supplement data from boreholes, meaning that fewer of these are necessary, an important consideration given that these are potential sources of pollution.

On the western side of the “Asse Attrezzato” (profile P2), in the distribution of the resistivity at the depths where the Brindisi sands and subapennine Clays are found, was observed an high resistivity anomaly. In places, the resistivity values were significantly higher than those typically associated with these formations. It is difficult to account for this abrupt east-west variation with reference to natural factors (be they geological or hydrogeological); it is more likely that it is caused by phenomena associated with human activity, possibly pollution. Support for this hypothesis is provided by profile P4, conducted on the western side of the “Asse Attrezzato”, which shows comparable resistivity values to the corresponding profile on the eastern side. This is due to the presence of the “Fiume Grande”, which flows between the “Asse Attrezzato” and profile P4, and is assumed to carry away any pollutants borne in the groundwater as it downflows eastwards, toward the “Canale di Scarico”. Recently, chemical analyses conducted by local agency along the “Asse Attrezzato” have confirmed this pollution: particularly high concentrations of Sb, Cd, Pb, Cu, Zn, Sn, Be and As have been found.

7 Discussions and conclusions

The researches presented in this paper have demonstrated that fine-scale stratigraphycal and physical features play a key role in modelling groundwater flow. The main advantages of an integrated stratigraphical, hydrogeological and geophysical method lie in its multidisciplinary approach and in the fact that it may productively be used for the study of other areas. Some aspects of the method used here are obviously open for discussion and leave room for improvement. The stratigraphic and hydrogeological targets used for the calibration phase of the model provide a means of assessing calibration quality because an error term has been computed for each target location. The value of residuals, less than 10%, point out the good calibration of the model. This result just depends on the detailed knowledge of the physical-stratigraphycal attributes of the area to be studied and field data collection. Particular interesting is the application of the geophysical methods for hydrogeological problems. Generally, these methods are useful to estimate aquifer parameters in combination with pumping tests for micro-area (Soupios et al., 2007). In this condition, lack of data can be filled with geophysical surveys. For macro-area, it is not possible to carry out geophysical methods because this provides increase of cost and of time of performance. In this paper, the flow model point out, inside the macro-area of Brindisi, a micro-area of particular interest. Geoelectrical surveys carried out have been demonstrated to be adequate to improve the knowledge of the subsoil of this micro - area. The main contribution of the ERT survey across resistivity parameter is to reconstruct in detail the stratigraphy improving the spatial resolution of the data and consequently the scale of observation. An other important contribute of ERT surveys could be the correlation of anomaly resistivity values with type of pollution. One limitation lies in the uncertainty of correlation of the resistivity values with geological and hydrogeological faces. As we intended to show here, this can be resolved through a detailed geological characterization but major chemical data and laboratory test are required.

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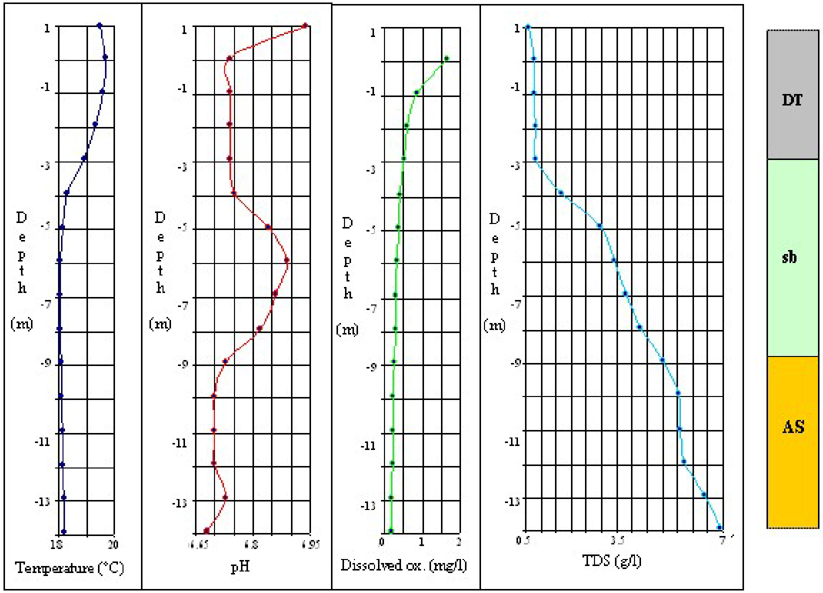
Table 1. Example of hydrogeological survey.

