Electromagnetic methods used for the characterisation of aquifers in Timor-Leste

Yusen Ley Cooper
CSIRO
Address
Yusen.ley@csiro.au

Tim Munday
CSIRO
Address
Yusen.ley@csiro.au

SUMMARY

This work was done in the frame of a greater project aimed at assessing possible impacts of climate change on the groundwater resources in Timor-Leste.

With the intention to contribute to the understanding of the area's aquifer characteristics and groundwater quality, two lines of time domain EM soundings were acquired in different coastal locations. The acquired data where then inverted and interpreted with in a contextual framework.

The geophysical component within the broader project was brought in to assist with coastal aquifer characterisation and to better understand the aquifers' architecture. The method employed has proven to be an effective way of sounding the ground in Timor-Leste. Some of the results we have produced have contributed to fill-in gaps between well logs and water chemistry and have helped identify the potential presence of a seawater wedge in proximity of some of the city's pumping wells.

Key words: Transient electromagnetics; Groundwater; saltwater intrusion; Timor-Leste; Hydrogeophysics.

INTRODUCTION

A combination of population increase and economic development in Timor-Leste has resulted in greater demands being placed on the country's water resources. In a number of areas, including the capital Dili, these demands are currently being met by extraction of groundwater from 80 m plus deep aquifers. Potable water is pumped from government regulated bores in some urban areas, but also by self-supply from an increasing number of unregulated spear point bores which tap the shallow aquifer systems.

Here we present results from a limited investigation of aquifers in two different areas; Tasitolo and the Comoro River, located near Dili, Timor-Leste's capital (Figure 1). We acquired data employing a terraTEM ground-based time domain electromagnetics (TEM) system, which is quit light, compact and easy to transport. TEM prospecting is a method well suited for investigating the electrical conductivity distribution of the subsurface materials. It particularly maps well good conductive bodies, and therefore is a good technique for identifying the top boundary interface between fresh and saline pore water saturated sediments.

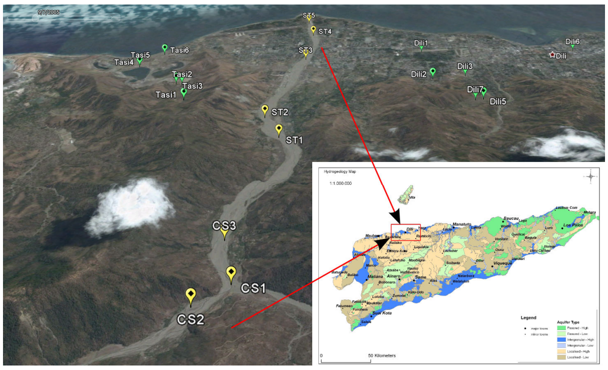

Figure 1 Hydrogeology map of East Timor developed bt Geoscience Australia and Location of soundings on a tilted satellite image on the Comoro River (yellow), Dili city and Tasitolu salt lakes (green) to the right and left of the Comoro river respectively.

METHOD AND RESULTS

The TEM method and instrument specifications

The sounding configuration we employed consisted of a 100x100 m square-loop, single turn transmitter-receiver wire-coil which is laid on the ground. The square-loop is as a transmitter whilst a pulse of current is made to circulate through it and is used as a receiver once the transmitting current has been shut-off. After shut-off, an electromagnetic field is induced into the ground generating a secondary magnetic field. That induced field can be thought of as receding image in the ground of the transmitter loop. An easy to conceive analogy, is that of a "smoke ring", put forward by Nabighian (1979), and describe by Reid and Macnae (1998) like a an image drifted from the transmitter, that moves downwards and outwards, causing the amplitude of the current flow decrees as time passes. This function of current amplitude and time is then quantified using the receiver loop coil, by measuring the decaying induced secondary magnetic field responses of the underlying materials it has passed through. More on the principles of time domain electromagnetic in Grant and West(1965) and Nabighian (Misac N. Nabighian, 1998).

The decay of this secondary magnetic field is called the transient and it depends on the electrical conductivity of the subsurface materials (generally the hosting medium and contained solution) and the porosity of the host rock and/or sediments.

