

Groundwater Potentiality Assessment Using Multidisciplinary Approach of Imerintsiatosika Basin, Highlands of Madagascar

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ABSTRACT: Hydrogeological study in basement rocks remains hard due to their heterogeneity. In this study, we propose to evaluate the groundwater potentiality of a sub-watershed in Imerintsiatosika basin constituted by Precambrian crystalline bedrock. ASTER and Landsat-8 images were used to manually and automatically extract lineaments from the study area. These results were then used as references for geophysical surveys using the SEV and the electric panel to detect and characterize aquifers. Physicochemical parameters analysis and transmissivity assessment of these aquifers were carried out to emphasize results from the above mentioned methods. We found that the study area has a single aquifer layer consisting of weathered and fracture aquifers. Potential groundwater zones are ankartrite formation and fractured zones. The obtained results also showed that methods used are complementary. They were able to meet the expectation of this study

KEYWORDS: Imerintsiatosika, groundwater, potentiality, remote sensing, GIS, electrical method, hydrogeology, hydrochemistry, hydrodynamics.

I. INTRODUCTION

The two thirds of the Island of Madagascar consist of Precambrian crystalline basement implying that groundwater resources are mainly from basement aquifers. These aquifers are complex and heterogeneous however, they may hold an important amount of groundwater.

Previous works have shown the presence of aquifers in the Imerintsiatosika basin. In this paper, one of Imerintsiatosika sub-watershed is taken to highlight its basement aquifer functioning. Indeed, we chose Imerintsiatosika basin for two reasons: no thorough hydrogeological study has been carried out in this region, and the second is the dependence of economical development of the municipality on water supply because the main economical activity in the region is agriculture. We used a multidisciplinary approach which consists of remote sensing and geographic information system (GIS), physico-chemical parameters analysis, hydrodynamic parameters study, and geophysics.

We found that the area is characterized by one layer aquifer of weathered and fractured rock aquifers.

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II. RELATED WORK

The basement aquifer of the Malagasy Highlands has become a subject of growing interests for Madagascar due to the decay of available rainfall feeding not only the agriculture but also the dams for drinking water supply. One of the very common sites is the Mahitsy watershed which is in the right bank of the Ikopa River (the largest river in the Antananarivo region), and in which the Ambohitrakoho sub-watershed is included. This sub-watershed was particularly chosen by many authors because: (1) its weathered formation is different from western African crystalline basement [1], (2) it was equipped with good hydrometric network [2] and (3) it seemed to be representative of the lowland system of the region. Ambohitrakoho aquifer system is composed by two layers ([1]; [2]; [3]; [4]; [5]). The upper layer consists of unconfined weathered aquifer. Whereas, the lower part is a semi-confined aquifer made up by fractured rocks. A semi-permeable clay layer of about 2 m thickness separates these two layers [5] which interact to each other [3]. However, [4] tested the representativeness of the Ambohitrakoho sub-watershed within the Mahitsy Basin and found that different hydrogeological areas were identified. Their results suggest that the Ambohitrakoho sub-watershed cannot be considered as representative of the whole basin of Mahitsy. Therefore, it cannot be considered as representative of the Madagascar high plateau aquifers as well.

Study site

The study area is a sub-watershed in the Municipality of Imerintsiasosika which belongs to the Highlands of Madagascar. It is in the west of Antananarivo agglomeration, in the Itasy Region (Fig 1). For the last two decades, the municipality has experienced an important population growth from 33262 in 2001 to 53698 in 2013 [6]. There is therefore an increase in water demand, not only for drinking purpose but also for the livestock and agricultures. The climate of the area consists of a high altitude tropical climate with an average annual rainfall of 1108 mm (Service météorologique Ampandrianomby).

