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SUSTAINABLE DEVELOPMENT OF WATER RESOURCES, WATER SUPPLY AND ENVIRONMENTAL SANITATION

The use of transient electro-magnetism method to localize saline water intrusion in Sri Lanka*J. Hoareau, R. Guérin, J. M. Vouillamoz and M. Vithanage, France, India and Sri Lanka*

On the east coast of Sri Lanka, groundwater resources mainly consist in coastal aquifers, which are exploited for both irrigation and domestic purposes. In case of an intensive exploitation, saline water intrusions can occur, which make the water in wells improper for consumption. Considering the future resettlements of internally displaced families in coastal areas, and in order to evaluate the potential of these coastal aquifers (before launching a well implementation program), one need to locate the extent of this saline water intrusion. This information can be obtained by intrusive means such as piezometers monitoring, or non-intrusive means with geophysical methods. Transient Electro Magnetism (TEM) method has been used on different coastal sites on the east coast of Sri Lanka and has given good results for estimating the aquifers geometrical parameters. This first study will be followed by a more complete geophysical survey involving other methods.

Introduction

In numerous coastal aquifers, over-exploitation has led to groundwater quality degradation, mostly by saline water intrusions. Indeed, the increasing demands for groundwater in coastal areas lead to the upconing of brackish groundwater, which makes the water improper for consumption.

This situation can however be controlled, and even prevented, by assessing clearly the characteristics of the aquifer (i.e. its geometrical and hydrodynamic parameters). This information enables then to define the maximal exploitation rate of the aquifer, and to develop a sustainable exploitation policy.

For this, locating the saline water intrusion and measuring its extension is a prior issue. This is often made with intrusive methods such as piezometer monitoring. This method has the advantage to give direct information about the groundwater, but is often limited by the number of piezometers required for a complete study of the aquifer. In that case, non-intrusive geophysical methods represent an interesting alternative.

Indeed, geophysical methods enable measurements at a wider scale than piezometers, and directly from the ground surface. Among these methods, Transient Electro Magnetism (TEM) methods (Nabighian and Macnae, 1991) have been used for different kinds of hydrogeological surveys, such as aquifers delineating or contamination mapping (Hoekstra and Bloom, 1990; Goldman et al., 1991; Danielsen et al., 2003).

Compared to Direct Current (DC) methods, TEM present the main advantage to operate without contact with the soil. This is valuable in coastal areas, where surface dry sand is

a serious limitation for DC surveys as it is very difficult to inject electrical current. Moreover, TEM does not require large electrode arrays as DC methods, and so is less sensitive to lateral heterogeneities in the soils. TEM is also very sensitive to conductive layers, and enables very accurate measurements of their resistivity and the depth of their upper limit. This method is then particularly efficient in coastal areas for delineating saline water intrusions.

This study takes part in a Water and Sanitation project implying, above all, the achievement of a well implementation campaign assisted by geophysical methods. The aim of this paper is to present the contribution of geophysical TEM methods for estimating aquifers geometrical parameters.

Background**Physical and hydrological environment**

This study focuses on the coastal part of the east coast of Sri Lanka (the first kilometers from the sea towards the land). Except for the places where crystalline rocks emerge, coastal areas here are flat and covered with semi-recent coastal sands. The northeast tropical monsoon occurs from November to February and brings an average annual rainfall of 1500mm.

Most of water resources on the east coast of Sri Lanka consist on coastal aquifers. Freshwater occurs in the form of freshwater "lens" floating above denser saline water. The volume of these freshwater lenses expands during the rainy season and contracts during the dry one (Panabokke and Perera, 2005).

Although these aquifers are exploited for irrigation and domestic purposes, their potential is limited because of their small extension and the small amount of effective rainfall

on this part of the country.

Considering the return and resettlements of internally displaced families in this region, an intensification of the exploitation of these aquifers is to be expected (Kodituwakku and Pathirana, 2003). Such intensification will lead to the development (or the worsening) of saline water intrusions and upconing processes, which can prevent the exploitation of these resources. The challenge is then to protect these aquifers in order to avoid salinisation problems, while implementing new boreholes and wells for the new settlers.

This kind of operation requires, among others, the accurate localization of the saline water intrusion. Indeed, its position defines the location and the depth of these new wells. This paper presents how this information can be obtained with TEM methods.

TEM Methods Generalities

Among geophysical methods involved for groundwater exploration and management, electric and electromagnetic methods are the leading ones (Goldman and Neubauer, 1994). These methods enable the measurement of electrical resistivity, which characterizes the capability to prevent current propagation. This parameter is often convenient for hydrogeological studies, because of its strong link with water content, ionic content and clay content (McNeill, 1980). These methods are particularly efficient in areas with saline water intrusion, for the close relation between salinity and measured electrical resistivity.

