GEOPHYSICAL APPROACH FOR MONITORING SALTWATER INTRUSION IN COASTAL AQUIFERS

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ABSTRACT. In many places around the world groundwater is used as a main source of fresh water. The alarming rate of increasing the world's population makes its monitoring and managing of great importance. Both anthropogenic activities and natural phenomena lead to displacement of fresh groundwater by saline water. Electrical Resistivity Tomography (ERT) performed with various electrode configurations is widely used geophysical technique for high resolution illustrations of sites with complex geology. 2D electrical resistivity surveys were conducted near Yovanitsa port on Mount Athos in Northern Greece. The obtained results suggest that the ERT can be a powerful tool for delineating aquifers, reconstructing saltwater wedge geometry and contouring the zones with higher level of salinization which are necessary for the process of prevention.

ГЕОФИЗИЧЕН ПОДХОД ЗА МОНИТОРИНГ НА СОЛНИЯ КЛИН В КРАЙБРЕЖНИТЕ ЗОНИ

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РЕЗЮМЕ. Като източник на питейна вода на много места по света се използват подземните води. Тяхната оценка и управление са изключително важни поради постоянното увеличаване на световното население. Изместването на сладката от солената вода е резултат както от антропогенна дейност, така и от природни феномени. Електросъпротивителната томография, реализирана с различни електродни схеми, е широко използван геофизичен метод за получаване на изображение с висока разделителна способност на райони с комплексна геология. Извършени са двумерни електротомографски изследвания в района на пристанище Йованица на полуостров Атон в Северна Гърция. Получените резултати показват ефективността на метода закартиране на хидрогеоложките условия,установяване на геометричните характеристики на солния клин и определяне на зоните с повишено съдържание на соли, които са необходими при планиране на превантивни дейности.

Introduction

The beauty, richness, wide variety of valuable habitats and ecosystems have made the costal zones one of the most popular settlement areas,tourist destinations, business zones and transit points. They are among the most productive areas in the world with currently more 200 million European citizens, stretching from the North-East Atlantic and the Baltic to the Mediterranean and Black Sea. Being heavily populated and excessively exploited in terms of natural resources puts costal ecosystems in a great risk. One of the critical phenomena which mainly effects these areas is contamination of the aquifers with seawater. The extent of saltwater intrusion (fig. 1) is a result of both natural processes (sea level rising, drought, changes in the timing of freshwater delivery to estuaries) and anthropogenic activities (damming rivers, freshwater removal for municipal, industrial or agricultural use, changes in freshwater inflow).

Estimation of salt intrusion can be made with the classical chemical methods measuring those parameters that best highlight the saline contamination as electrical conductivity and chloride concentration (Satriani et al., 2011). Alternatively, applied geophysical techniques characterizing the hydrogeology of coastal aquifers can be used. As saltwater intrusion may occur at different depths the most appropriate geophysical technique is the Electrical Resistivity Tomography (ERT). Performed with various electrode configurations the method is very effective for high resolution illustrations of near-surface resistivity anomalies.

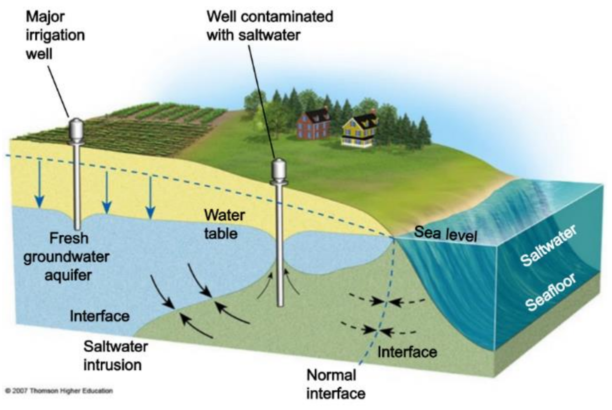

Fig. 1. Cross section of contacts between a coastal aquifer and saline groundwater (Miller and Spoolman, 2007)

