GEOELECTRICAL INVESTIGATIONS OF MARINE INTRUSIONS ON THE ROMANIAN BLACK SEA SHORE

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1. Introduction

More than half of the world's population lives in the vicinity of oceanic or marine coastal areas occupying, on a narrow strip of 200 km in width, only 10 % of Earth's surface. For the majority of the population living in coastal areas, the main potable water resource is represented by the fresh underground water, which is in a hydrodynamic equilibrium with the salty sea water. Between the fresh and salt waters there is a transition zone, whose geometry depends on local hydrogeological conditions. Changes in the hydrostatic level generated by natural or anthropic phenomena, such as the uncontrolled exploitation of fresh water, may lead to an invasion of the salt water towards the dry land (a so-called "*marine intrusion*"). These marine intrusions are one of the major sources of contamination for the aquifers located in coastal areas.

The contamination of fresh water with marine, salt water produces significant changes in the aquifers resistivity, thus allowing the application of geoelectrical methods for the detection and monitoring of marine intrusions. In this manner, an electrical resistivity model can always be associated with a hydrogeological model, being determined by means of suitable geoeletrical investigations. Based on this framework and using specific geophysical interpretation methods, one may achieve the hydrogeophysical model of the studied area.

Although an important progress was made in what concerns the modeling/simulation techniques for the resistivity anomalies associated with marine intrusions, some physical-mathematical aspects related to the existence of transition zones, the sensitivity characteristic of the geoelectrical investigations devices and the evaluation of local perturbing conditions influence ("*site effects*") upon the measurements, still are insufficiently studied.

2. Local perturbing effects ("*Site effects*")

The escarpment effect

For the processing and interpretation of vertical electrical sounding (VES) curves recorded in the vicinity of coastal areas, one has to take into consideration the influence of the coastal escarpments / steep cliffs upon the recorded apparent resistivity values, measured using current lines whose length exceeds several times the escarpment's height.

From obvious reasons, nearby the shoreline the VES current lines are, usually, oriented parallel to the escarpment (Fig. 2.1-a). In these conditions, the apparent resistivity corresponding to a certain AB length will be influenced by the height h of the escarpment and the distance d between the observation profile and the escarpment's edge.

Although this phenomenon was observed since 1934, the effect produced by the steep coastal cliffs upon the recorded VES curves (the "*escarpment effect*") has been neglected or, sometimes, estimated in the framework of a geoelectrical model corresponding to a vertical fault, model which have a simple mathematical formulation but poorly describes the reality.

Due to the fact that the "escarpment effect" is obvious in the VES carried out in Vama Veche area, we considered that it is necessary to evaluate it using a two-layers model (Fig. 2.1-b), in which the first layer of thickness h is divided in two parts: **a**) one part corresponding to the dry land, with resistivity ρ_1 and **b**) one part corresponding to the air, with resistivity ρ_2, behaving like an insulating medium.

