GEOPHYSICAL DETECTION OF MARINE INTRUSIONS IN BLACK SEA COASTAL AREAS (ROMANIA) USING VES AND ERT DATA

Florina CHITEA[1,2], Paul GEORGESCU[1], Dumitru IOANE[1]

[1]*University of Bucharest, Department of Geophysics, 6 Traian Vuia Street, 020956 Bucharest, Romania,*
e-mail: f_chitea@yahoo.com, pag66ster@gmail.com, dumitru.ioane@g.unibuc.ro
[2]*"Sabba S.Stefanescu" Institute of Geodinamics of the Romanian Academy*

Abstract. Communities living in coastal areas depend in a great extent on the fresh water resources exploited from aquifers which are usually in a natural hydrodynamic equilibrium with the sea water. The contamination of fresh water with marine saltwater determines a significant increase in the aquifers electric conductivity, allowing an efficient application of resistivity methods in detecting and monitoring the marine intrusions. We present case studies from Romania (Costinesti and Vama Veche areas, southern Dobrogea) based on vertical electric soundings (VES) and recent electric resistivity tomography (ERT) measurements, relevant for the detection and monitoring of coastal marine intrusions. The results of the geophysical investigations are mostly represented as apparent resistivity but also as inverted cross sections, both illustrating by means of resistivity anomalies the spatial development and evolution in time of the marine intrusions.

Key words: Vertical electric sounding, electric resistivity tomography, marine intrusion, Black Sea

1. INTRODUCTION

Freshwater quality continues to be generally a problem for the human living communities worldwide because, despite the great demand for drinking and industrial activity, water resources are affected by anthropogenic contaminants. Coastal aquifers in hydraulic contact with the sea are even more prone to water deterioration as being susceptible also to natural hazards such as marine intrusions.

The displacement of fresh groundwater by saline water is a complex process influenced by both anthropogenic activities and natural phenomena. It is considered that between fresh water aquifers and salty groundwater is a hydrodynamic equilibrium which can be destabilized by several natural and anthropogenic factors (Fig. 1).

As the main fresh water resource for coastal communities is represented by underground water from continental aquifers, intensive exploitation for drinking water supply and agricultural use is often a trigger for saltwater intrusion (Georgescu *et al.*, 1993, Sathish *et al.*, 2011). Sea level rise due to the climate changes (Nguyen *et al.*, 2009, Werner and Simmons, 2009) and fractured rocks along faults (Papadopoulou *et al.*, 2005) are also factors that can influence the inland penetration of the salt groundwater.

The extent of saline water intrusion may vary between a few meters to kilometers and it is mainly determined by the geological formations (Himi *et al.*, 2010), aquifer type, thickness and his hydraulic conductivity (Chachadi and Ferreira., 2005), climate conditions (influence the recharge grade of aquifer and sea level), ground water level with respect to mean sea elevation (Chachadi and Ferreira., 2005) and distance from the coastline of pumping wells.

The limit between fresh and saltwater is usually a transition zone as a result of hydrodynamic dispersion of the dissolved salts (Wu *et al.*, 1993) and its inland extension may vary, being strongly influenced by aquifer properties (Bear and Cheng, 2010).

The location and movement of the saltwater interface has been extensively studied, being subject to numerous research activities including geochemical, hydrological and geophysical studies. Among the geophysical methods applied in saltwater intrusion studies best results were obtained with electrical methods adequately implemented (Mitrofan, 1983; Georgescu *et al.*, 1993; Gemail *et al.*, 2004; Al-Sayed and El Qady, 2007; Georgescu *et al.*, 2010; Himi *et al.*, 2010), due to the main influence of the pore water content over electrical conductivity or resistivity. As saltwater causes a major decrease in electrical resistivity of the saturated formations, contamination of the coastal aquifer can be delineated in electrical resistivity/conductivity resulted models, which can be many times associated with hydrogeological models (Kirsch, 2006).

As saltwater intrusion may occur at different depth levels the best geophysical techniques are represented by Vertical Electric Sounding (VES) and Electric Resistivity Tomography (ERT). Vertical Electric Sounding is a reliable investigation method also in cases when the saltwater intrusion is located at major depths, difficult to be revealed by boreholes or other geophysical techniques.

The VES method was previously applied successfully in areas located in the vicinity of the Romanian Black Sea coastline for marine intrusions detection at Techirghiol, Costinesti and Vama Veche (Mitrofan, 1983; Georgescu *et al.*, 1993; Georgescu *et al.*, 2010) or monitoring at Costinesti (Georgescu *et al.*, 2010).

ERT, performed with various electrode configurations, proved to be very effective in illustrating with higher resolution near-surface resistivity anomalies for a wide range of environmental problems, including the contamination of underground waters (Ioane *et al.*, 2009).

2. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The shallow geological structure consists of Sarmatian and Quaternary sedimentary deposits overlapping Cretaceous and Eocene formations (Chiriac, 1968a, 1968b).

Sarmatian sediments, Bessarabian and Kersonian in age, are represented by alternations of limestones, clays, sands and sandstones. Starting in Upper Sarmatian and ending in Pleistocene the eastern part of South Dobrogea was uplifted, an event which determined in a great extent its present day geomorphology.

The Quaternary formations include red clays (Lower Pleistocene) at the contact with Sarmatian limestones, alternating beds of loess and paleosol (Middle and Upper Pleistocene) and beach sands (Upper Holocene).

The main fault systems are trending NW-SE and N-S, parallel to regional tectonic lineaments such as Peceneaga-Camena and Capidava-Ovidiu and to those determining the N-S direction of the seashore between Vama Veche and Navodari. The area where Vama Veche is located was "recently" downlifted, Quaternary deposits bearing traces of faulting and vertical displacements being situated between sectors where the Sarmatian limestones outcrop at the sea level (Fig. 2).

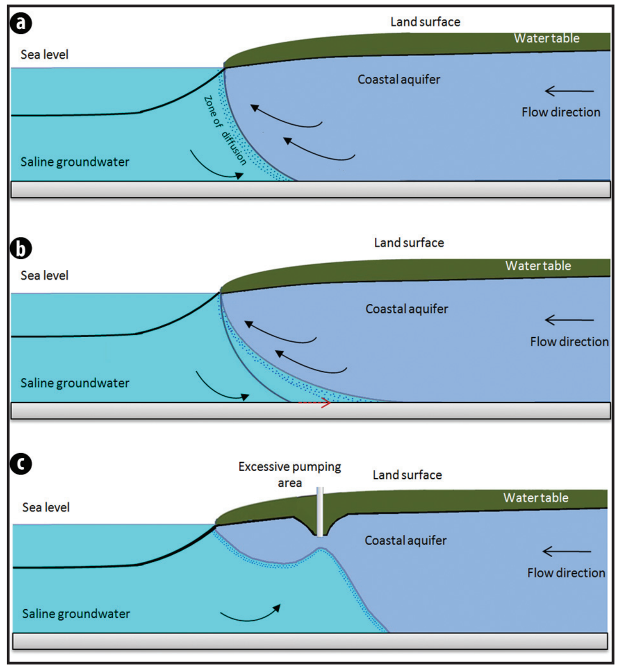

Fig. 1 Schematic cross sections: (a) contact between coastal aquifer and saline groundwater over an impermeable layer; (b and c) models of saline intrusion (not to scale) (Redrawn after Kirsch, 2006 and Spichak, 2007)

Fig. 2 Fault and vertical displacements of Quaternary deposits in the Vama Veche area

Two main regional aquifers located in Jurassic and Sarmatian limestone are hydrogeologically investigated and exploited in South Dobrogea, the latter being in contact with the Black Sea water and affected by marine intrusions in places located in the vicinity of the shoreline. Besides the high permeability of Sarmatian limestones, characterized by a large number of voids, active faults continuously affecting the inland and offshore geological formations may favor the development of marine intrusions close to the seashore.

3. GEOPHYSICAL METHODS AND DATA PROCESSING

Vertical electric resistivity soundings were previously performed in the Costinesti area on a W-E trending profile situated at 1 km distance from the seashore; VES points were situated at 50 m interval and a maximum AB/2 = 100 m was deployed (Georgescu *et al.*, 1993). Since only qualitative interpretation was intended for monitoring resistivity changes in the aquifer the geoelectric results obtained using VES were displayed as resistivity pseudosections aiming to avoid any distortions determined by inversion techniques (Georgescu *et al.*, 2010).

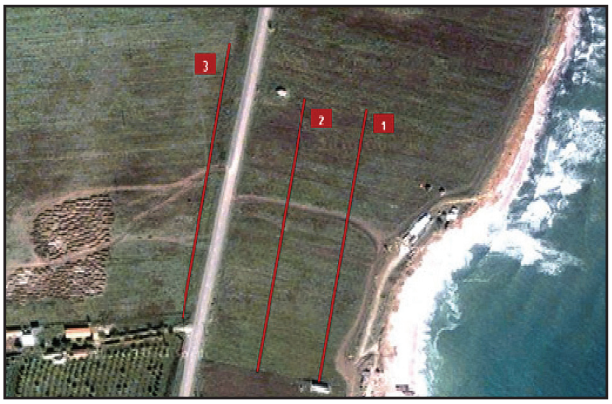

Fig. 3 Location of ERT profiles surveyed in the Vama Veche area

Three ERT profiles parallel with the shoreline were recently measured in the Vama Veche area (Fig. 3). The multi-electrode resistivity measurements used 28 electrodes deployed at 10 m interval, in Schlumberger mode. ERT profiles 1 and 2 were measured twice, using the Wenner and hybrid Wenner-Schlumberger arrays. Resistivity data acquired with the multi-electrode system have been processed using the 2D inversion technique performed with EarthImager (AGI) software. Data inversion started from a discretized model of the investigated area which can be one of the following:

1. custom model when information from boreholes is available;
2. constructed model starting from average apparent resistivities on measured pseudosection.