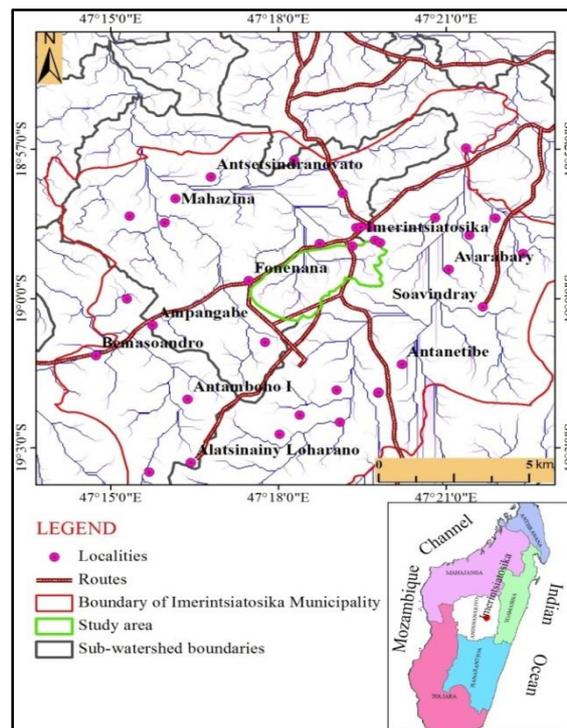


Fig 1: Location map of the study area

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The Imerintsiosika watershed is on the left bank of the Ikopa River (see Fig 1). The area is geomorphologically formed by low hills and flat areas accommodated into paddy fields. Its geology consists of Cambrian crystalline basement of Antananarivo domain [7]. The basement is mainly composed of granitoid migmatites, migmatitic granites, migmatites and gneisses [8]. The basement is partially covered by the Ankaratra volcanic flow in the southern part of the municipality, and also, covered by alluvial deposits and laterites (Fig 2).

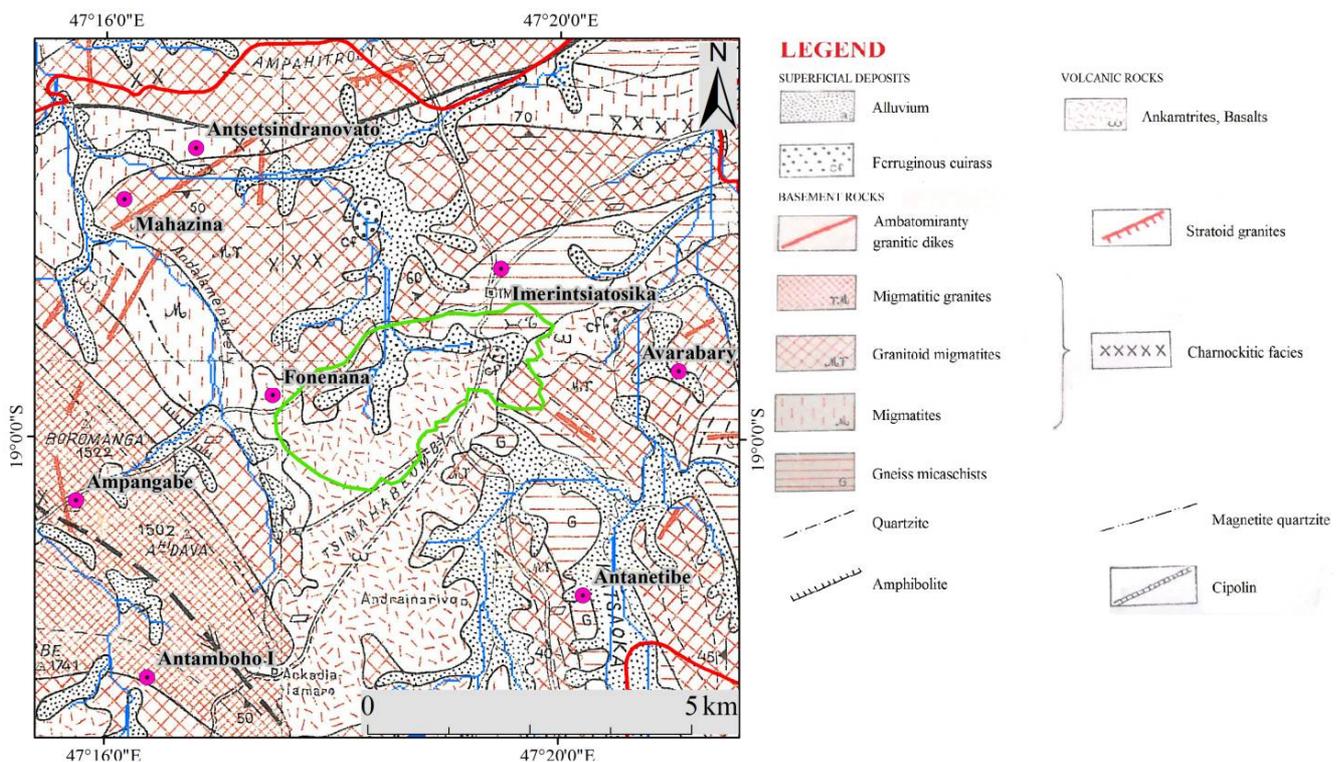


Fig 2: Geological map of the study area (Service géologique d' Ampandrianomby)

Methods

We used different approaches including remote sensing and GIS, hydrochemistry, hydrodynamics and geophysics for this study, in order to have more information about the aquifer systems of the area.