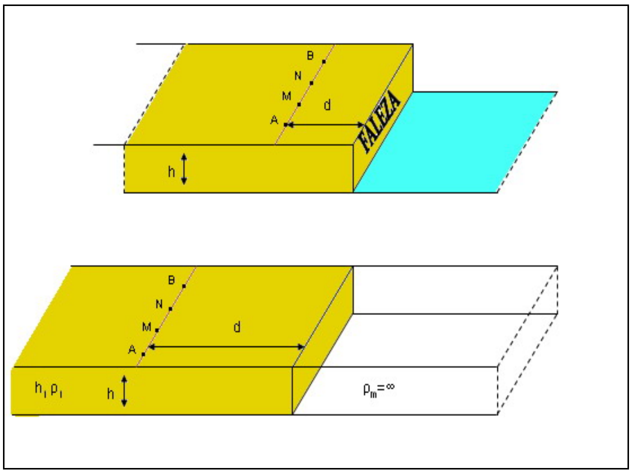


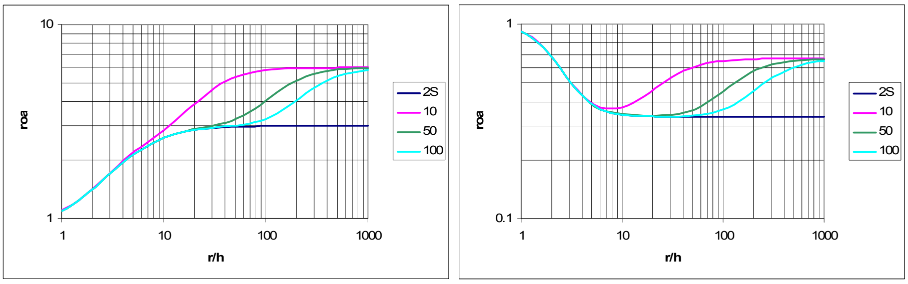
Figure 2.1. *The escarpment effect.*

Under these conditions, using the electrical images method, it can be demonstrated that the apparent resistivity may be computed using the equation:

$$\rho_a / \rho_1 = 1 + \frac{n^3}{\left(n^2 + 4m^2\right)^{3/2}} + 2n^3 \sum_{i=1}^{\infty} k^i \left[\frac{1}{\left(n^2 + 4i^2\right)^{3/2}} + \frac{1}{\left(n^2 + 4m^2 + 4i^2\right)^{3/2}} \right]$$

where: $r = AB/2$, $n = r/h$, $m = d/h$ and $k = \dfrac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$.

Taking into consideration this equation, VES curves were computed for various values of the d/h ratio, in two distinct cases: **a**) basement more resistive than the first layer (Fig. 2.2-a); **b**) basement more conductive than the first layer (Fig. 2.2-b).



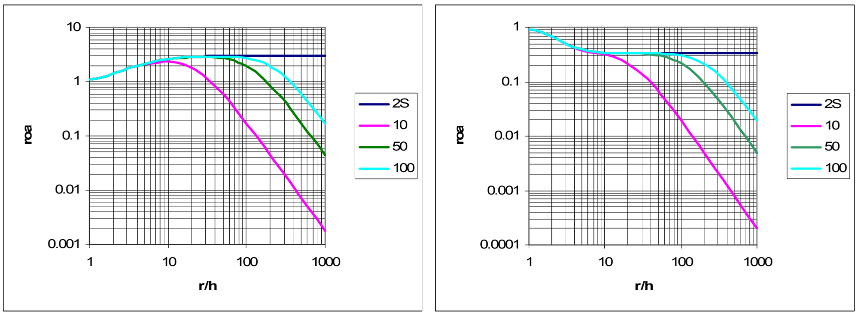
a **b**

Figure 2.2. *Influence of the escarpment upon VES measurements.*
(*2S - reference curve*; *10, 50, 100 -* d/h *ratio values*)

It can be noticed that for large values of the r/h ratio there is a strong difference between the reference VES curve (2S) corresponding to a simple, two-layers model and the other VES curves computed for different values of the d/h ratio. This difference, which we have called "escarpment effect", increases along with the increase of AB distance, no matter if the basement is more conductive or more resistive. By analyzing the presented curves, it results that for an escarpment height of 5 m, the "escarpment effect" corresponding to an AB/2 length of 100 m could be ignored only if the distance between the current line and the escarpment's edge is larger than 200 m.

The conductive layer effect

Due to the actual conditions in the coastal areas, VES measurements are oriented along the shoreline. In this case, the electrical effect of the sea is similar to that of a conductive layer. The computation model is identical to the one used to study the "escarpment effect", the insulating layer being replaced with a perfectly conductive one. The numerical simulation was performed for a basement layer more resistive than the upper layer and, also, for a more conductive basement. The modeling's results are presented in Fig. 2.3-a and Fig. 2.3-b and one may observe that the conductive layer's presence in the neighborhood of the VES leads to considerably lower apparent resistivity values with respect to the ones obtained for the two-layers reference model (2S). This difference between the values corresponding to an arbitrary VES and the ones corresponding to the two-layers reference model will be called "*conductive layer effect*".



a **b**

Figure 2.3. *The conductive layer effect.*
(*2S - reference curve*; *10*, *50*, *100 -* d/h *ratio values*)

In this case, the "conductive layer effect" corresponding to a AB/2 distance of 100 m could be ignored only if the distance between the profile and the escarpment's edge is larger than 200 m.