As it was expected to encounter a combination of both sharp and smooth resistivity variations, the inversion routine was performed using smoothness-constrained least square inversion and robust modeling inversion. The iteration process was performed using quasi-Newton method.

4. RESULTS AND DISCUSSION

4.1. Costinesti area

The marine intrusion observed originally in water exploitation wells in Costinesti area has been geophysically investigated during a long time span (1991-2009), using Vertical Electric Soundings (Georgescu *et al.*, 2009; 2010). The measurements started in September 1991 and detected an intense low resistivity anomaly in the sector where contaminated water was already noticed. This highly conductive part of the aquifer, displaying a classical cone of depression shape, was associated with contamination of fresh water by marine saltwater (Fig. 4 – Resistivity section 1991).

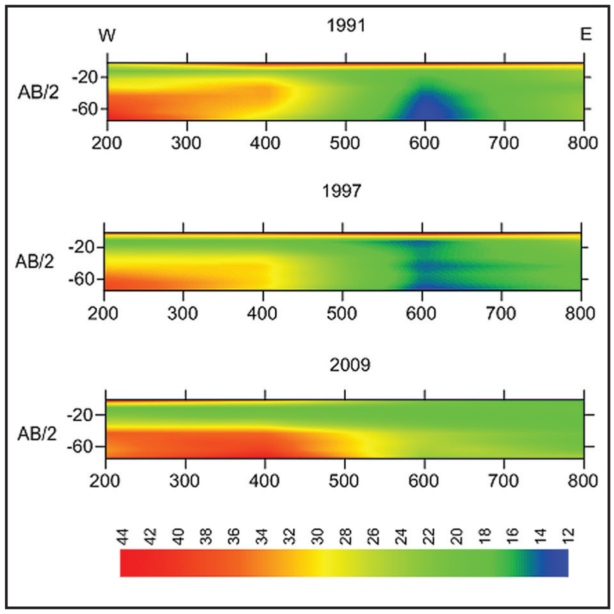

Fig. 4 Apparent resistivity cross-sections in Costineşti area. Horizontal axis: distance along profile [m]; vertical axis: estimated depth [m]

The VES resistivity measurements carried out in 1997 offered a modified picture of the contaminated area by marine water. Due to the severely diminished water exploitation during the passed seven years the cone-shaped resistivity anomaly, interpreted as an upward penetrating saltwater intrusion, looked more diffuse and laterally developed. The saltwater was horizontally displaced in sedimentary beds having higher permeability, such as fissured or fractured limestone, as compared to clay beds (Fig. 4 – Resistivity section 1997). During the next 12 years, the saltwater intrusion entirely vanished, as shown by the lack of low resistivity anomaly (Fig. 4 – Resitivity section 2009), due to either downward retreat (since the water exploitation was severely diminished) or to continuous mixing with fresh water.

The spatial modifications of resistivity within the aquifer during 1991-1997 and 1991-2009 respectively, are shown in Fig. 5. Sectors with high percentage differences, meaning increases in resistivity, illustrate a gradual decrease in salt concentration due to mixing with fresh water of both cone shaped intrusion and its deeper horizontal part.

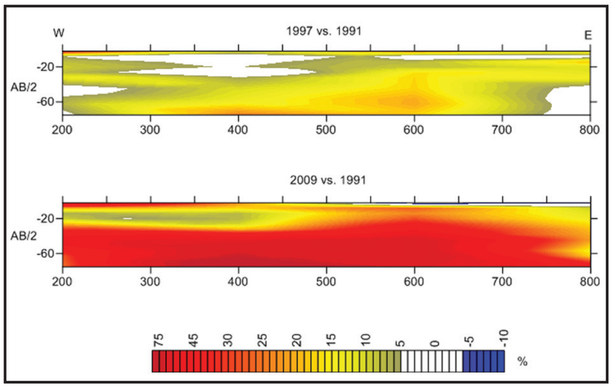

Fig. 5 Percentage differences of apparent resistivity anomalies in the Costinesti area with 1991 apparent resistivity section as reference

4.2. Vama Veche area

The effect of the shoreline escarpment on resistivity measurements in the Vama Veche area was recently evaluated using 1D modeling (Georgescu *et al.*, 2010). Consequently, the ERT profiles were located parallel to the shoreline (Fig. 3) in order to diminish the escarpment effect.