First, we extracted lineaments both automatically from Landsat-8 images (pan sharpened band 4) using PCI Geomatica [9] and manually from digital elevation model images of the area of study. Lineaments play an important role in hydrogeology given that in crystalline basement; they indicate not only the groundwater occurrence but also the direction of the flow [10].

In addition, we conducted an inventory of 18 wells (Fig 3) in order to analyze some physico-chemical parameters such as temperature, pH, and conductivity over the area. These parameters were measured on site with the Combo pH & EC multiparameter (Hanna Instruments). We also performed a pumping test at well W9 (Fig 3). The goal of this pumping is to determine the transmissivity of the aquifers.

Finally, geophysical surveys were carried out to detect and characterize aquifers. Aquifers and host rocks present a net contrast of resistivity. Thus, electrical method is more suitable to highlight our target. We particularly chose the vertical electrical sounding (using Schlumberger array) and electrical resistivity tomography (ERT using Wenner array)

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techniques to characterize the aquifer geometry, due to their manipulation rapidity and simplicity. Data were collected using SYSCAL R1 of IRIS Instruments.

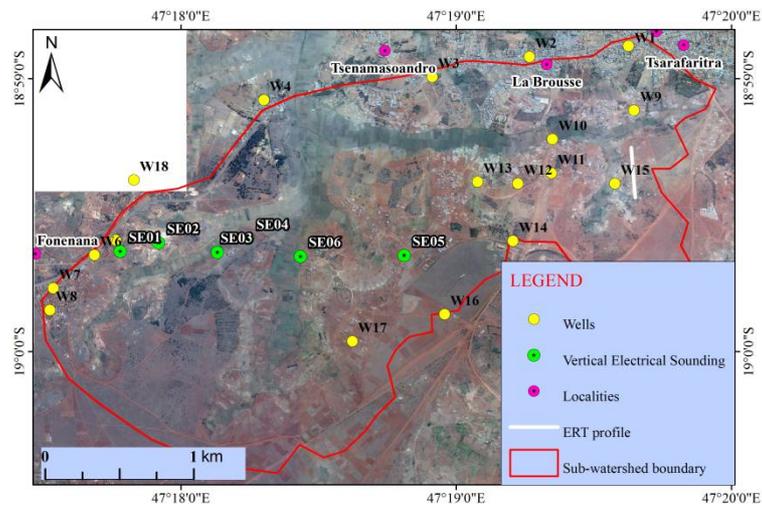


Fig 3: Locations of wells, vertical electrical sounding and ERT line on Google Earth image.

The Fig 3 above shows the location of conducted measurements.

III. RESULTS AND DISCUSSION

Remote sensing and GIS

The Fig 4 displays the map of extracted lineaments from Landsat-8 and DEM images all over the Municipality of Imerintsiatosika.