Date	28 Nov. 2007	**Geographical coordinates**		**Stratigraphy S 14**				
ID	18	**X**	**Y**	**G.L. (m)**	**A0**	**DT**	**sb**	**AS**
Borehole	P 42	2772313	4502069	4.10	4.10	3.30	-3.10	-8.70
P.L.	1.08 (m/sl)							



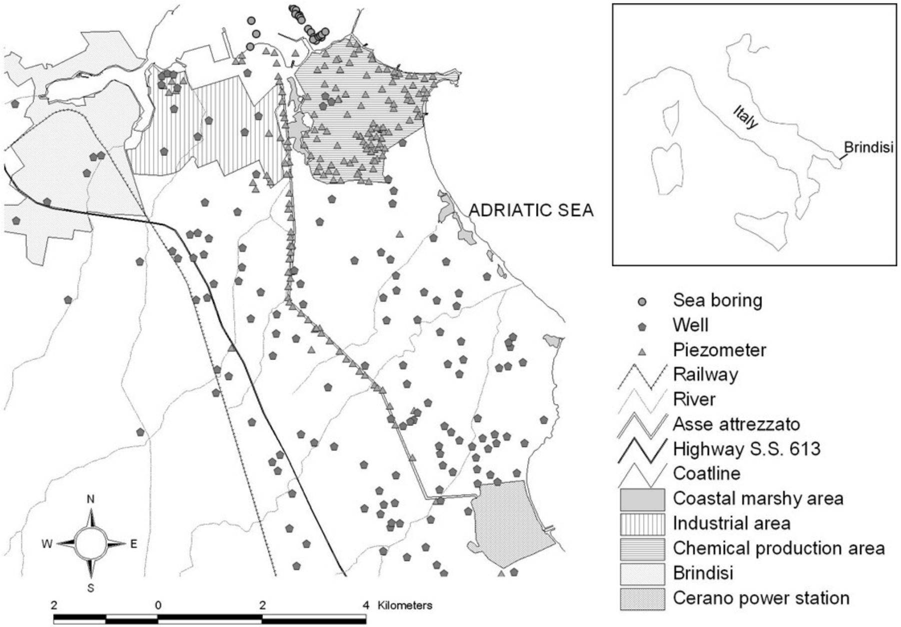


Fig. 1. Collected data in the studied area.

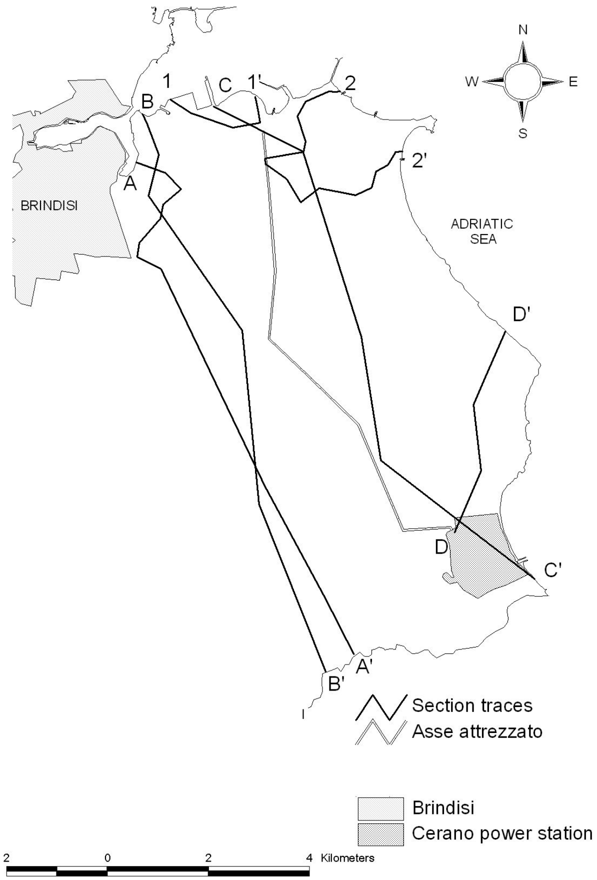


Fig. 2. Map of geological sections.