As previously mentioned, ERT Profile 1 was measured twice, using both Schlumberger and Wenner arrays. Analyzing the obtained variations of apparent resistivity only small differences between results were noticed (8 to 23.4 Ωm for Schlumberger array and 10.5 to 22.5 Ωm for Wenner array). The measurements were processed identically, using the forward modeling method (Finite Difference) with conjugate gradient method as forward equation solver. Imposed boundary condition (BC) for the presented results were Neumann for ground/surface and Dirichlet for bottom and lateral limits.

When comparing the inverted resistivity data represented on Profile 1 for Wenner array (Fig. 6) with those obtained using the Schlumberger array (Fig. 7), two ways of interpretation may be derived:

1. the Wenner array favors the illustration of general distribution of resistivity related to the geological structure, as also remarked by M.N. Loke (2002);
2. the Schlumberger array better illustrates details in resistivity variations related to local tectonics (faults, fractures) and water quality (fresh or saltwater).

The resistivity pseudosections for profiles 1, 2 and 3 in the Vama Veche area, obtained by using the Schlumberger array, display important resistivity variations which may be interpreted in terms of both local geology and hydrogeology.

The high resistivity northern sector that is associated with an uplifted compartment consisting of quite compact Sarmatian limestones, is separated by a fault of the lower resistivity southern compartment, considered to include less compacted Sarmatian limestone and clay beds.

The low resistivity zone, located in the deeper part of the northern compartment on Profile 1, is interpreted as a "natural" marine intrusion, penetrated inland over a distance of a few tens of meters due to the difference in density as compared to the fresh water.

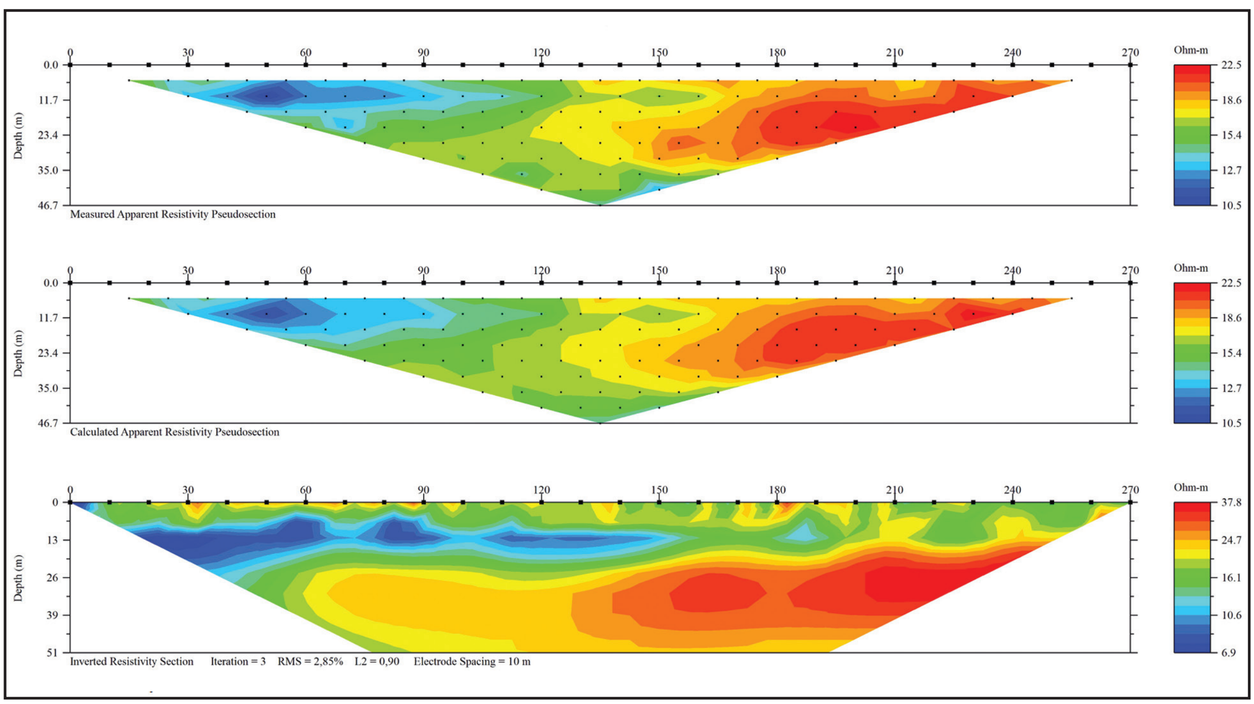

Fig. 6 ERT resistivity data for Profile 1 (Wenner array): measured resistivity pseudosection, calculated apparent resistivity section and inverted resistivity section