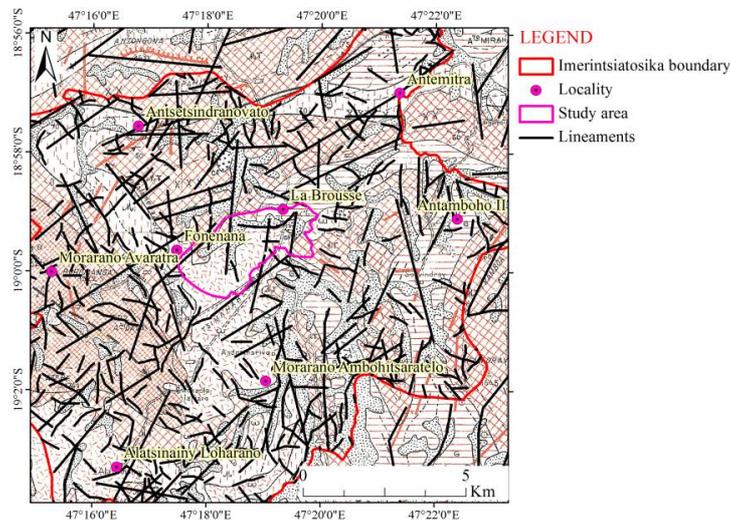


Fig 4: Lineaments map

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The statistical analysis of the lineaments (Fig 5) shows that the main strike directions are Northwest-Southeast, Northeast- Southwest and North-South. The Northeast- Southwest direction corresponds to the ancient fractures detected northwest of Antananarivo, in the right bank of the Ikopa River [11]. The North-South direction, on the other hand, should be the results of tectonic phases during the late tertiary era [11]. [11] also highlighted the presence of a recent tectonic in the high plateau of Madagascar characterized by a North-South distension over the northwest and south of Antananarivo. This could explain the result East-West direction fractures displayed in the rose diagram (Fig 5).

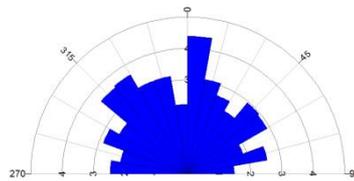


Fig 5: Rose diagrams of extracted lineaments.

Physico-chemical parameters analysis

In May 2017, during dry season, 18 wells were inventoried within the area of study. The water temperatures within the wells vary between 19.8 °C and 23.1 °C with an average value of 21.3 °C. These temperatures are around the external temperature during the month of May (around 22 °C during the day). Figure 4 shows the spatial distribution of water pH and conductivity.

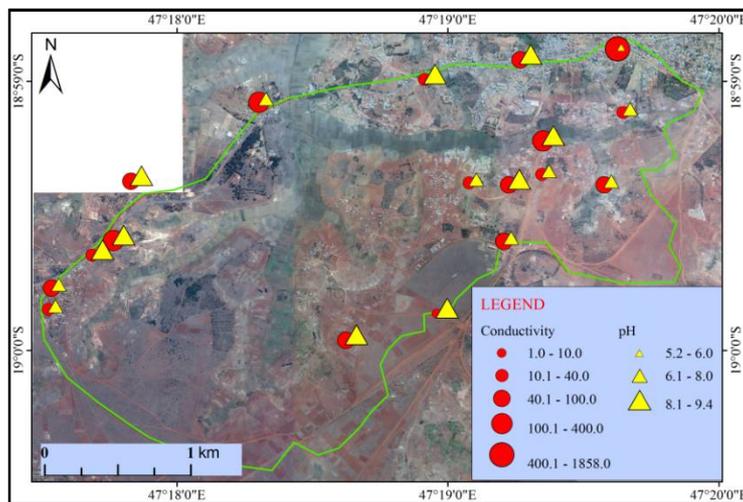


Figure 6: Spatial distribution of pH and conductivity ($\mu\text{S}/\text{cm}$) values

According to this spatial distribution of these values, pH and electrical conductivity of the groundwater show heterogeneity among the aquifers. The well W1 (Fig 3) has exceptionally high value of water conductivity with low value of pH. This high value could be due to anthropogenic pollutant which has already reached the aquifer.

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Hydrodynamic parameters

During the well inventory, we also collected static water level data. The levels range from 4.4 to 17.1 m. Well W15 (Fig 3) is the shallowest level and well W5 (Fig 3) is the deepest. These data were then gridded in order to map the static water level over the area as shown by the piezometric map in Fig 7.

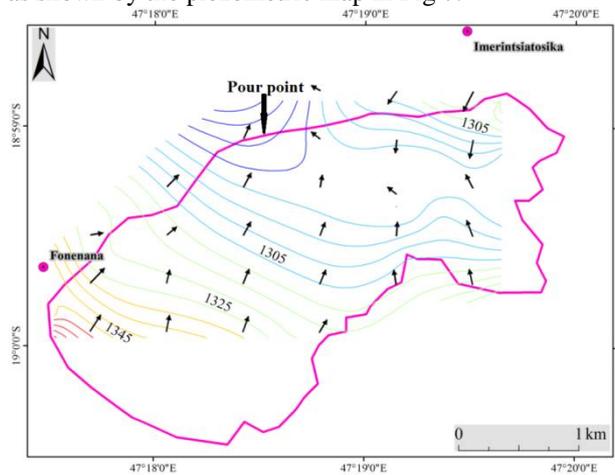


Fig 7: Piezometric head (altitude in meters) and groundwater flow map.