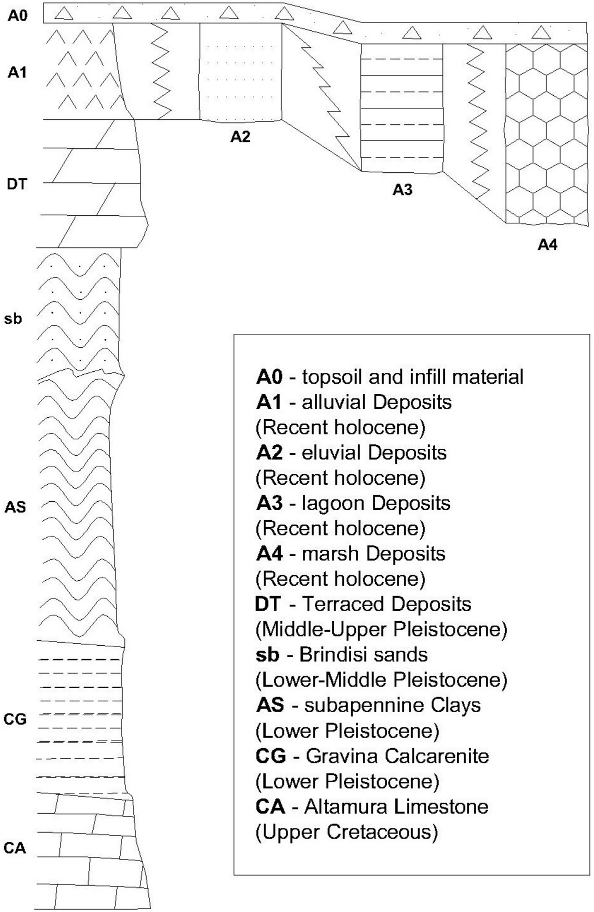


Fig. 3. Schematic diagram showing the relations between different lithostratigraphical formations.

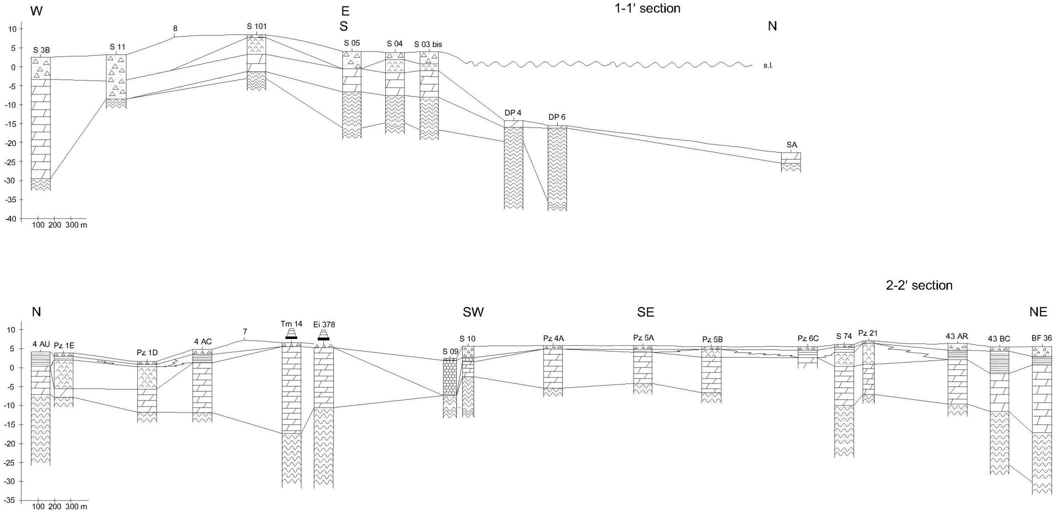


Fig. 4. Examples of geological cross sections.