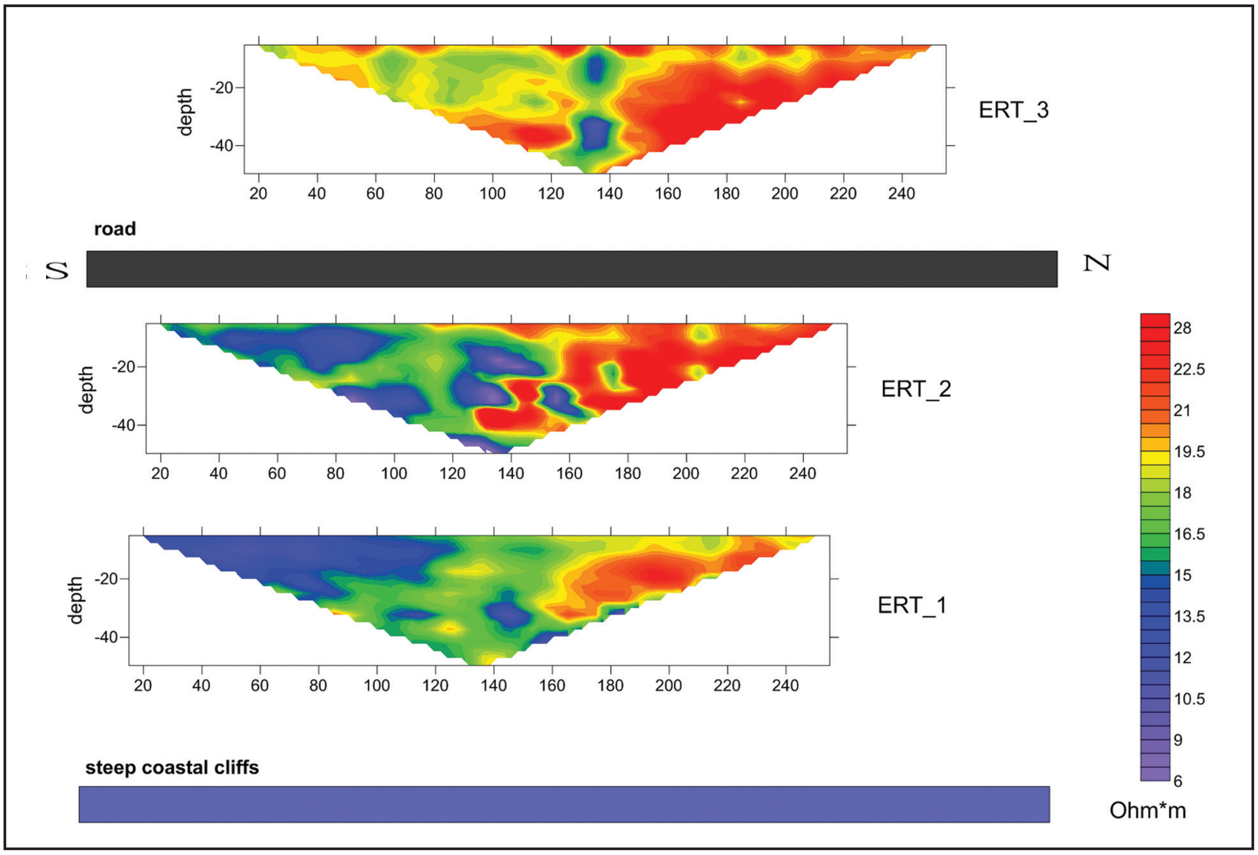

Fig. 7 ERT measured apparent resistivity sections in the Vama Veche area

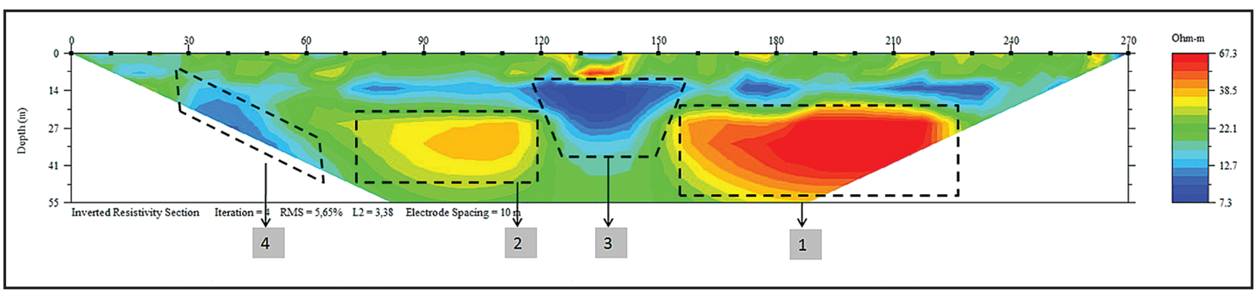

Fig. 8 ERT inverted resistivity section on Profile ERT_3

The low resistivity anomalies situated between the geological compartments separated by fault are interpreted as an inland advanced marine intrusion for at least 200 m, using the highly fractured rocks along the NW-SE fault that may be traced on the ERT profiles. Previous hydrogeological data obtained in a well located ca 500 m west of the seashore showed the presence of saltwater at 40 m depth, where chemical analyses were available.