The terraTEM transmitter is a 50% duty cycle bipolar square wave, it has an output capacity of up to 10A and a selectable transmitting frequency that can range from [0.25 to 25] Hz. The turnoff (or ramp-down) time and the on-time current are measured internally, as a function of the loop inductance and the transmitted current. The receiver has a fixed 500 kHz sampling frequency in the A/D converter (Massie, 2010).

We transmitted on average 3.5A of current at 25 Hz through a single turn 1mm solid-wire loop with an area of 1000 m^2. The received signal was stacked the data 256 times and sampled over 30 quasi-logarithmically increasing windows.

Processing and inverted models

The decay of the secondary magnetic field recorded by the receiver coil was measured over logarithmically decaying time gates. Each sounding was then processed and analysed in order to determine which time gates where above the noise level at each sounding location (Munkholm and Auken, 1996). Gates were culled depending on the surrounding anthropogenic noise and the in-situ geological conditions. In Figure 2 the black and red decay curves, acquired over conductive and resistive ground respectively, show how the depth of investigation (penetration) differs for different geological locations and how noise and underlying geology alters the instrument's response. Culled gates are shown as dimmed grey markers.

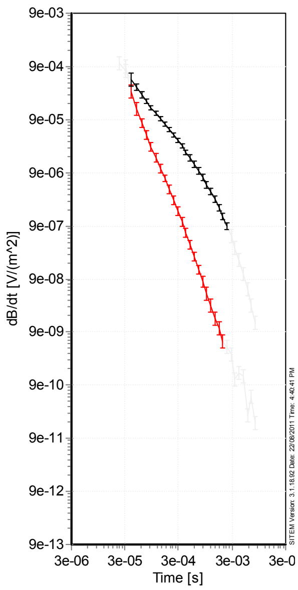

Figure 2 Two contiguous sounding acquired at Tasitolo. Black and Red decay curves, acquired over conductive and resistive ground respectively, shows noticeable different responses. Culled gates (deemed as noisy) are shown as dimmed grey markers.

For every TDEM sounding, a conductivity–depth model can be obtained through an iterative process (inversion) which, in simple terms, results from iteration between predictions and observations and an assessment as to how well the suggested models fit the processed data. Processed data are fed into a computer algorithm (Flemming *et al.*, 1999) along with the geometric characteristics of the loop, the current and other system characteristics. Then a geo-electric structure (model) can be defined by a number of layers, conductivities and thickness for each transient-voltage soundings as a function of time. The workflow we followed is shown in Figure 3.

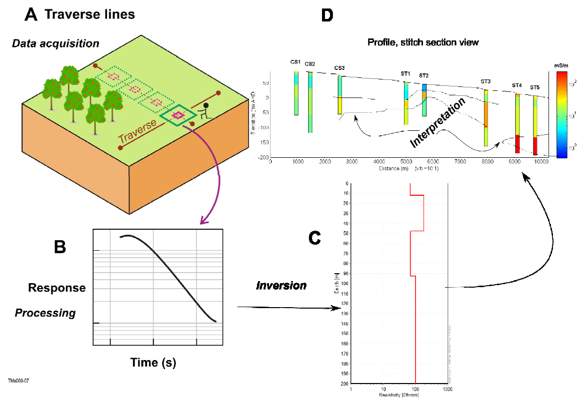

Figure 3 A) Survey set up and data acquisition, B) response analysis and processing C) Iterative process (inversion) between predictions and observations and an assessment as to how well the suggested models fit the data D) Analysis in spatial context in order to get coherent hydro-geological interpretation.

One of the main questions that constantly arise regarding a final model selection from EM inversion, and geophysical interpretation more generally, is the level of "uniqueness" of that selected model in relation to the fitted data. In more recent time there has been a push to quantify this uncertainty (Malinverno, 2002; Minsley, 2011). Form our experience with this data, we attest that an isolated assessment made on a 'numerical best-fit' as a model selection criteria, can often lead to inaccurate interpretations. In Figure 4 six different models, all of which fit the data well within set tolerance, are shown. The Blue model is the numerical 'best fit' (a very sharp thin layer with high conductivity), as presented is quite un-plausible. We favoured the thicker more gently varying conductor, which is much more spatially coherent in the hydro-geological context.