3. 1-D modeling of the fresh water / salt water transition zone

The interpretation of apparent resistivity measurements carried out using the VES method can be achieved using either a forward modeling or data inversion techniques. Commercial 1-D modeling programs (RES1D - *Geotomo Software*, IPI2WIN - *Geoscan-M Ltd*. etc.) take into consideration a succession of horizontal layers with well-defined resistivities and thicknesses. This is why they are less useful for analyzing and quantifying the effect of the transition zone, where the resistivity is continuously variable with respect to depth.

In order to set up and analyze geoelectrical models corresponding to the marine intrusions, we have elaborated a 1-D modeling software and computed theoretical VES curves for structures which include layers with continuously varying resistivity. The programs were coded in MATLAB programming environment, taking advantage of the advanced set of mathematical, logical, indexing/addressing and graphical functions/instructions which are included in this high-level environment.

Figure 3.1 presents a modeling example in which one may notice a strong difference between the VES curves corresponding to the analyzed situations. If the transition zone is approximated using an average resistivity value, significant errors may arise in the interpretation of VES data.

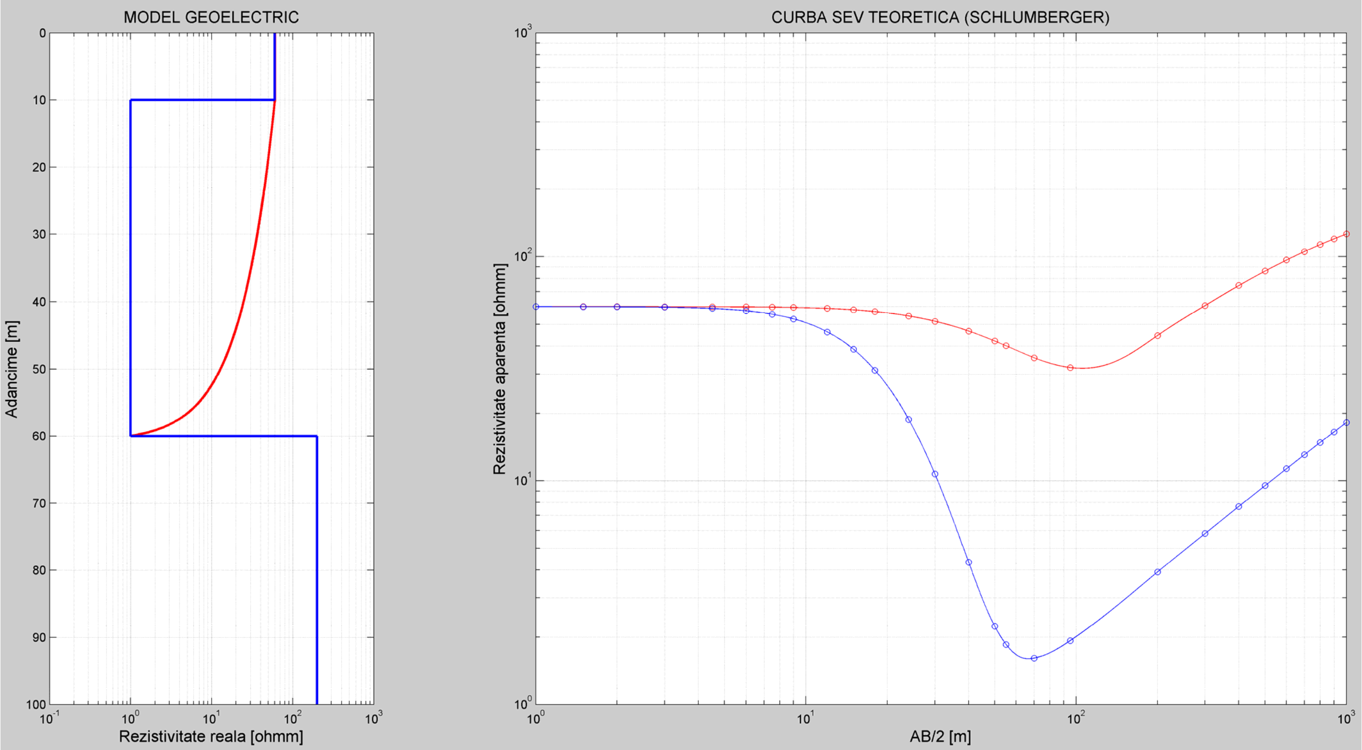


Figure 3.1. *1-D VES modeling of the transition zone.*

4. Case studies: Southern Dobrogea

As a result of a study carried out on shallow-depth wells drilled for the exploitation of drinking water from Sarmatian limestones in Southern Dobrogea, a marine intrusion was detected. The dynamic of this intrusion depends on natural conditions (fault systems, pluvial regime) as well as on the management of local pumping stations.