TEM methods, (also called TDEM for Time Domain Electro-Magnetism) have been used for mining exploration for several decades. They were improved in the 1980's with the development of efficient field equipment and computer interpretation techniques, and are now used for groundwater studies as well.

In terms of field operating, a square loop of electrical wire is placed on the ground, its dimensions chosen to suit the required investigation depth (from 12.5m for shallow investigations to more than 200m for deep ones). The earth is energized by abruptly shutting off the current in the loop, acting as a transmitter. According to Faraday's law, currents are induced in the subsurface, decaying with time and producing a secondary magnetic field that creates a signal at the surface measured by the receiver. This receiver is usually the same loop that the one used previously as transmitter. In terms of timing, 20 minutes are enough to complete a sounding, which makes TEM an easy-to-use and rapid geophysical tool.

However, as for all geophysical methods, results obtained with TEM are not unique and can present equivalence: for one sounding, different interpretations are possible. Selecting the "correct" model requires some knowledge about the studied site.

Material used for this survey

This survey was carried out with a TEM-FAST 48HPC device

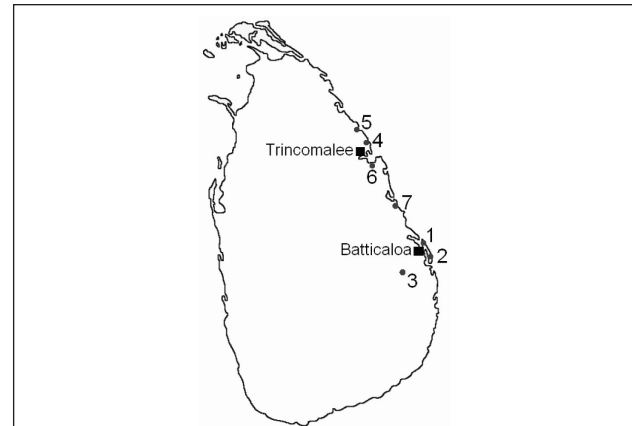


Figure 1. TEM investigated sites

1: Navalady, 2: Kirankulam, 3: Nelikadu, 4: Nilavelly, 5: Jayanagar, 6: Navalady (Muttur), 7: Punniyadi

from Applied Electromagnetic Research (AEMR), using the coincident loop configuration of 25mx25m, and an injection current of 1 to 4A. Successive soundings were carried out from the sea towards the land, perpendicularly to the sea in order to follow the saline water intrusion. When possible, soundings were carried out close to dug wells or piezometers in order to compare water conductivity or geological data with measured resistivity.

Several coastal sites were investigated during this survey (Figure 1), one very carefully (Site n°1, Navalady in Batticaloa DS). Results from this site will be presented in the next section.

Results in Navalady site

Navalady village is located in Batticaloa District (7.741171° , 81.704573°), on a 500m wide strip of land running NNW-SSE between the sea and the lagoon (Figure 2). The area is almost flat, with sand covering the shallow crystalline bedrock (15

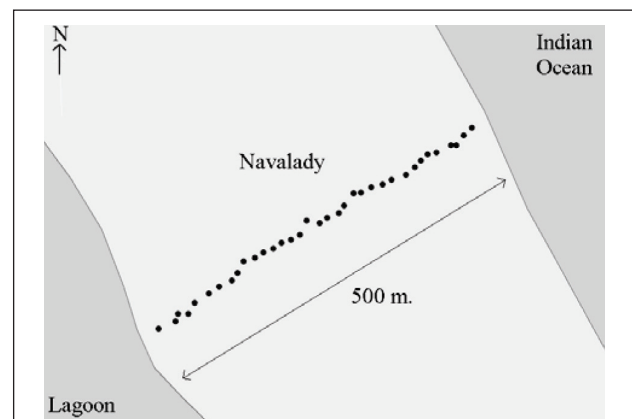


Figure 2. TEM Soundings in Navalady

(Each black dot represents one sounding point)

to 25m deep). This enables the development of unconfined sandy aquifers, which are exploited with shallow wells.

Thirty six soundings have been carried out on this site, from the sea towards the lagoon (Figure 2). In order to follow the saline water intrusion, and to ensure high data quality, the 25mx25m sounding loops were placed at 12.5m intervals along the section. This enables a very accurate characterization of the variations of resistivity from the sea to the lagoon.