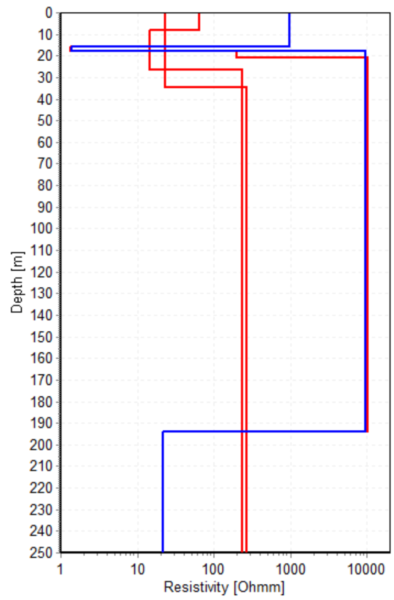

Figure 4 Multiple models for one same sounding. The curve in blue represents the best fit to the data, but is the least plausible in the hydro-geological context. The red curves all fit the data within the set tolerance levels.

Quantification of our model selections has not been incorporated in this work , but we acknowledge how an algorithm as the one suggested in Malinvino (2002) for DC resistivity, would be of great assistance in the assessment of model arising from ground based TEM inversions.

INTERPRETATION AND RESAULTS

Comoro River

Eight soundings were acquired along the Comoro River, which reaches the coast just to the west of the capital. The river, a braided system, carries low flow during the dry season, time of year when the soundings where acquired. Soundings start inland from the coast in the southern most part of the river at station CS2 (which has an elevation of 100m above sea level) and descend to 6m above sea level at station ST5, as can be seen in Figure 5.

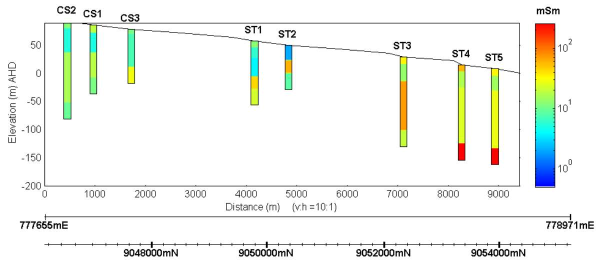

Figure 5 Spaced EM sounding profile following the topography and stream down the Comoro River.

The river channel is actively mined for gravels and sands which provided us with some stratigraphical insight into the near surface alluvial (Figure 6), where we found an inter-bedded sequence of clay and gravel materials transported and eroded from the surrounding highland. These activities are also potential sources of anthropogenic noise for our EM.

Figure 6 Stratigraphical layering at the Comoro River showing inter-bedded gravels and clays eroded from the adjacent highland areas overlying weathered schists and volcanic rocks.

Results from individual soundings can be dull difficult and hard to interpret without the spatial context, therefore we have plotted soundings in a conductivity-depth section, what we consider to be a more amiable way of displaying the data Figure 5. CS2. Our EM soundings seem to reflect an alternation of semi- resistive layers, consistent with a range of conductivities often encountered for those of weathered metamorphic rocks and unconsolidated sandy clay sediments. These results propose a depositional sequence of materials which is to be expected higher upstream. Stations St1, St2 and St3 all have, at 40 to 60 m depths, a more conductive “orange” layer that can be associated with a lining clay which seems to be underlying the previously described inter-bedded sequence of gravel and clay unconsolidated sediments. Finally our interpretation for stations ST4 and ST5 located virtually at sea level and close to the shore line, show a very conductive deep layer 120 m plus, which most probably can be related to a fresh/salt water transition. Interpretation that (although difficult to sustain), could be interchanged by that of an unknown deep large-scale conductive clay rich facies deposit.

Tasitolu Salt Lakes

West of Dili follows a small town named Tasitolu. It is enclosed by two ridges which open to a small bay. Groundwater is close to the surface just inland of the coast and water quality is generally of poor drinking quality. Six soundings were acquired in the Tasitolu area; one of which was taken up on the ridge, another four recorded in the low lying areas and a last sounding acquired adjacent to the coast right on the beach.

Tasitolu is a small example of how a TEM response can distinctively discriminate the response between a resistive and conductive medium. Figure 2 shows two adjacent transient curves taken at Tasitolu Salt lakes. The response of poor conductive material interpreted as fresh rock (in Red) is clearly distinct from that of a high conductive medium, of what we have interpreted as a layer unconsolidated sediments saturated by salt water (black curve). The profile in Figure 7, shows a sounding Tasi1 which reflects a poor conductive layer on the ridge (potentially fresh host rock). Contiguous to it are soundings Tasi2-Tasi6 which we have interpreted to be; a thick layer of unconsolidated sediments saturated by salt water.