Resistivity data acquired in areas where high conductivity bodies are expected to be encountered is best to be interpreted after analyzing resistivity simulations models. In the case of very conductive bodies, a major part of induced electrical current flows through the respective body. This special distribution of current may generate high resistivity anomalies located near the conductive body, symmetrically or not, depending on the chosen array type and the conductive body position on the profile. Fictitious anomalies are also possible to be encountered (Nostrand and Cook, 1966).

Before interpreting the resulted 2D apparent resistivity section on Profile ERT_3 in the Vama Veche area (Fig. 8), several synthetic resistivity models were developed. In 2D modeling, electric resistivity values are allowed to vary vertically (Z) and only for one horizontal direction, along the survey line (X). The previous VES data (Georgescu *et al.*, 2010) interpreted for the specific shallow geological structure of the Vama Veche area, associated with the ERT inverted sections, showed significant electrical resistivity variations in a direction perpendicular to the survey line. As a consequence of all these observations, synthetic resistivity 3D models were considered to be more adequate for Vama Veche area (Fig. 9).

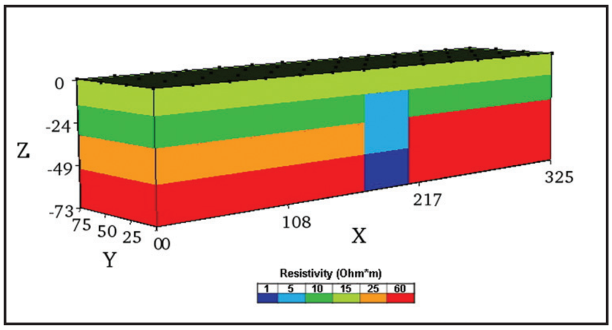

Fig. 9 3D Synthetic resistivity model in the area of Profile ERT_3

To each rectangular cell resistivity values were given considering the geological information from boreholes and estimating strong electrolytes effects over electrical resistivity of fresh water. Sodium chloride and potassium chloride can reduce the resistivity of groundwater to less than 1Ωm (Loke, 2002).

Best fitting synthetic resistivity models were obtained when the presence of a fault zone invaded with very conductive water (saline water) was simulated. Resulted inverted resistivity image (Figs 10 and 11) and 3D resistivity contour plots (Fig. 12) for this synthetic model were used to explain the main anomalies observed on the 2D inverted resistivity section of Profile ERT_3 (Fig. 8).

1. High resistivity anomalies (marked 1 and 2 in Fig. 8) are probably due to different depth levels of the most resistive layer (red area in the synthetic model). This layer is interpreted as quite compact limestone with evaluated mean resistivity of 60 Ωm;
2. Low resistivity anomaly (marked 3 in Fig. 8) is mostly caused by the presence of a saltwater intrusion located in a quasivertical fractured zone associated to a NW-SE fault. This interpretation is based on numerous synthetic models which showed bad correlations with the ERT results in cases of a body with resistivity values higher than 5Ωm. Even if very low resistivity values were obtained mainly in the upper part of the conductive body, our models showed that this anomaly is generated by a deeply extended source;