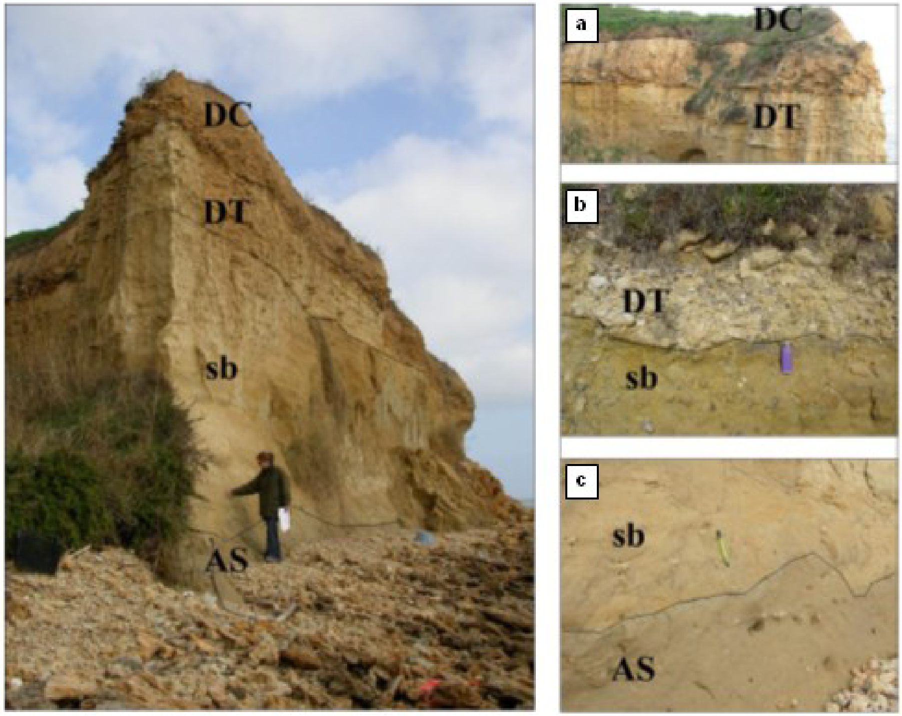


Fig. 5. Outcrop north of the Cerano power station (cliff). **(a)** Contact between continental deposits (DC) and terraced deposits (DT), **(b)** contact between terraced deposits (DT) and brindisi sands (SB), **(c)** contact between brindisi sands (SB) and subapennine clays (AS).

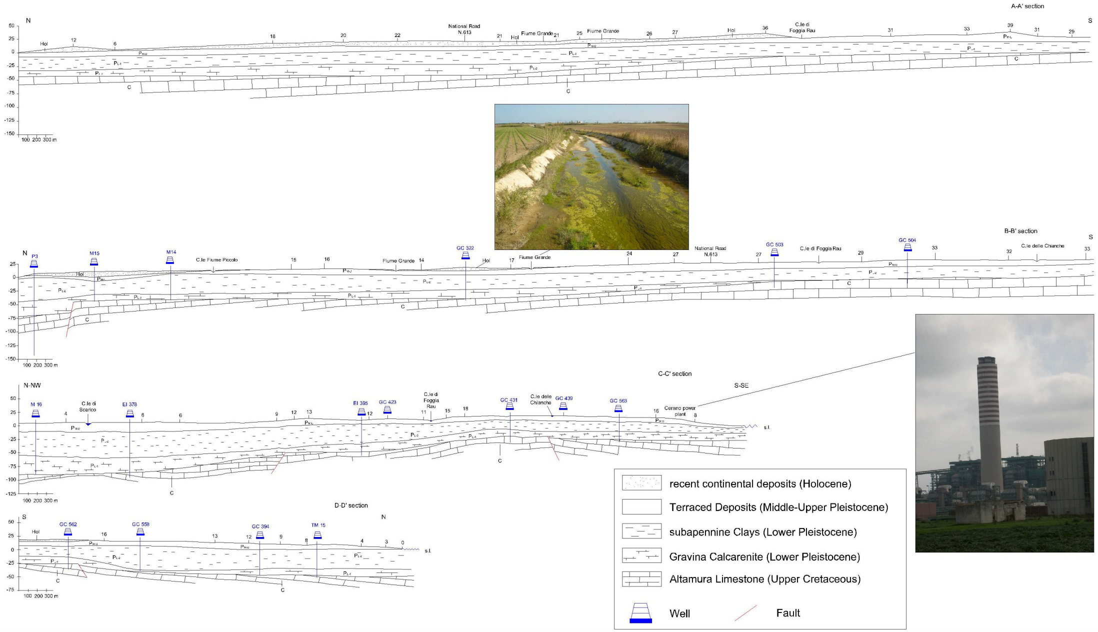


Fig. 6. Geological cross sections.

Fig. 7. Spring along the cliff near cerano: the aquifer formed by the pleistocene marine terraced deposits overlying the pleistocene clays meets the cliff.

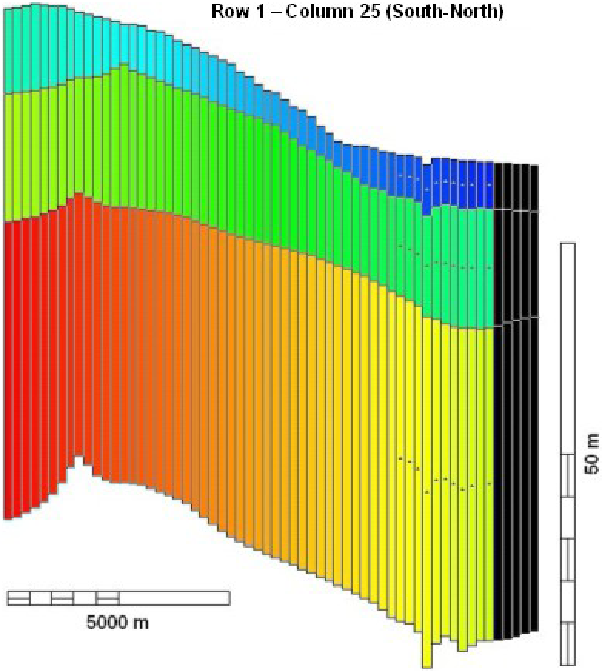


Fig. 8. Geological section along row1, column 25. Blue: continental deposits; green: terrace deposits and brindisi sands; yellow: subapennine clays.

