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THEMATIC ISSUE

Sustainable groundwater resources exploration and management in a complex geological setting as part of a humanitarian project (Mahafaly Plateau, Madagascar)

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Abstract

Southwestern Madagascar is a semi-arid region and a hot-spot of global change. On the Mahafaly plateau, people live with quasi-permanent water stress and groundwater, the only available resource, is difficult to exploit due to a complex hydrogeological environment. A methodology (suitable for humanitarian projects; <40 k€) was developed in four phases to assess the sustainable exploitation of the water resource: (A) regional scale exploration, (B) village scale exploration, (C) drilling campaign, and (D) hydro-climatic monitoring. This integrated hydrogeophysical approach involves geophysical measurements (262 TEM-fast soundings, 2588 Slingram measurements, 35 electrical soundings), hydrochemical analyses (112 samples), and a piezometric survey (127 measurements). Two groundwater resources were identified, one deep (below 150 m) and one shallow (<20 m). Hydrochemical results highlighted the vulnerability of both resources: anthropic contamination for the shallower and seawater intrusion for the deeper. Therefore, subsequent geophysical surveys supported the siting of six boreholes and three wells in the shallow aquifer. This methodological approach was successful in this complex geological setting and requires testing at other sites in and outside Madagascar. The study demonstrates that geophysical results should be used in addition to drilling campaigns and to help monitor the water resource. In fact, to prevent over-exploitation, piezometric and meteorological sensors were installed to monitor the water resource. This unique hydro-climatic observatory may help (1) non-governmental organization and local institutions prevent future water shortages and (2) scientists to understand better how global change will affect this region of the world.

Keywords Humanitarian project · Groundwater resources · Mahafaly plateau · Hydrogeophysics · Saline intrusion · Water access

Introduction

Characterizing aquifer systems and identifying groundwater resources are of primary importance for sustainable groundwater management. Disorderly groundwater resource extraction can lead to ecological, economic, and humanitarian disasters (e.g. Leduc et al. 2007; Re et al. 2011; Lee

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et al. 2015). Facing global warming (IPCC 2014), intensive pastoralism, and deforestation (e.g. Lavee et al. 1998), numerous regions around the world are suffering and will continue to undergo intense changes. For these reasons, the scientific community must seek to limit these effects (e.g. Wilkinson 1996; Moustadraf et al. 2008; Dai 2013; Taylor and Scanlon 2013).

Southwestern Madagascar is a global warming hot spot (Dai 2013). Since 2016, El Nino conditions resulted in reduced rainfall. Widespread charcoal production results in deforestation and spread overgrazing which amplifies desertification process. Fifty percent of the population of southern Madagascar (850,000 people) required humanitarian assistance in 2016. The study site is known as, the Ankazomanga basin, the name comes from one of the main villages of the region in the northern part of the Ankazomanga basin. The basin is a depression covered by red sand, overlying a karstified carbonate formation in the middle of the Mahafaly plateau where 14,000 people were living in 2013 (Lazzarini and Ratsimbazafy 2013). Since 2013, 11 villages have been targeted as a humanitarian priority by the Non-Governmental Organization (NGO) Action Against Hunger (AAH). In this basin, rains are weak and scattered and scarce, the ground is highly permeable, and there are no rivers. In this setting, groundwater is the unique source of water supply. An AAH survey (Lazzarini and Ratsimbazafy 2013) reported that 66% of households use less than 15 L/capita/day. According to the same assessment report, many villages do not have perennial water sources; during the dry period, the 20 existing water collecting points are constantly surrounded by crowds of people seeking water. Despite poor water quality the waiting lines are very long, a water "trading center" is installed at the expense of the poor, and small conflicts related to the difficulty of obtaining water are also observed. Women have to walk several kilometers for water and traditional water collecting points are of poor quality. The population has limited coping capacity and drought evolves rapidly into humanitarian crises. Between 2012 and 2016, AAH implemented a 4-year integrated project linked to the alarming rate of food insecurity in the area. The project aimed to prevent chronic malnutrition in children under age 5 and included the construction of water collecting points and installation of new boreholes.

During humanitarian crises, whether for camps or for people in place, NGOs and local institutions look for quick solutions to urgent water needs (Carter 2007). However, in many developing countries, interim solutions become definitive and unsuitable facilities or modes of exploitation can create other problems (e.g. sewage treatment, over-exploitation of the resource). There is often a gap between hydrogeology and humanitarian goals. Groundwater dynamics are slow, droughts or pollution may be related to old environmental conditions or human activities, while humanitarian interventions are often linked to emergencies that require rapid responses (Villholth and Neupane 2011). However, it is often difficult to exploit an underground resource sustainably if the environment is not well known and if historical water records are not available. In this context, it is essential to associate each humanitarian Water Sanitation and Hygiene (WASH) action with an integrated hydrogeological study of the area to promote sustainable groundwater management. Sustainable groundwater management requires an understanding of the following three components: aquifer structure and limits, resource exploitation, and recharge monitoring. This is clearly understood by researchers (e.g. Carter 2007; Lytton and Bolger 2010) but is not always prioritized by local authorities and decision makers (politicians, NGOs, donors). It is therefore necessary that NGOs share the activities they conduct worldwide and communicate related data. This communication will allow humanitarian teams to conduct their activities more efficiently when they arrive at a new site, a priori poorly known (e.g. Jackson et al. 2009; Skokan and Munoz 2010) and to propose sustainable water resource exploitation and management.