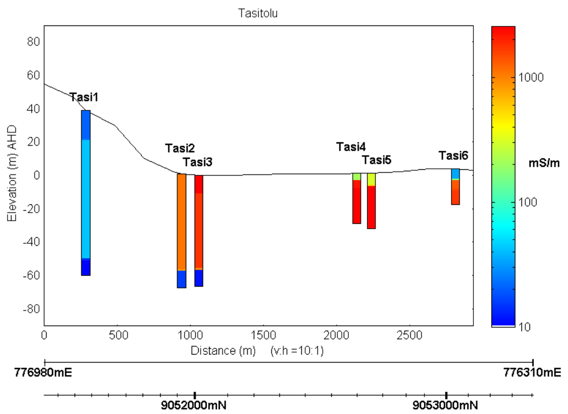

Figure 7 Profile of six soundings with a sharp decent from 50m elevation in station Tasi1, to a quick decline of 1 m above sea level in sounding Tasi2.

Discussion

Isolated interpretation of individual inverted soundings, based exclusively on a numerical ‘best fits’ of the data can produce misleading interpretations of data. The better interpretation EM can be achieved by calculating the degree of uncertainty of the multiple parameters of the thousands of models that could fit the data with a probabilistic approach and by constraining models with auxiliary information that is geologically and spatially coherent, as has been suggested by Minsley (2011) for frequency domain AEM, and by Malinverno (2002) For DC resistivity. We are working on a model assessment algorithm for ground based TDEM which we believe can be of great use in reducing model parameter uncertainty, intrinsic to the pure ambiguity of the inversion problem.

CONCLUSIONS

Coverage with a limited number of soundings can only produce coarse snippets of the underlying earth materials. Nevertheless we have demonstrated the potential ability to map the extent of clay lining barriers in the different geological environments in Timor-Leste and we have identified what seems to be the transition from freshwater-saturated sediments to saline pore water saturated sediments.

The findings presented in this study have contributed to better understand the composition of the coastal aquifers in the vicinity of Timor-Leste's capital Dili, and show how hydro-geophysical methods are an efficient way of gaining and understanding of the subsurface and are an effective way of assisting the construction of a conceptual construction of the a hydrological model.

ACKNOWLEDGMENTS

This work is part of a greater project entitled "Assessment on Climate Change Impacts on Groundwater Resources in Timor-Leste". We would like to acknowledge Geoscience Australia for its commitment and lead on the project the main funding body; the Department of Climate Change and Energy Efficiency (DCCEE), the Government of Timor–Leste's National Directorate for Water Resource Management (DNGRA) and the helping hands of people from Timor.

REFERENCES

Flemming, E., et al. (1999), Inversion of band-limited TEM responses, Geophysical Prospecting, 47, 551-564.

Grant, F. S., and G. F. West (1965), Interpretation Theory in Applied Geophysics, Mc Graw-Hill.

Malinverno, A. (2002), Parsimonious Bayesian Markov chain Monte Carlo inversion in a nonlinear geophysical problem, Geophysical Journal International, 151, 675–688.

Massie, D. (2010), terraTEM operation Manual edited by M. Geoscope.

Minsley, B. J. (2011), A trans-dimensional Bayesian Markov chain Monte Carlo algorithm for model assessment using frequency-domain electromagnetic data
Geophysical Journal International.

Munkholm, M. S., and E. Auken (1996), Electromagnetic Noise Contamination on Transient Electromagnetic Soundings in Culturally Disturbed Environments, Journal of Environmental and Engineering Geophysics, 1(2), 119-127.

Nabighian, M. N. (1979), Quasi-static transient response of a conducting half-space - An approximate representation, Geophysics, 44(10), 17O10-1705.

Nabighian, M. N. (1998), Electromagnetic Methods in Applied Geophyics, SEG.

Reid, J. E., and J. C. Macnae (1998), Comments on the electromagnetic "smoke ring" concept, Geophysics, 63(6), 1908-1913.