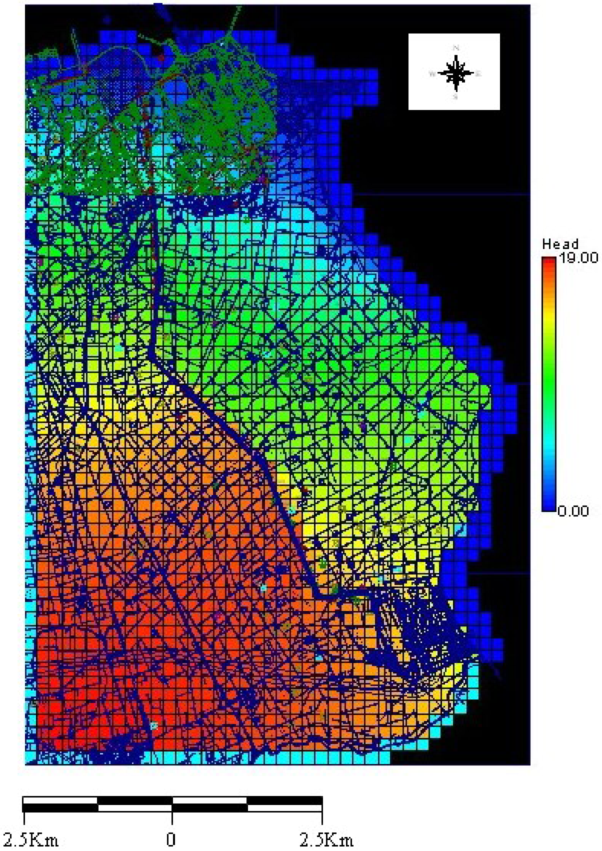


Fig. 9. Simulation of groundwater flow in terrace deposits.

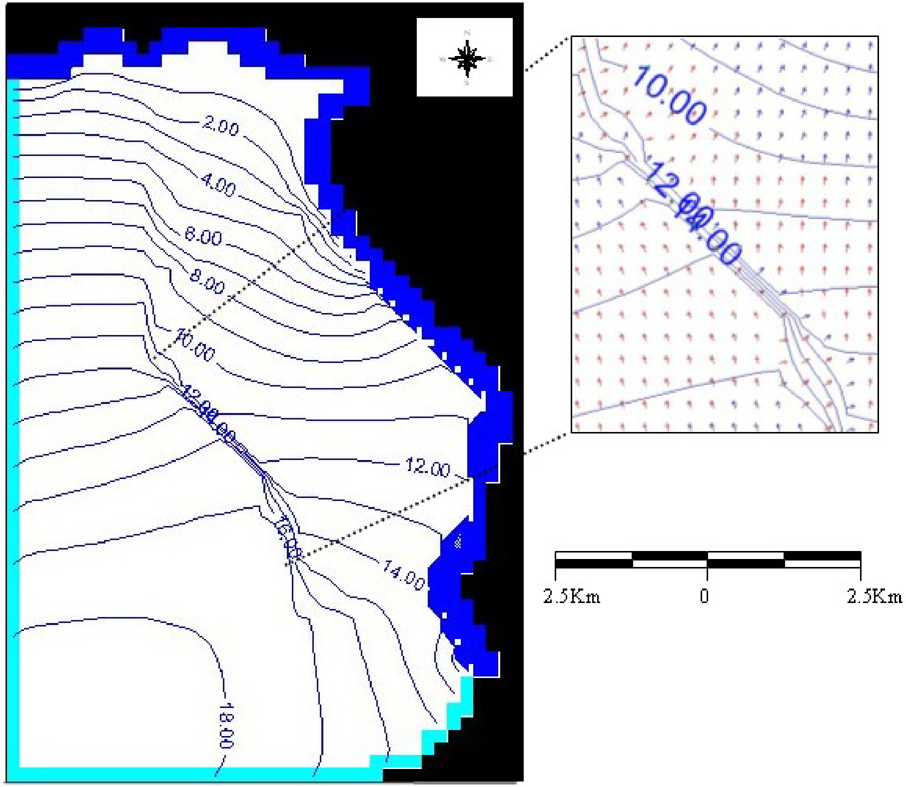


Fig. 10. Groundwater flow near the “Asse Attrezzato”.