The piezometric map allows us to determine the groundwater flow. The Fig 7 shows that groundwater mostly flows northward and joins the outlet point of the sub-watershed. This suggests that the groundwater is drained by the local streams during dry season. Note that the main direction of extracted lineaments in the area of study is North-South, implying that the groundwater flows alongside the fractures and fissured zones.

Moreover, a pumping test was conducted at well W9 (47°19'38.80"E, 18°59'7.00"S). Its depth is 9.5 m with 1 m of diameter and the static water level is at 8.4 m. We carried out two types of test such as step-drawdown and recovery tests. Figure 6 shows the curve obtained during the test.

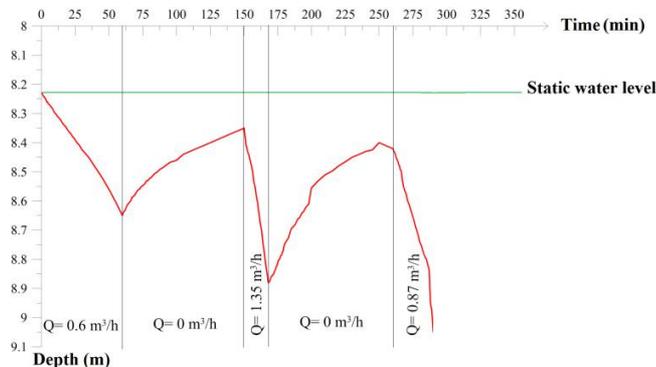


Fig 8: Drawdown curve

As we are dealing with a 1 m diameter well, approaches used to determine the hydrodynamic parameters from a borehole, for example the Theis solution [12], could not be applied here. In the borehole case, the diameter is negligible

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thus the water stored in the borehole at the beginning of the pumping is not taken into account in the approaches, which is not the case for large diameter wells.

The method described in [13] was chosen to evaluate the flow rate of the water table.

$$Q_{aq} = \frac{s - s_0}{\Delta t} \times S_{well}$$

Q_{aq} : aquifer discharge (m^3/h)

s : final drawdown in the dug well (m)

s_0 : initial drawdown in the dug well (m)

Δt : relaxation time (time of ascent in h)

S_{well} : surface of the water body in the dug well (m^2)

For the first ascent, we have $Q_{aq} = 0.157 m^3/h$

For the second ascent, we have $Q_{aq} = 0.251 m^3/h$

The specific capacity from these two values is given by

$$Q_s = Q_{aq}/s = 0.523 m^2/h$$

We then deduce the transmissivity T by using Logans formula [14]:

$$T = 1.25 \times Q_s$$

In our case, $T = 1.816 \cdot 10^{-4} m^2/s = 15.69 m^2/day$

Here the value of T is higher than those found by [1] for a regolith aquifer. They found a transmissivity varying between $1 \cdot 10^{-5}$ and $2 \cdot 10^{-5} m^2/s$. This suggests that the studied aquifer here is more high-yielding than those studied by [1] even though they are both composed of regolith.

Geophysical surveys

We carried out six East-West oriented vertical electrical soundings (VES), with AB/2 separation 300 m. The corresponding depth of investigation varies between 1/4 to 1/3 of AB/2 [15]. In addition, an electrical resistivity tomography (ERT) profile was conducted using 64 electrodes with 5 m spacing. In this case, we had 315 m profile length and about 50 m depth of investigation. The localization of these profiles is shown in fig 3.

Vertical electrical soundings (VES)

The Fig 9 displays the VES curves obtained from data measurement.