The main objective of the geoelectrical measurements was to establish the suitable data acquisition and interpretation techniques, in order to identify the dynamic of shallow marine intrusions under the specific tectonic conditions of Southern Dobrogea. In this area, a fault system with NNW-SSE orientation separates into compartments / tectonic blocks the Jurassic-Cretaceous sedimentary complex, which is covered by quasi-horizontal Sarmatian limestones and Pliocene deposits.

The marine intrusion from Costineşti area

The marine intrusion from Costineşti area has been geophysically investigated during a long time span (1991 - 2009), by means of vertical electrical soundings carried out at various intervals, between 4 and 7 years.

The geophysical researches started in September 1991, when it was observed that in the apparent resistivity cross sections, constructed along several observation profiles, resistivity minima occur. These conductive anomalies may be associated with the contamination of fresh water aquifers by marine salt water. The most interesting results were obtained on a VES profile located on the alignment of water exploitation wells (Fig. 4.1), the resistivity minimum in the vicinity of P2 well taking a classical cone of depression shape.

Figure 4.1. *Location of the main geoelectrical profile.*

Based on the measurements carried out in November 1997, September 2005 and June 2009, the apparent resistivity cross sections presented in Fig. 4.2 were constructed. The spatial and temporal evolution of the marine intrusion associated with the resistivity minimum can be easily noticed.

The dynamic of the above mentioned resistivity anomaly during the period 1991-2009, starting with the cone of depression shape and until its total disappearance, suggest that due to a diminishing level of drinking water exploitation the marine salt water contamination has continuously decreased, reaching the acceptable salinity allowed for the water in order to be considered potable.