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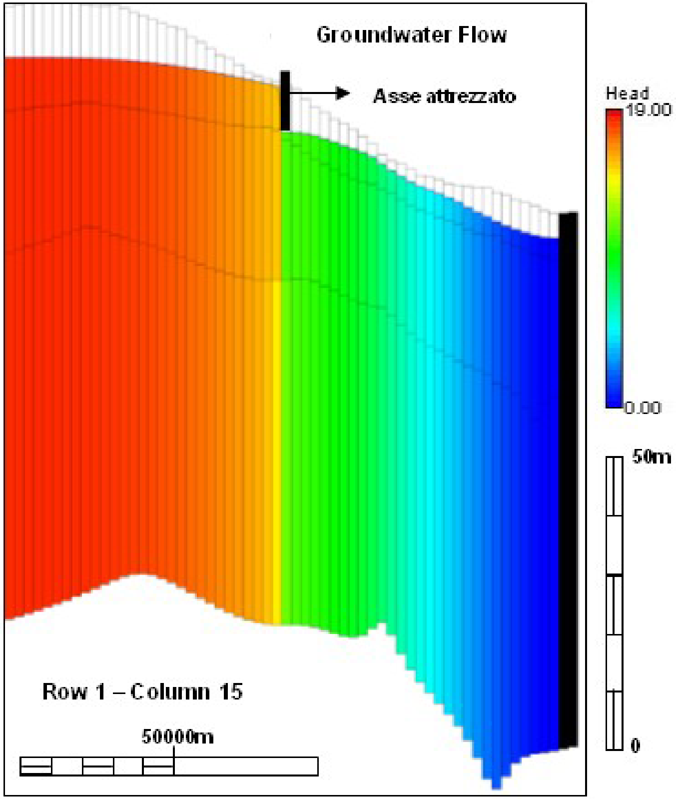

Fig. 11. Effect of the "Asse Attrezzato" on groundwater flow.

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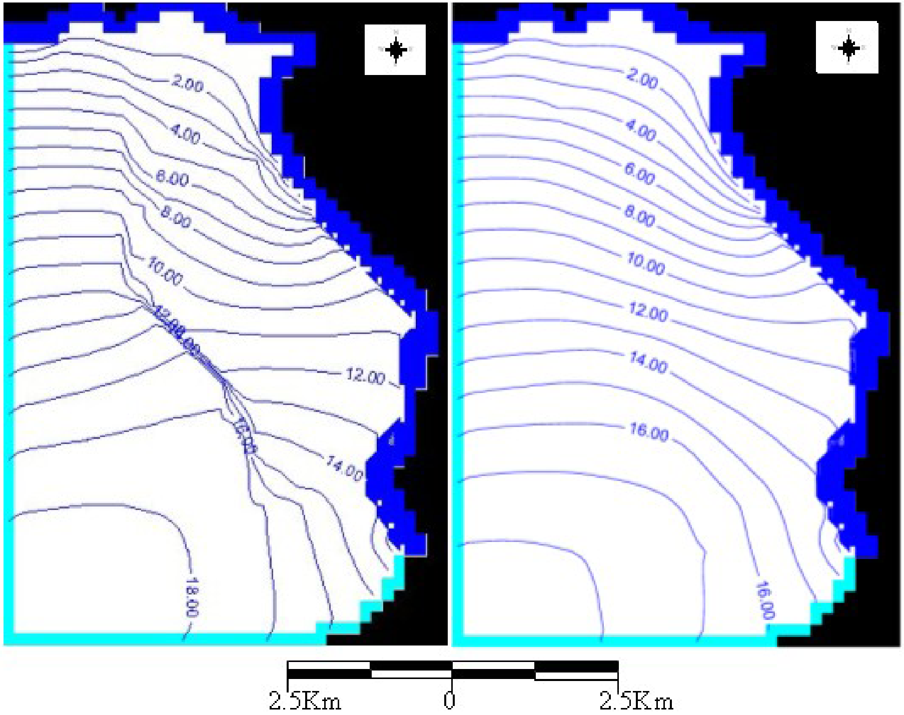

Fig. 12. Comparison of the groundwater flow in presence and absence of the “Asse Attrezzato”.