The carbonate Mahafaly plateau (3600 km^2), which is poorly documented, is particularly complex from a hydrogeological point of view. The Ankazomanga basin is covered by Quaternary red sand and geological outcrops are scarce (Besairie 1970). Limestone outcrops can be found at the margins of the study area at distances of a few kilometers from the target villages. Moreover, the study area is located on the karstified Mahafaly plateau (Fig. 1) where karst morphologies can be highly developed. In the southern part of the Mahafaly plateau, numerous large sinkholes (20–500 m wide) are present; they have a cauldron shape, as identified by De Saint-Ours (1959) and Karche (1961, 1963). In this setting, traditional hydrogeological tools such as photographic interpretation or field cartography are not very useful for borehole siting. However, geophysics offers a wide range of techniques to improve successful borehole implementation (Vouillamoz et al. 2002). Numerous studies have shown the significant contribution of geophysics in zones of limited geological outcrops (e.g. Edet and Okereke 2002; Lachaal et al. 2011; Descloitres et al. 2013).

This paper presents the main results of an integrated hydrogeophysical approach undertaken in Madagascar since 2013. The paper includes: (1) the methodological approach specifically developed for the study; (2) results at both regional and local scales and the validity of the approach through the drilling campaigns; (3) the first results from the newly established hydro-climatic observatory.