Generally, all water contains dissolved chemical materials called "salts". When the concentration of these dissolved materials increases drastically, the water is referred to as "saltwater". As freshwater is usually consideredwater having a total dissolved-solids concentration of less than 1,000 mg/L whereas saltwater ones as greater than 1,000 mg/L. The upper limit of freshwater can vary and is based on its suitability for domestic use. Concentration of 2,000 to 3,000 mg/L is considered the limit of water being too salty to drink. Waters with total dissolved-solids concentration of 1,000 to 35,000 mg/L are called "brackish" with upper concentration limit set at the approximate concentration of seawater of 35,000 mg/L (Table 1). When dissolved-solids concentration exceeds that of seawater, we have concentrated seawater usually called brine, in most cases containing mostly sodium chloride (Chitea et al., 2011; Barlow, 2003).

Table 1
Average concentrations of major dissolved constituents of seawater (Hem, 1989)

Constituent	Concentration (mg/L)
Chloride	19,000
Sodium	10,500
Sulfate	2,700
Magnesium	1,350
Calcium	410
Potassium	390
Bicarbonate	142
Bromide	67
Strontium	8
Silica	6.4
Boron	4.5
Fluoride	1.3

Higher salt level triggers a cascade of events that impact coastal ecosystems at different scales from small (cm to m) scale changes in sediment biogeochemistry and materials processing to large (m to km) scale alterations in the distribution of flora and fauna. Increased chloride (salt) and sulfate concentration are most likely the reason for the significant impact of saltwater intrusion in coastal zones. Small changes in chloride concentration can physiologically stress microorganisms, plants, and animals and alter metabolic pathways, rates of activity, and abundance. Sulfate is a terminal electron acceptor for anaerobic respiration that is present in limited amounts in freshwater but that is abundant in seawater. Changes in sulfate availability may result in dramatic changes in sediment biogeochemistry, which may drive ecosystem-level changes in plant and animal distributions (Joye, 2013).

Physical formulation

Saltwater intrusion occurs when aquifers in coastal areas have hydraulic contact with seawater as a result of the higher density of saltwater. As freshwater has a density of about 1,000 g/cm^3 at 20 °C, whereas the saltwater is slightly denser at about 1,025 g/cm^3, fresh water floats on top of the sea water resulting in amore or less well-defined salt/freshwater interface. Freshwater reservoirs on small islands can be lens shaped (fig.2). There is no distinct boundary between the salty sea water and fresh groundwater but rather a transition zone of intermixture known as brackish water.

In case of hydrostatic equilibrium and homogeneous aquifers, an estimate of the depth of this interface is given by the classical formulation of Ghijben (Drabbe et al., 1888 and Herzberg, 1901), which are the first physical formulations of saltwater intrusion deriving analytical solutions to approximate the intrusion behavior.

$$z = \frac{\rho_f}{\rho_s - \rho_f} h, [m]$$

h - thickness of the freshwater zone above sea level, [m];
z - thickness of the freshwater zone below sea level, [m];
ρ_f - density of freshwater, [kg/cm^3];
ρ_s - density of saltwater,[kg/cm^3].

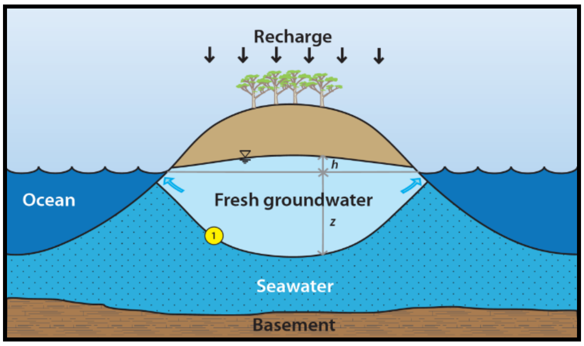

Fig. 2. Freshwater lens on a small island. The Ghijben-Herzberg relation provides an approximation of the lens thickness: z≈40h
1 - interface between seawater and groundwater (Werner et al., 2013)

In well-balanced groundwater conditions with known density of seawater and depth to the water table, the depth of salt/freshwater interface can be calculated (fig.3). However, if the equilibrium between freshwater and saltwater is disturbed by high pumping rates for water supply, the depth of the salt/freshwater interface is lowered and an enforced saltwater intrusion can occur (fig.4) (Kirsch, 2009).