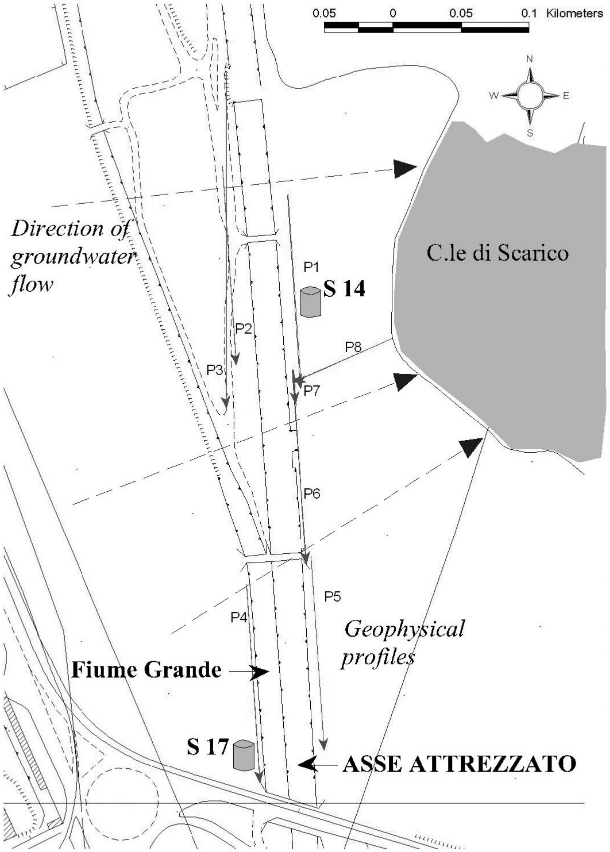

Fig. 13. Map of geophysical profiles.

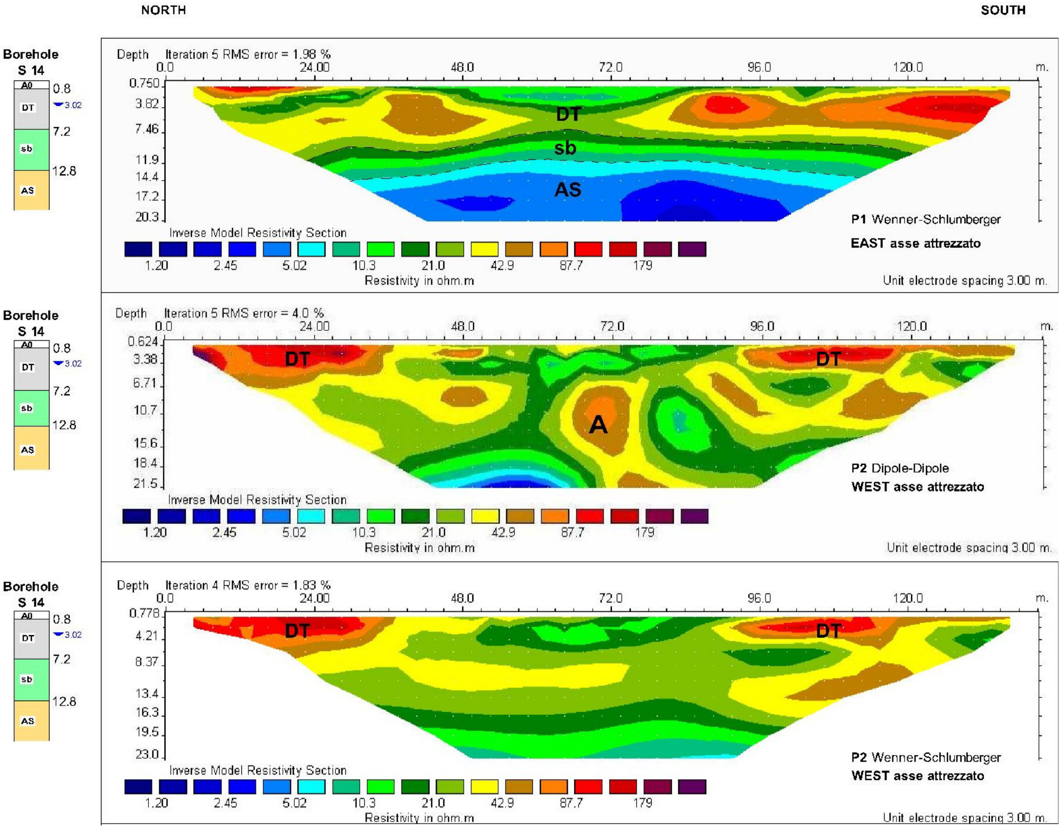

Fig. 14. Profiles P1 and P2 interpretation 2-D resistivity models realized at the north of the investigated area.