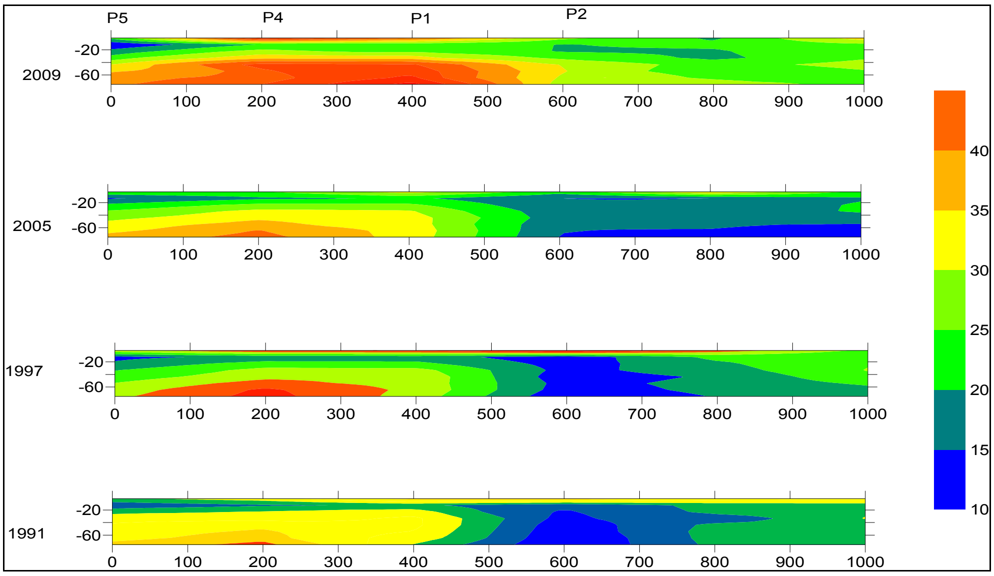


Figure 4.2. *Apparent resistivity cross sections in Costineşti area.*

Vama Veche area

The geoelectrical researches in Vama veche area took into account the information received from the Autonomous County Waters Enterprise (R.A.J.A. - " Regia Autonomă Judeţeană a Apelor") Constanţa, that a water well drilled at about 500 m distance from the shoreline, in the neighborhood of Vama Veche town, encountered a saline aquifer at a depth of 60 m, in Sarmatian limestones. As a result, a second well was drilled at 1400 m North with respect to the location of the first one and at a distance of about 1000 m from the shoreline. In this well, at the same depth, an exploitable aquifer was intercepted, the salinity conforming to normal drinking water quality.

The results of these drillings lead to the hypothesis that a marine intrusion has occurred and its spatial distribution could be determined via adequate geophysical researches. For this purpose, two vertical electrical sounding profiles have been performed, their orientation being normal to the shoreline.

The VES stations location (Fig. 4.3) was chosen in order to achieve the investigation goals, but also taking into consideration the specific field conditions, such as the presence of buildings and agricultural works. It should be mentioned that in the vicinity of the escarpment or the beach, due to the field circumstances, the soundings had to be oriented parallel to the shoreline, even if in such situations the escarpment or conductive layer effects are maximal.

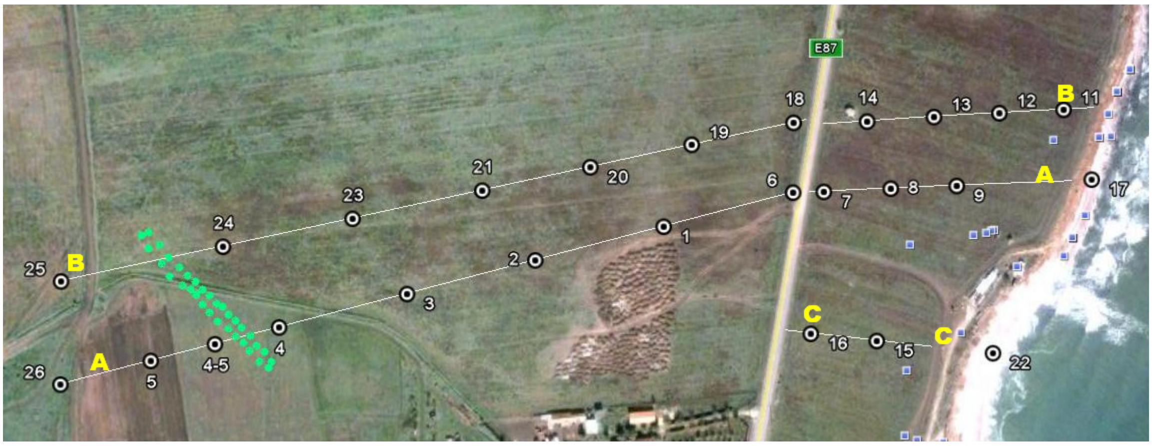


Figure 4.3. *Location of the VES stations.*

A preliminary analysis of the recorded VES curves evidenced an obvious selective distribution of two main curve types. In the East part KHK curves were obtained, while in the West part the curves are of K type. By simply grouping the two VES curve patterns, an approximate zonation into compartments of the studied area became possible, pointing out the presence of a fault (or fault zone) which may separate the Eastern and Western domains.

The existence of a fault zone is emphasized by two apparent resistivity cross sections corresponding to the profiles A (Fig. 4.4) and, respectively, B (Fig. 4.5). The cross sections were initially constructed on the basis of raw measured data (top profiles in Fig. 4.4 and Fig. 4.5), without an adequate processing / analysis. Subsequently, an original "leveling-correction" processing technique was applied, in order to eliminate or reduce the possible errors associated with local measurement conditions ("site effects"). It was observed that the raw and processed cross sections did not present major differences, but the existence of the fault zone and, especially, its position were better indicated in the processed cross sections (bottom profiles in Fig. 4.4 and Fig. 4.5).