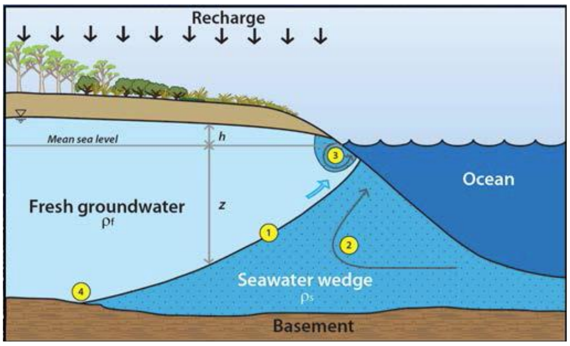

Fig. 3. Natural equilibrium of seawater and groundwater in an undisturbed system
1 - interface between seawater and groundwater; 2 - movement of water affected by density (ρ_s>ρ_f); 3 - movement driven by the tide; 4 - furthest extent of seawater intrusion (Werner et al., 2013)

The Holy Mountain

Cloaked by beautiful chestnut and other types of Mediterranean forest, the steep slopes of Mount Athos are punctuated by twenty imposing monasteries and their subsidiary establishments. Covering an area of just over

33,000 hectares, the property includes the entire narrow rocky strip of the easternmost of the three peninsulas of Chalcidice which jut into the Aegean Sea in northern Greece. The subsidiary establishments include sketae (daughter houses of the monasteries), kellia and kathismata (living units operated by the monks), where farming constitutes an important part of the monks' everyday life.

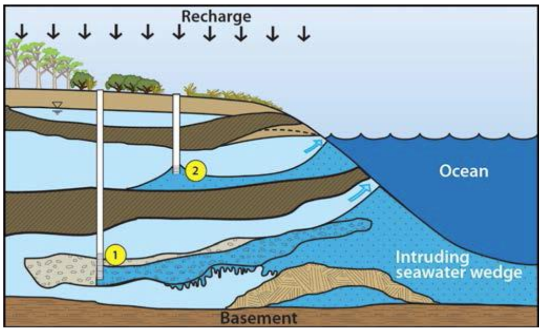

Fig.4. Seawater intrusion occurring in a more complex aquifer with human activity contributing
1 - seawater moving preferentially through high-permeability layers in the ground; 2 - excessive pumping drawing seawater upwards, causing the bore to become contaminated (Werner et al., 2013)

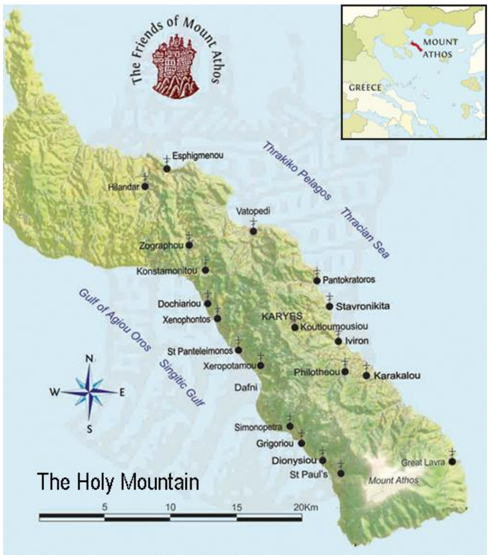

Fig. 5. Map of the Mount Athos Peninsula (The Friends of Mount Athos, 2016)