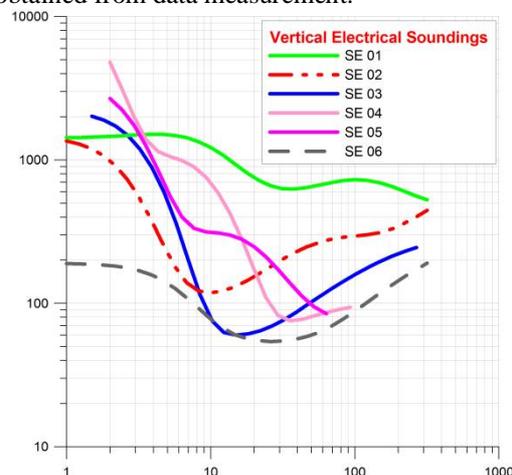


Fig 9: Schlumberger sounding curves (x axis: AB/2 in meter, y axis: apparent resistivity in Ohmmeter)

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The fig 9 shows the obtained VES curves. Among the six VES, the sounding SE 01 looks different from the others and presents the highest resistivity range (500 to 1700 Ω m). This result suggests the absence of an aquifer below the sounding point. The five other profiles show a succession of three layers despite the heterogeneity near the surface. At the surface, a set of resistant layers (resistivity > 900 Ω m except for VES SE 06 which was conducted near the paddy field) covers a conductive layer of resistivity ranging from 40 to 75 Ω m which corresponds to alteration and/or alluvial aquifers. At the bottom, a resistant layer (resistivity > 300 Ω m) matching the basement rocks and serves as a substratum is seen. Figure 8 shows the corresponding lithology for each SEV. The major part of the study area is covered by laterite. Alluvial deposits are observed in the flat and low areas which are accommodated into paddy field. Under this layer is located the weathered rocks which form the aquifer. At the bottom, we located the fresh rock constituted by granitoid migmatite.

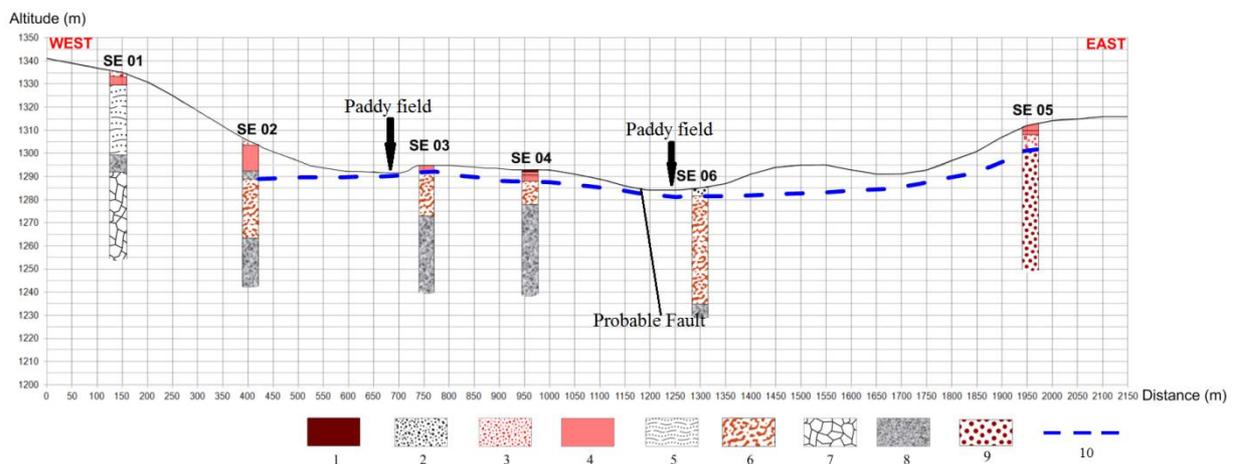


Fig 10: Inverse model of vertical electrical soundings. 1: Ferruginous cuirass; 2: Alluvium; 3: Sandy laterite; 4: Lateritic cover; 5: Weathered granitoid migmatite; 6: Saturated weathered granitoid migmatite; 7: Fissured granitoid migmatite; 8: Granitoid migmatite; 9: weathered ankaratrite; 10: Water level.

The satellite imagery analysis (Fig 4) revealed that faults extending North-South pass through the study area. In Fig 10, we can notice that the difference between the altitudes of the top of substratum in VES SE 04 and VES SE 06 (about 43 m) as well as in VES SE 02 and VES SE 03 (about 15 m) confirm the presence of these faults.

Electrical resistivity tomography (ERT)

Electrical resistivity data were collected along a profile oriented North/South. This profile crosses two different lithologies such as ankaratrites in the northern part and granitoid migmatites in the southern part. The aim was to highlight the aquifer characteristic in each geological formation. The section in Fig 11 shows the result from collected data which were processed using Res2Dinv software developed by [16].