All these soundings were interpreted as one-dimensional layered models using TEM-Researcher software (AEMR). Interpretation is based on the inverse modeling approach: a hypothetical layered model (resistivity vs. depth) is generated and the corresponding theoretical response is calculated. The model is then refined using automated iterative processes until the calculated response matches the measured field data. An example of data and interpretation is shown Figure 3.

Measured data (left panel on Figure 3) consists in the decay of the induced magnetic field with time (dB/dt). The model calculated to fit this field data (solid line in the left plot) is represented on the right plot as a distribution of resistivity with depth. The interpretation consists of wet sand from the surface to 2m deep, then a very low resistive layer identified as sand with sea water for 12m thick, and the resistive bedrock at 17m deep.

The thirty six soundings were interpreted and combined to construct a two dimensional cross-section of subsurface resistivity (Figure 4). This section reveals a very low resistive layer (less than 1 Ω .m, in black) corresponding to the saline water intrusion. Above this intrusion stand the freshwater lens (light grey) and a brackish water lens (darker grey). Below stands the resistive bedrock (light colors).

Two parallel resistivity sections were then realized 100m

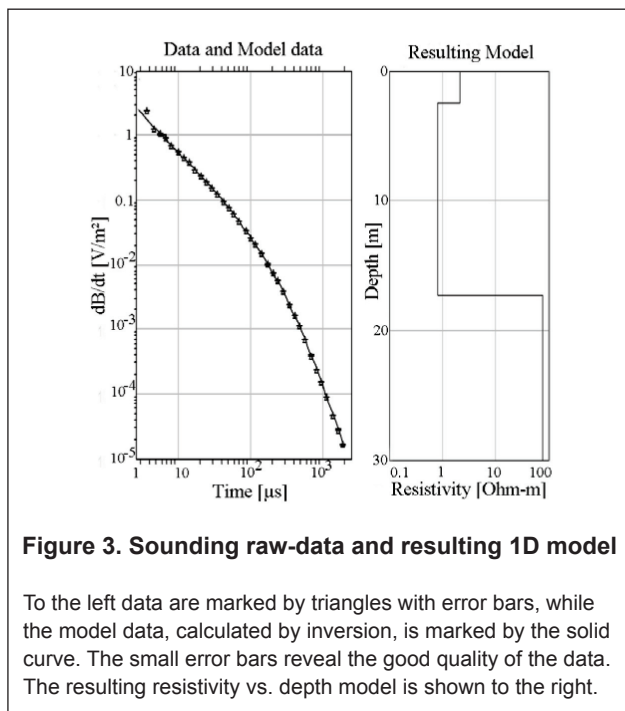


Figure 3. Sounding raw-data and resulting 1D model

To the left data are marked by triangles with error bars, while the model data, calculated by inversion, is marked by the solid curve. The small error bars reveal the good quality of the data. The resulting resistivity vs. depth model is shown to the right.

Table 1. Comparison of geophysical and EC data for three full screened piezometers along the section

	Pz A	Pz E	Pz G
Interpretation of geophysical measurement at a depth corresponding to the bottom of the piezometer	Sea water	Fresh to brackish water	Fresh water
Surface and bottom water conductivity of the piezometer ($\mu\text{S}/\text{cm}$)	580 to 25000	500 to 2800	300 to 450

north and 100m south of this first section in order to check for lateral variations of resistivity. These two sections have given the same results than the first one, meaning resistivity on Navalady site varies only from the sea to the lagoon, and not perpendicularly.

These geophysical results were also confirmed by the use of three full screened piezometers implemented on the section (Pz A, Pz E and Pz G, Figure 4) and reaching a depth of 4 meters. An electrical conductivity (EC) log was made for each piezometer and the measurements were compared to the geophysical results. The comparison is given in Table 1.

These results reveal the good match between geophysical interpretation and water EC data. TEM methods are then well adapted for fresh and saline water delineating in coastal areas. This makes TEM a good tool for freshwater well positioning in such areas.