An Orthodox spiritual center since 1054, Mount Athos has enjoyed an autonomous statute since Byzantine times. Its first constitution was signed in 972 by the emperor John ITzimiskes. The 'Holy Mountain' (fig. 5), which is forbidden to women and children, is also a recognized artistic site. The layout of the monasteries (which are presently inhabited by some 1,400 monks) had an influence as far afield as Russia, and its school of painting influenced the history of Orthodox art. The landscape reflects traditional monastic farming practices, which maintain populations of plant species that have now become rare in the region. (UNESCO, World Heritage Centre)

Geological Settings of Mount Athos

The Mount Athos Peninsula belongs to the Serbo-Macedonian Massif (fig.6), a large basement massif within the Internal Hellenides. The south-eastern part of the Mount Athos peninsula is built by fine-grained banded biotite gneisses and migmatites forming a domal structure. The southern tip of the peninsula, which also comprises Mount Athos itself, is built by limestone, marble and low-grade metamorphic rocks of the Chortiatis Unit. The northern part and the majority of the western shore of the Mount Athos peninsula are composed of highly deformed rocks belonging to a tectonic mélange termed the Athos-Volvi-Suture Zone, which separates two major basement units: The Vertiskos Terrane in the west and the Kerdillion Unit in the east.

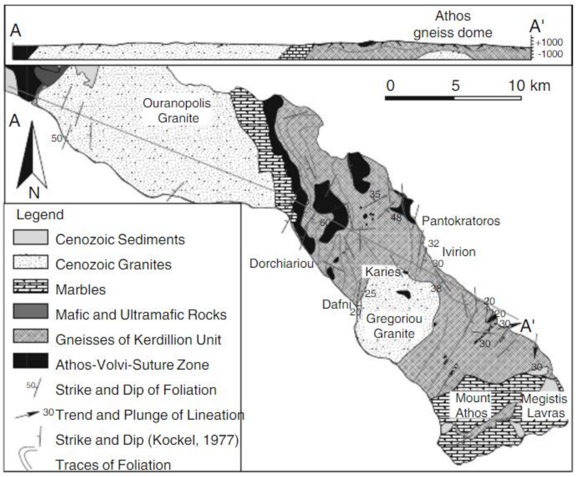

Fig. 6. Structure of the gneissdome on the Mount Athospeninsula (Himmerkus et al., 2011)

The rock-types in this mélange range from metasediments, marbles and gneisses to amphibolites, eclogites and peridotites. The gneisses are tectonic slivers of the adjacent basement complexes. The mélange zone and the gneisses were intruded by granites (Ierissos, Ouranoupolis and Gregoriou). The Ouranoupolis intrusion obscures the contact between the mélange and the gneisses. The granites are only slightly deformed and therefore postdate the accretionary event that assembled the units and created the mélange. (Himmerkus et al., 2011).

Bulgarian Ortodox Monastery Zograf

Named after the 13th or 14th century icon of Saint George the Zograf which is believed to mysteriously paint itself on the prepared board(zografos) the monastery exists since 980 as per the earliest written evidence. During the Middle Ages, Zograf monastery was generously supported by the Bulgarian rulers, such as Ivan Asen II and Ivan Alexander as a matter of pride. In 1275 the monastery was plundered and burnt down by Crusaders and rebuilt with the support of the Paleologan dynasty, as well as that of rulers of eastern Europe.

The monastery exists in its modern appearance since the 16th century, while its present-day buildings date from the middle 18th century. The south wing was built in 1750, the east in 1758, the small church in 1764 and the large one in 1801. (igs. 7, 8 and 9).

The north and west wing are from the second half of the 19th century and large-scale construction ended in 1896 with the Saints Cyril and Methodius Church and the raising of the bell tower.

Fig. 7. The east wing and the large church of Zograf monastery

Fig. 8. The north and west wings of Zograf monastery

Fig.9. The bell tower of Zograf monastery

Survey Summary

Geophysical approach of survey is based on physical measurements from which the spatial distribution of different physical properties of the rocks can be derived. Pore-water electrical conductivity and its inverse resistivity are the properties that can be related to hydrologic or geologic aspects of aquifers. Aquifers conductivity depends mainly on their porosity and the level of salinization of the water filling the pore space. Ground water conductivity increases when either porosity or concentration of dissolved ions increase. Mass movement of saltwater in zones of fresh water is localized by analyzing the spatial distribution of electrical conductivity (Barlow, 2013; Stewart, 1999).