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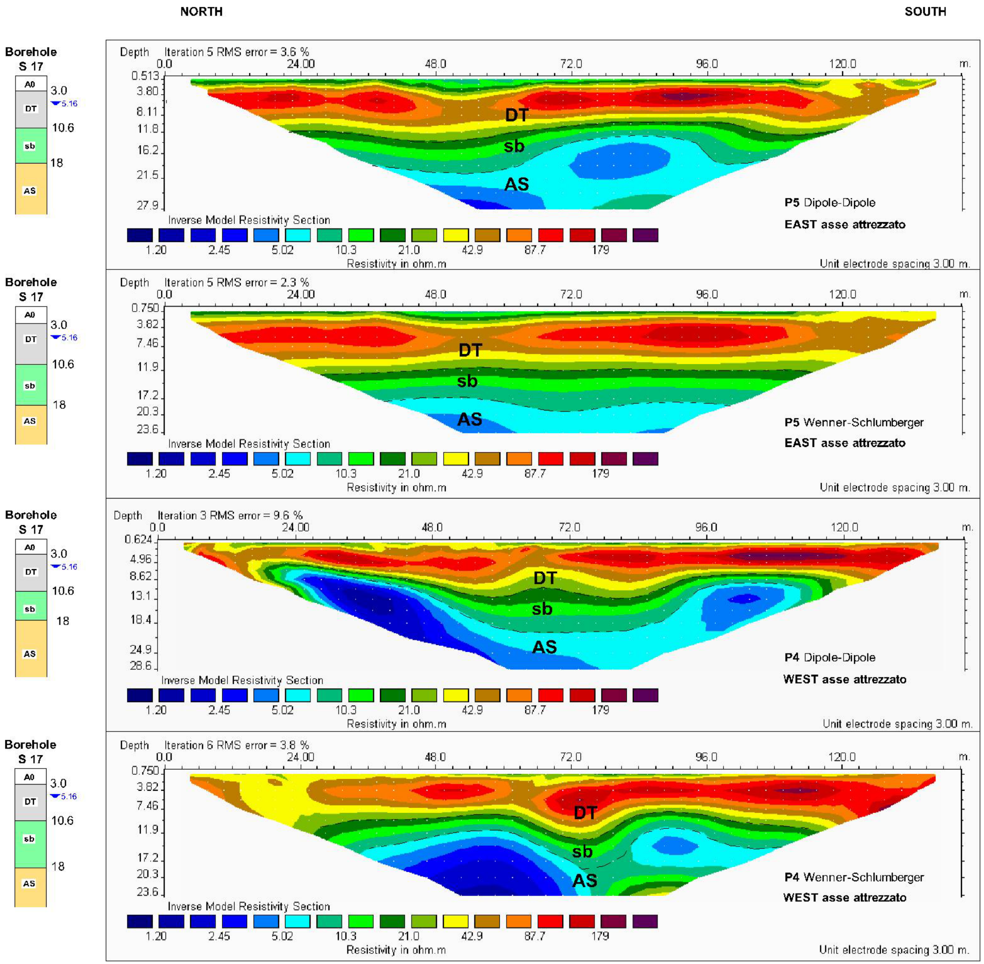

Fig. 15. Profiles P5 and P4 interpretation 2-D resistivity models realized at the south of the investigated area.

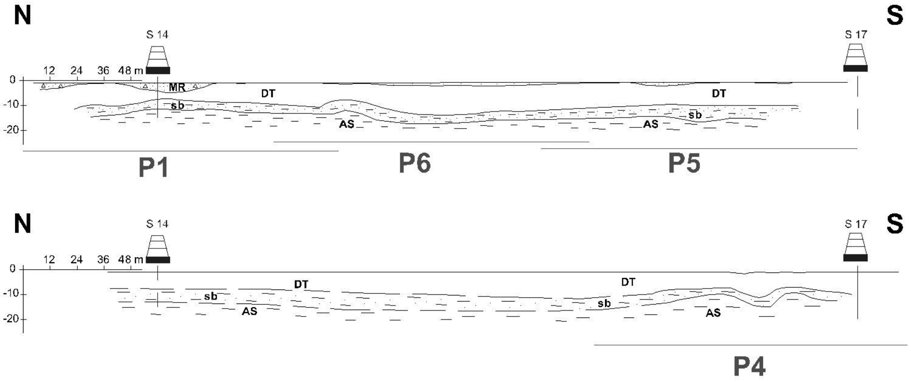

Fig. 16. Geological cross sections of eastern side (above) and western side (below) of the "Asse Attrezzato", extrapolated from geophysical cross sections and stratigraphies from boreholes present in the area.