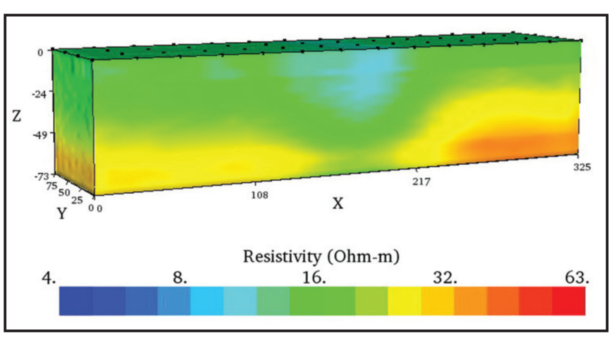

Fig. 10 3D inverted resistivity image of the synthetic model

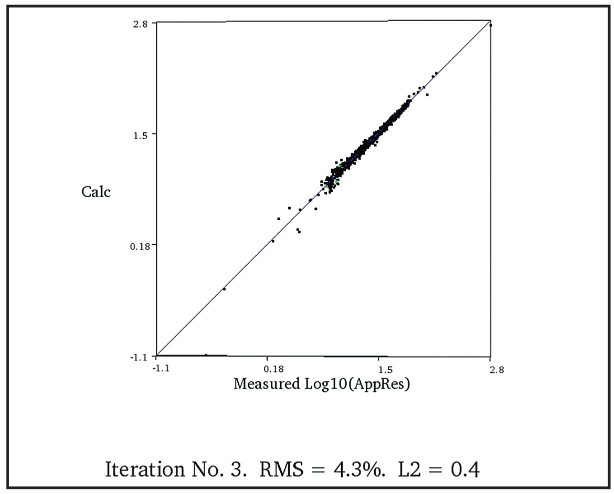

Fig. 11 Apparent resistivity crossplot for the 3D synthetic resistivity model (1% induced Gaussian noise)

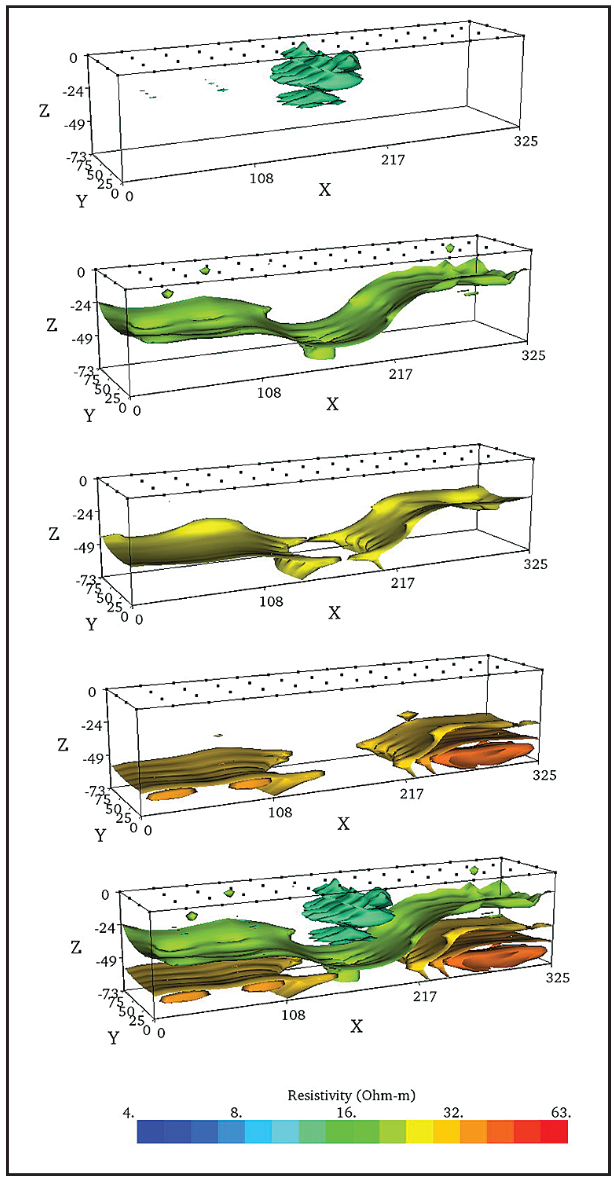

Fig. 12 3D resistivity contour plots of the synthetic model

3. Low resistivity anomaly (marked 4 in Fig. 8) might be generated by a conductive body situated in the vicinity of the measured profile (not covered by real measurements). Considering the results of the 3D modeling this low resistivity anomaly may also represent an artifact of the applied boundary conditions (BC) in the 2D modeling procedure.

5. CONCLUSIONS

Repeated VES measurements in the Costinesti and Vama Veche coastal areas allowed both detection and monitoring of a marine intrusion along high permeability zone within the Sarmatian limestone. The 1991, 1997 and 2009 resistivity data of Costinesti area illustrated the cone-shaped marine intrusion and its subsequent lateral development into high permeability rocks, also seen as percentage differences of apparent resistivity anomalies with 1991 as reference.

The ERT method, first time employed in Romania in such hydrogeological environment, proved to be effective in depicting with higher resolution, by means of resistivity spatial variations, lithological and structural features of the shallow geological structure. Considering the relationship between marine saltwater and the aquifers, the data obtained on ERT profiles in Vama Veche coastal area showed good possibilities of locating marine intrusions which, due to the difference in density, advanced inland horizontally. A "fingering" saltwater front may occur in response to local exploitation of fresh water or along fault lines.

Geophysical 2D and 3D modeling, using synthetic data extracted from direct measurements or borehole information (when available), proved to represent a useful tool for the correct interpretation of resulted electrical resistivity sections, either of apparent resistivities, or real ones.

6. ACKNOWLEDGEMENTS

This work was supported by CNCSIS - UEFISCSU project numbers PNII - IDEI 992/2009 and 998/2009.