Electrical Resistivity Tomography scans the subsurface along the survey line for both vertical and lateral variability of ground electrical resistivity using different electrode arrays. Variations in electrical resistivity usually correlate with variations in lithology, water saturation, fluid conductivity, porosity and permeability, which may be used to map stratigraphic units, geological structure, sinkholes, fractures and groundwater.

Traditionally, resistivity measurements involve four electrodes in standard configuration. Two current electrodes injecting low frequency electric current into the ground and two potential electrodes measuring the resultant voltage response which are then converted in resistivity value. The field set-up requires the deployment of an array of regularly spaced electrodes connected to a central control unit via multi-core cables. Resistivity data set is collected via combinations of systematical changes of the location of the four electrodes. The depth of investigation depends on the electrode spacing and the geometry of the used array. Incremental increase of the electrode spacing allows for successively deeper sub-surface levels to be investigated. The underlying resistivity distribution is computed by means of inverse modeling and used to produce a resistivity cross-section (Loke and Barker, 1996).

Fig.10. The coast near the western port of Hilandar Monastery -Yovanitsa

To investigate the hydrogeological conditions, 2D electrical resistivity surveys were conducted on the coast near the western port of Hilandar Monastery - Yovanitsa on Mount Athos in Northern Greece (fig.10). Measurements were carried out using twenty-four electrodes connected by a multi-core cable to the ABEM Terrameter SAS 1000 with a maximal current output of 100 mA. The electrodes were positioned in straight profile lines with a constant spacing using a Wenner-Schlumberger resistivity array. The electrical survey was based on four measuring profiles located close to the sea line (fig. 11).

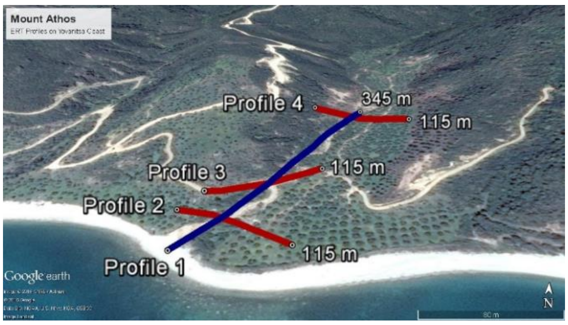

Fig.11. Location of the ERT profiles on Yovanitsa coast

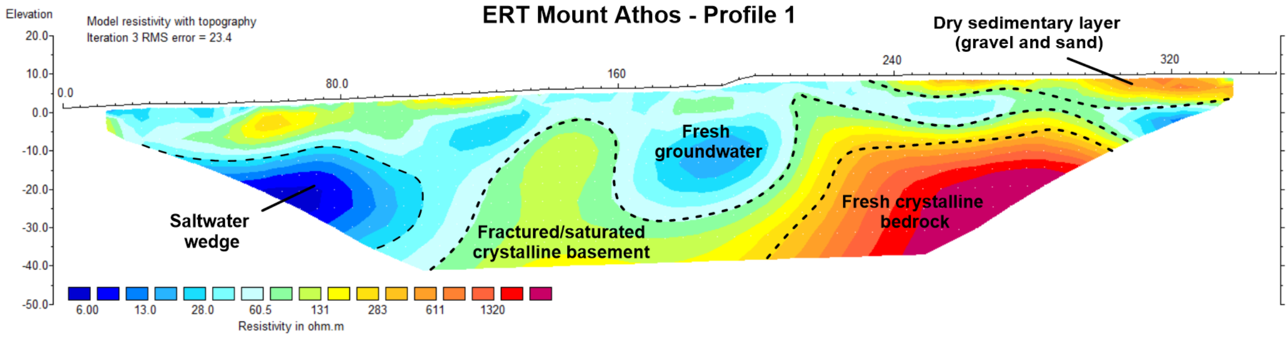

Fig.12.Geoelectrical resistivity cross-section of Profile 1 (345 m)