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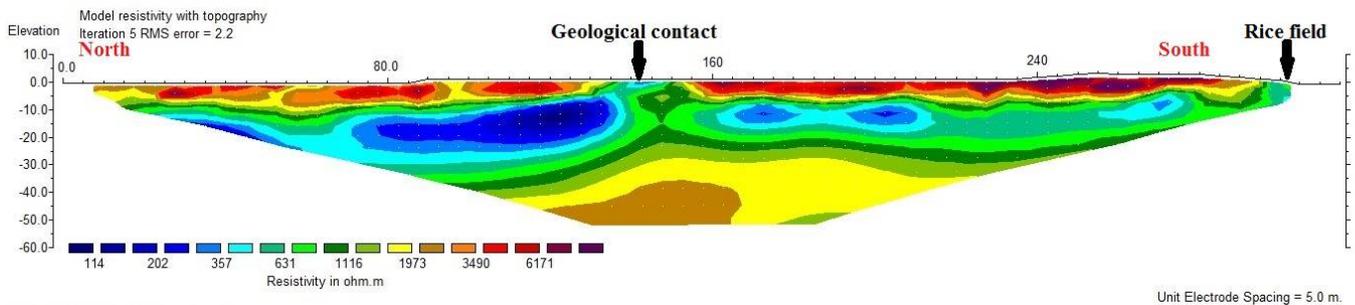


Fig 11: Resistivity section

The resistivity profile can be divided into three geoelectrical formations. First, a very resistant layer with resistivity value greater than 2000 Ωm covers the superficial part of the section along the profile. The average thickness of the layer is about 10 m, interpreted as the lateritic cover. In fact, the high plateau of Antananarivo is known to be covered by lateritic layer up to 40 m thick [11]. Below that, a low resistivity layer (ranging from 100 to 300 Ωm) occupies the central part of the section. This response is separated into northern and southern parts by a vertical higher resistivity response pattern in the middle of the profile ($X= 140$ to 155 m) which might be the contact between the two geological formations. The northern part of the layer is thicker than that of the south. This layer corresponds to weathered basement aquifers. The northern part is characterized by weathered ankaratrites whereas the south by granitoid migmatites which consists of perched aquifer. The third formation, an extensive high resistivity pattern ranging from 1000 to 3000 Ωm is located at the base of the section. It is located at about 30 m depth under the ankaratrite in the north and at about 20 m in the southern. This layer consists of an unweathered basement rock.

The VES gave us the thickness of each layer which constitutes the underground. From these VES results, we could highlight a low resistivity pattern layer which could be an aquifer. This low resistivity pattern layer is also detected by the 2D resistivity method (ERT) with its lateral extension. Both of these two techniques are efficient not only in detecting and characterizing aquifers but also in studying structural geology.

IV. CONCLUSION

The exploitation of groundwater from basement rocks still remains an issue as the occurrence and potentiality of these waters require a massive investigation. The most commonly used methods are the combination of remote sensing, GIS, hydrochemistry and geophysics. In some cases, hydrodynamic study is added to define the sustainability and productivity of the aquifer. This multidisciplinary approach is proven effective in the detection and characterization of aquifers from previous studies conducted in the Mahitsy watershed. The presence and functioning of a bi-layer aquifer system in this basin has been highlighted.

In this study, we adopted this multidisciplinary approach to assess the groundwater potentiality of a sub-watershed of Imerintsiatosika. Remote sensing and GIS revealed the presence of faults extending North-South over the area of study. These results have prompted us to choose the orientation of the conducted geophysical profiles. The geophysical results confirmed the presence of these faults and also highlighted the three types of aquifers existing in the area: the perched aquifer, the alteration aquifer and the fracture aquifer. The perched aquifer is unexploitable because of its low yield and it dries up during dry season. Fractured aquifers on the other hand could be exploitable for an important amount of water table supply whereas, weathered aquifer is suitable for a little community. The analysis of some physico-chemical parameters with geophysics has led to the conclusion that these existing aquifers within the area of study would be a single layer aquifer. These aquifers are also unconfined so they are vulnerable to anthropogenic pollutants. We could notice from the low pH value (5.2) and high conductivity value (1858 $\mu\text{S}/\text{cm}$) that the aquifers at the Imerintsiatosika agglomeration are already polluted.

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