REFERENCES

Al-Sayed E.A., El-Quady G., 2007. Evaluation of sea water intrusion using the electrical resistivity and transient electromagnetic survey: case study at Fan of Wadi Feiran, Sinai, Egypt. EGM 2007 International Workshop, Italy.

Bear J., Cheng A.H-D., 2010. Theory and applications of transport in porous media – Modelling Groundwater flow and contaminant transport, volume 23, DOI:10, 1007/978-1-4020-6682-5, Springer.

Chachadi A.G., Ferreira J.P.L., 2005. Assessing aquifer vulnerability to sea-water intrusion using GALDIT method: Part 2- GALDIT indicators description. The 4th Inter-Celtic Colloquium on Hydrology and Management of Water resources, Portugal.

Chiriac M., 1968a. Geological map, 46 (Constanta), scale 1: 200,000. Geological Institute, Bucharest.

Chiriac M., 1968b. Geological map, 50 (Mangalia), scale 1: 200,000. Geological Institute, Bucharest.

Gemail K., Samir A., Oelsner C., Mousa S.E., Ibrahim S., 2004. Study of saltwater intrusion using 1D, 2D and 3D resistivity surveys in the coastal depressions at the eastern part of Matruh area, Egypt. *Near Surface Geophysics*, 2, p 103-109.

Georgescu P., Dinu C., Niculescu V., Ion D., 1993. Some applications of VES to groundwater exploration in the vicinity of Romanian coast of the Black Sea. *Revue Roumaine de Geophysique*, vol. 37, p.113-121.

Georgescu P., Ioane D., Niculescu B.M., Chitea F., 2009. Long-time geoelectrical monitoring of groundwater contamination. Case studies from Romania. EAGE 15th European Meeting of Environmental and Engineering Geophysics, Abstracts volume, Dublin.

Georgescu P., Ioane D., Niculescu B.M., Chitea F., 2010. Geoelectrical investigations of marine intrusions on the Romanian Black Sea shore. *Geo-Eco-Marina* 16, p.85-92, Bucharest.

Himi M., Stitou J., Rivero L., Salhi A., Tapias J.C., Casas A., 2010. Geophysical surveys for delineating salt water intrusion and fresh water resources in the Oued Laou coastal aquifer. Near Surface - 16th European Meeting of Environmental and Engineering Geophysics, Abstracts volume, Switzerland.

Ioane D., Georgescu P., Chitea F., 2009. Geophysical monitoring of contaminated shallow structures. Study case–Petrobrazi refinery area, Ploiesti, Romania. 71st EAGE Conference–Abstracts volume, Amsterdam.

Kirsch R., 2006. Groundwater Geophysics: A Tool for Hydrogeology, 493 pp, Springer.

Loke M.H., 2002. Tutorial: 2-D and 3-D electrical imaging surveys, 127 pp.

Mitrofan H., 1983. Noi informatii asupra hidrogeologiei zonei lacului Techirghiol, furnizate de masuratori electrometrice si termometrice(New geoelectric and geothermic data on the Lake Techirghiol hydrogeology) . *Hidrotehnica*, vol. 28, p. 161-192.

Nguyen F., Kemna A., Antonsson A., Engesgaard P., Kuras O., Ogilvy R., Gisbert J., Jorreto S., Pulido-Bosch A., 2009. Characterization of seawater intrusion using 2D electrical imaging. *Near Surface Geophysics*, vol. 7, p. 377-390.

Nostrand Van R., Cook K., 1966. Interpretation of resistivity data, Geological Survey Professional Paper, US government printing office, Washington, p. 261-271.

Papadopoulou M.P., Karatzas G.P., Koukadaki M.A., 2005. Modeling the saltwater intrusion phenomenon in the industrial zone of Herakleio, Crete. Proceedings of the 9th International Conference on Environmental Science and Technology, Greece.

SATHISH S., ELANGO L., RAJESH R., SARMA V.S., 2011. Application of three dimensional electrical resistivity tomography to identify seawater intrusion. *Earth Science India*, ISSN:0974-8350, vol. 4(I), p 21-28.

SPICHAK V.V., 2007. Modelling of magnetotelluric fields in 3-D media, in Electromagnetic sounding of the Earth's interior (Ed. V.V. Spichak), pp. 388, Elsevier.

WERNER A.D., SIMMONS C. T., 2009. Impact of Sea-Level Rise on Sea Water Intrusion in Coastal Aquifers. *Ground Water* Vol. 47, No. 2, p 197–204.

WU J., XUE Y., LIU P., WANG J., JIANG Q., SHI H., 1993. Sea-Water intrusion in the Coastal Area of Laizhou Bay, China: 2. Sea-Water Instrusion Monitoring. *Ground Water*, vol. 31, no. 5, p 740-745.