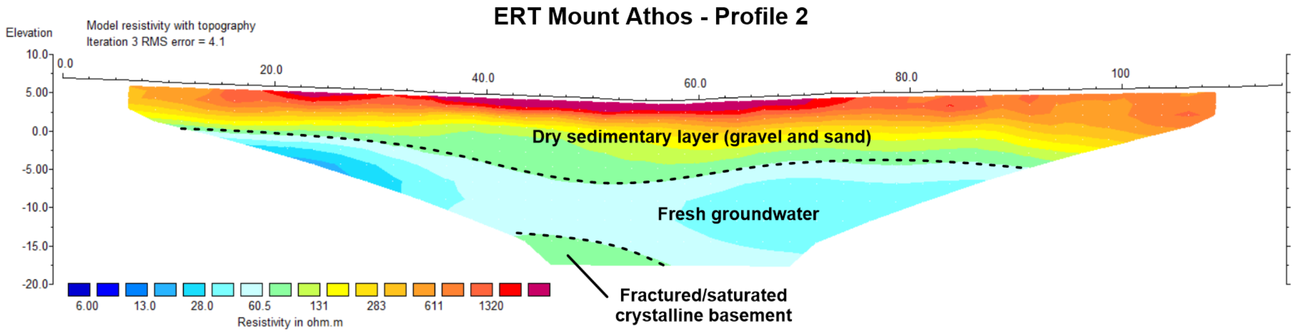

Fig. 13.Geoelectrical resistivity cross-section of Profile 2 (115 m)

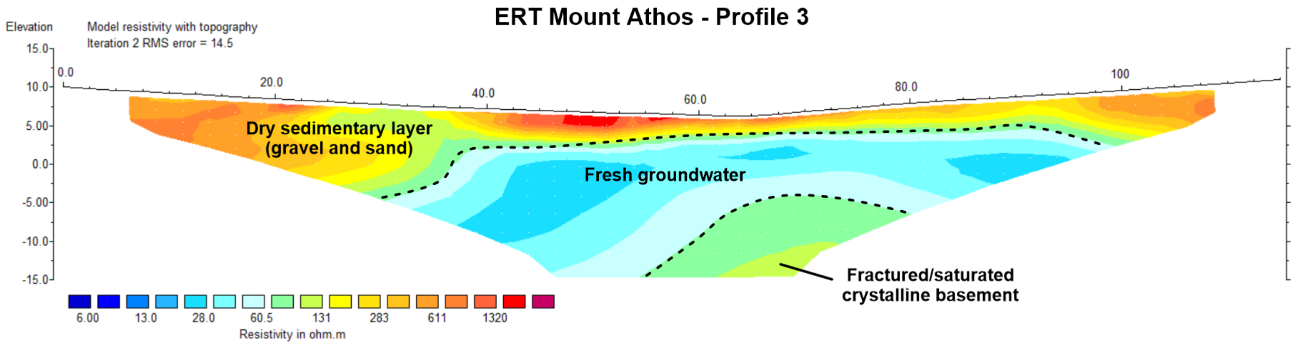

Fig.14. Geoelectrical resistivity cross-section of Profile 3 (115 m)