Outlooks

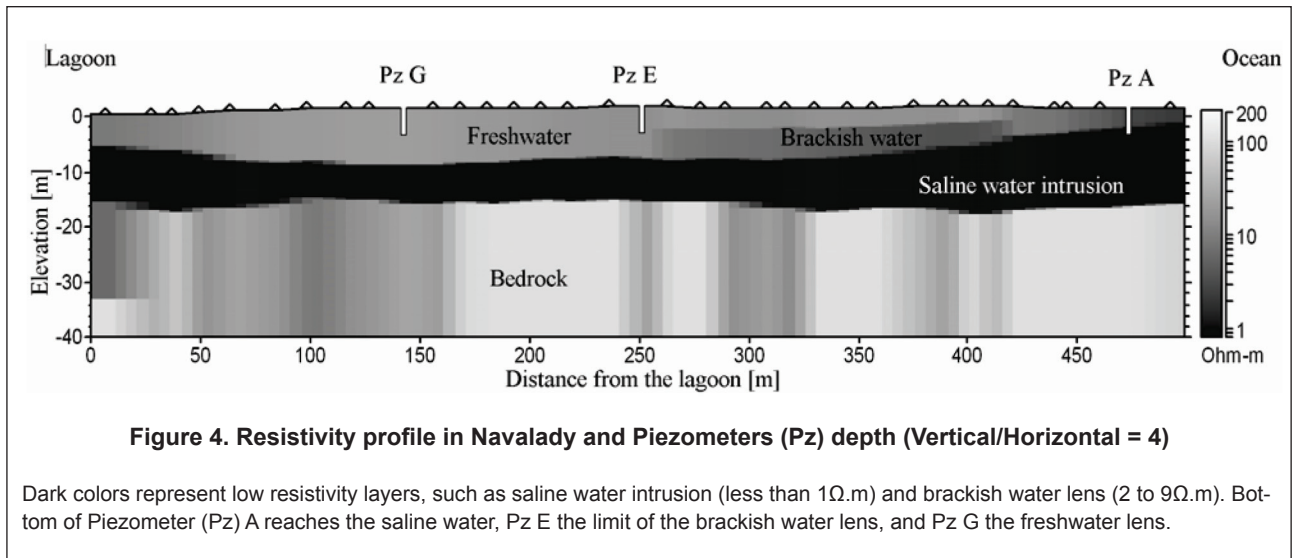
TEM soundings on coastal sites of Sri Lanka have enabled to localize easily and rapidly the saline water intrusion and the exploitable freshwater lens. Obtaining this information usually implies to drill piezometers or to use heavier methods like DC. In this case, it took less than one day to investigate Navalady site.

The next step of this study is the drilling of three full screened deep piezometers (around 20m) in Navalady, close to piezometers A, E and G. This will enable to compare geophysical and hydrological data on the whole log and to reduce the equivalence for TEM interpretation. This will also enable to calibrate Archie's law (Archie, 1942) and to estimate porosity with depth, in order to have a complete description of the aquifer.

Then, a detailed geophysical survey involving TEM, DC and Magnetic Resonance Soundings (a complementary method enabling the direct estimation of water content with depth) will be carried out on different sites of the East and the North coasts. Transfer functions between geophysical and hydrodynamic parameters will be obtained with pumping tests. Then, hydrogeological modeling will be carried out using the geometry and the hydrodynamic parameters given by geophysics.

Acknowledgements

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References

- Archie, G.E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. *Trans. AIME*, 146: 54-62.
- Bear, J.; Cheng, A.H.-D.; Sorek, S.; Ouazar, D.; Herrera, I.; 1999. *Seawater intrusion in coastal aquifers: concepts, methods and practices*. Kluwer, Dordrecht.
- Danielsen, J.E.; Auken, E.; Jørgensen, F.; Søndergaard, V.; Sørensen, K.I.; 2003. The application of the TEM method in hydrogeophysical surveys. *Journal of Applied Geophysics*, 53, 181-198.
- Goldman, M.; Gilad, D.; Ronen, A.; Melloul, A.; 1991. Mapping seawater intrusion into the coastal aquifer of Israel by TDEM method. *Geoexploration*, 28, 153-174.
- Goldman, M.; Neubauer, F.; 1994. Groundwater exploration using integrated geophysical techniques. *Surveys in Geophysics*, 15, 331-361.
- Hoekstra, P.; Bloom, M.W.; 1990. Case histories of TDEM soundings in environmental geophysics. In: *Geotechnical and Environmental Geophysics, 2: Environmental and Groundwater*, Ward S.H. (ed.), *Investigation in Geophysics n°5*, SEG, 1-15.
- Kodituwakku, K.A.W.; Pathirana, S.R.K.; 2003. North Eastern coastal sand aquifer in Trincomalee district, Integrated Food Security Program, 20p.
- McNeill, J.D. 1980. *Electrical Conductivity of Soils and Rocks*. Technical Note TN-5, Geonics Limited, Mississauga, Ontario, Canada, 22p.
- Nabighian, M.N.; Macnae, J.C.; 1991. TDEM prospecting methods. In: *Electromagnetic Methods in Applied Geophysics, 2: Applications*, Nabighian M.N. (ed.), *Investigation in Geophysics n°3*, SEG, 427-520.
- Panabokke, C.; Perera, A.; 2005. *Groundwater resources of Sri Lanka*. Water Resource Board, 29p.

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