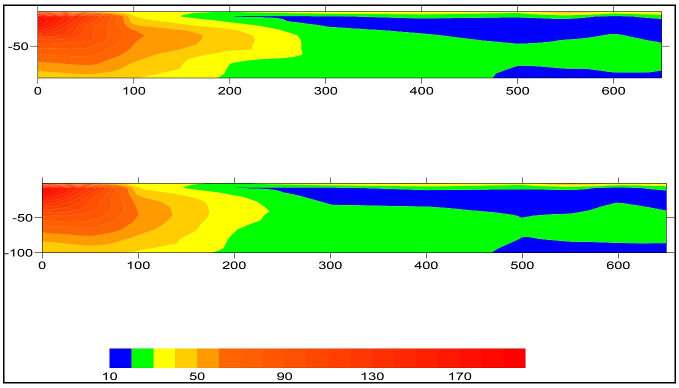


Figure 4.4. *Apparent resistivity cross sections in Vama Veche area* (*Profile A*).

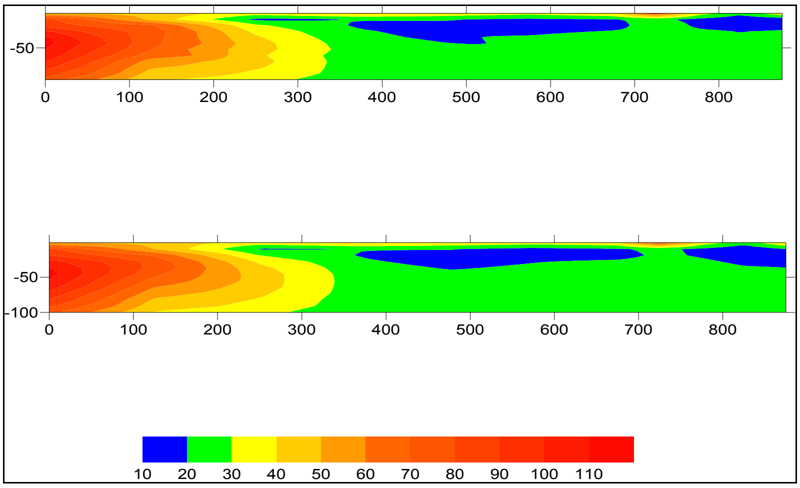


Figure 4.5. *Apparent resistivity cross sections in Vama Veche area* (*Profile B*).

In the first apparent resistivity cross section, along profile A, the resistivity minimum (ρ_A < 20 Ωm) from the Eastern part, corresponding to large current line lengths (AB/2 > 60 m), can be associated with a marine intrusion located deeper than 50 - 60 m. This deep resistivity anomaly does not appear in the cross sections corresponding to profile B. It is possible that the lack of this resistivity minimum is partially due to the "escarpment effect", which was observed at VES stations 11 and 12. The extended resistivity minimum located at shallow depths, in the upper part of the cross sections, is generated by the presence of a shale layer/intercalation which was also identified by means of direct observations at Vama Veche shoreline escarpment.

In this phase of the researches we may conclude that the marine intrusion takes place mainly along a fault zone, with a maximum lateral extension in the Southern compartment and a minor one in the Northern compartment. The origin of this intrusion is entirely natural, because in this area the exploitation of drinking water through deep wells has ceased, due to the diminishing agricultural and animal raising activities of the farms for which the Vama Veche water supply was initially created.

5. Conclusions

The presented case studies demonstrate that in complex conditions the DC electrical prospecting can be successfully used to study the hydrodynamic state of underground water contamination. The natural contamination monitoring may be achieved using exclusively the direct results of VES measurements (apparent resistivity cross sections and maps), in addition to supplementary hydrogeological information obtained via direct measurements in boreholes. Simulating the apparent resistivity anomalies by using novel computer programs for the modeling of media characterized by a continuous variation of the resistivity represents a valuable tool for geoelectrical data interpretation.

References

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