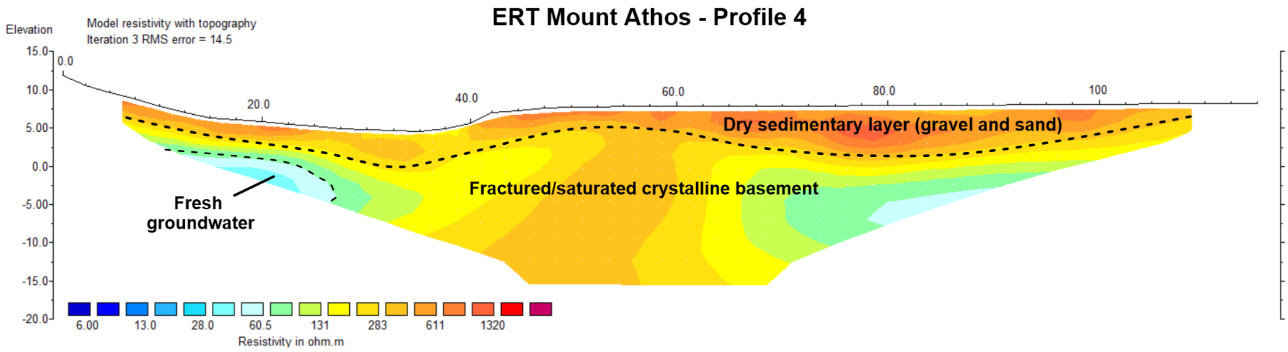

Fig.15. Geoelectrical resistivity cross-section of Profile 4 (115 m)

The long profile (fig. 12), which purpose is to delineate the aquifer and reconstruct the geometry of the saltwater wedge, has a total length of 345 m. It is oriented in North-South direction perpendicularly on the coastline with a step of 10 m between the electrodes on the surface. The maximum achieved depth of the investigation is about 40 m.

Additionally, three more profiles (figs. 13, 14, 15), positioned perpendicularly to the main profile, were performed for detailed evaluation of the geological conditions. The profiles are placed 60, 130 and 320 m off the sea line. They have a total length of 115 m each, distance of 5 m between the electrodes on the surface and a maximum achieved depth of the investigation about 20 m.

The derived resistivity images clearly delineate four main geoelectrical zones: sedimentary cover, saltwater wedge, groundwater aquifer and crystalline basement.

- *Sedimentary Cover*

The top layer, which is partially seen on Profile 1 (fig.12)and clearly outlined on Profiles 2, 3 and 4 (figs. 13, 14 and 15) has electrical resistivity varying between 500 and 3000 Ωm. It corresponds to dry sedimentary layer composed from gravel and sand. The very resistive upper part exposed on Profile 2 and 3 (figs. 13 and 14) follows the gravel roads on the site.

- *Saltwater Wedge*

There sistivity cross-section of Profile 1 (fig.12) clearly contours a tongue-shaped featureat a depth of about 10 munder the Earth surface, which intrudes into the coast to a distance of 100 m. This highly conductive zone with resistivity values between 6 - 10 Ωmrepresents the geometry of the saltwater wedge and the contact between the salty seawater and the fresh groundwater.

- *Groundwater Aquifer*

Near the surface, alongside the whole cross-section of Profile 1 (fig.12) occurs a geo-electric layer with moderate resistivity of about 30 Ωm and a deeper central part of about 25 m. This conductive layer is also found on Profiles 2, 3 and partially 4 (figs. 13, 14 and 15) andmapsthe fresh water aquifer.

- *Crystalline Basement*

The fresh groundwater layer is underlined by fractured/saturated crystalline basement with resistivity values between 150 and 700 Ωm visible on all profiles. The high resistivity values between 1400 -3000 Ωmobservedat depthon Profile 1 (fig.12) characterize the fresh crystalline bedrock.

Conclusion

Combination of both natural process and anthropogenic activities, lead to contamination of the fresh groundwater reserves with salty seawater. The cost and the time needed for groundwater remediation make the processes of monitoring and managing crucial for preservation of coastal areas of great environmental, economic, social and cultural importance.

The derived near surface, high resolution resistivity images suggest that geophysical approach of investigation and the Electrical Resistivity Tomography in particular is highly effective for delineating aquifers, reconstructing saltwater wedge geometry, contouring zones with higher level of salinization and detecting resistivity contrasts caused by interfaces between highly conductive seawater and saturated fresh water layers.

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The article is reviewed by Assist. Prof. Dr. Maya Grigorova and recommended for publication by the Department „Applied Geophysics".