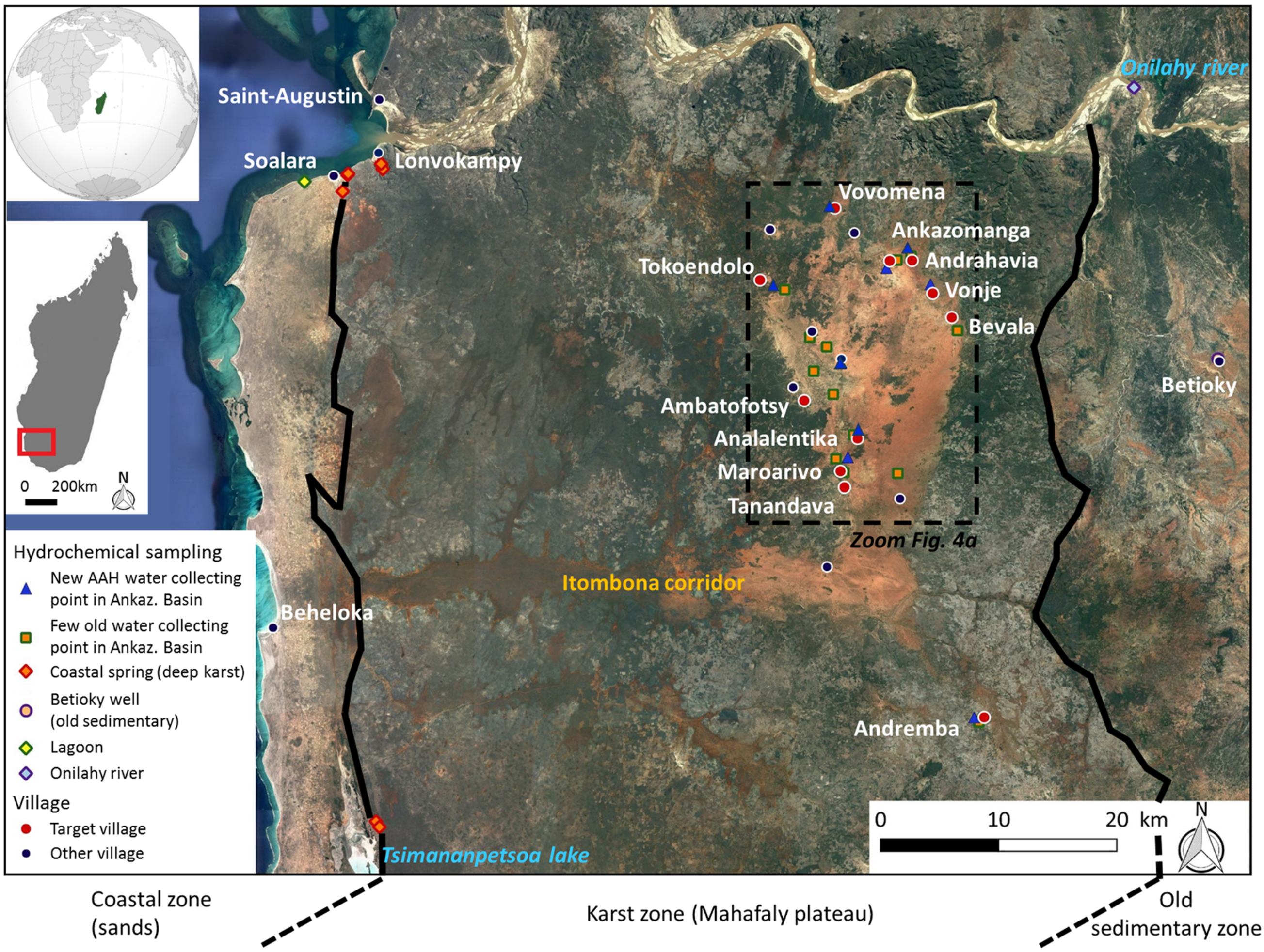

Fig. 1 General setting of the study zone. Additional geological setting is presented in Fig. 3

Background information and site constraints

Geographic and climatic setting

The study area is located 55 km southeast of the city of Toliara and south of the Onilahy River, between 160 and 230 m above sea level. Ankazomanga is quite isolated (a 7–10 h drive from Toliara and 2 to 3 h from Betioky). The study area has no electricity and all material supplies come from Toliara. Logistical constraints were a major challenge during the hydrogeological study.

Southwestern Madagascar is semi-arid; annual rainfall is the lowest in the country (Chaperon et al. 1993; Ferry et al. 1998). Annual rainfall distribution follows a bi-seasonal cycle; the wet season lasts from December to March, and generally reaches maximum precipitation in January. However, precipitation shows very strong spatial and temporal irregularities. Annual precipitation may vary by a factor of five from 1 year to the next (De Haut de Sigy 1965; Guyot 2002). By extrapolation, precipitation should be around 500–600 mm/year at Ankazomanga, with increasing rainfall inland (Guyot 2002). Unfortunately, weather records are not continuous and weather recording stations are located 20–55 km from Ankazomanga.

Hydric stress and humanitarian background

The semi-arid climate causes high water stress for vegetation and populations. The Mahafaly carbonate plateau is a large area that lacks permanent rivers because rainwater infiltrates quickly (because of lapiazed limestones or permeable sands), or rainfall flows towards the bottom of depressions to create temporary ponds. Therefore, runoff from the Ankazomanga basin and Itombona corridor does not reach the ocean. The villages on the Mahafaly plateau are located exclusively in depression areas, such as the Ankazomanga basin or Itombona corridor, where people can access water from temporary ponds or perched aquifers.

In the 1950s, following a severe famine in the Great South of Madagascar, research on water resources intensified and the first hydrogeological map was published at a scale of 1/500,000 (Besairie and Pavlovsky 1950; Aurouze 1957). Numerous local hydrogeological studies have been carried out in the Mahafaly (Aurouze 1957; Karche 1961), which led to drilling campaigns that were not very successful (Guyot 2002). In such a hydrogeological setting, water is more valued than in other areas. A 2013 AAH survey (Lazzarini and Ratsimbazafy 2013) reported that 66% of households use less than 15 L/capita/day, the minimum required quantity is 15 L/capita/day to ensure basic personal and food hygiene (Sphere 2015), while 92% use less than 30 L/capita/day. In the drought season, the humanitarian situation becomes critical and limited access to water results in extremely poor hygiene practices and very high pressure on functioning water collecting points. A vast number of inhabitants have to queue for hours to fill their jericans. As a result, a water market develops in which water transporters sell expensive water and water conflicts arise.

In the Ankazomanga basin 74% of the population expressed dissatisfaction with its water access (Lazzarini and Ratsimbazafy 2013). 28% of the surveyed population lacks water, 26% suffer from poor quality, and 14% report a too great distance to water collecting points. When temporary ponds dry out, women in some villages, such as Vovomeena, must walk 10 km daily to fetch water. In addition to the problem of distance, water is mostly drawn from traditional wells where water quality is poor and promotes water-related diseases. Only 40% of the population of the Ankazomanga basin has access to wells equipped with pumps. During drought periods, malnutrition severely affects the population and 37.5% of children under 5 years of age are undernourished (Lazzarini and Ratsimbazafy 2013).

Methodological approach

A four-stage methodological approach was developed in accordance with the objectives and constraints of the project. The cost was adjusted to the realities of humanitarian projects and was keeping below 40 k€. The Mahafaly plateau was studied at different scales due to the scant available knowledge concerning geology and hydrogeology.

Phase A: regional scale survey

This stage began with standard field geological exploration and analysis of available aerial photos (Fig. 2a). 42 water collecting points were sampled for hydrochemical analyzes in the Ankazomanga basin and its surroundings. Regional scale geophysics was applied to image the general geological structure of the filling of the Ankazomanga basin. The main hydrogeological targets and a conceptual hydrogeological schema were identified. All water collecting points in the Ankazomanga basin were surveyed to produce a piezometric map of the near surface water table.

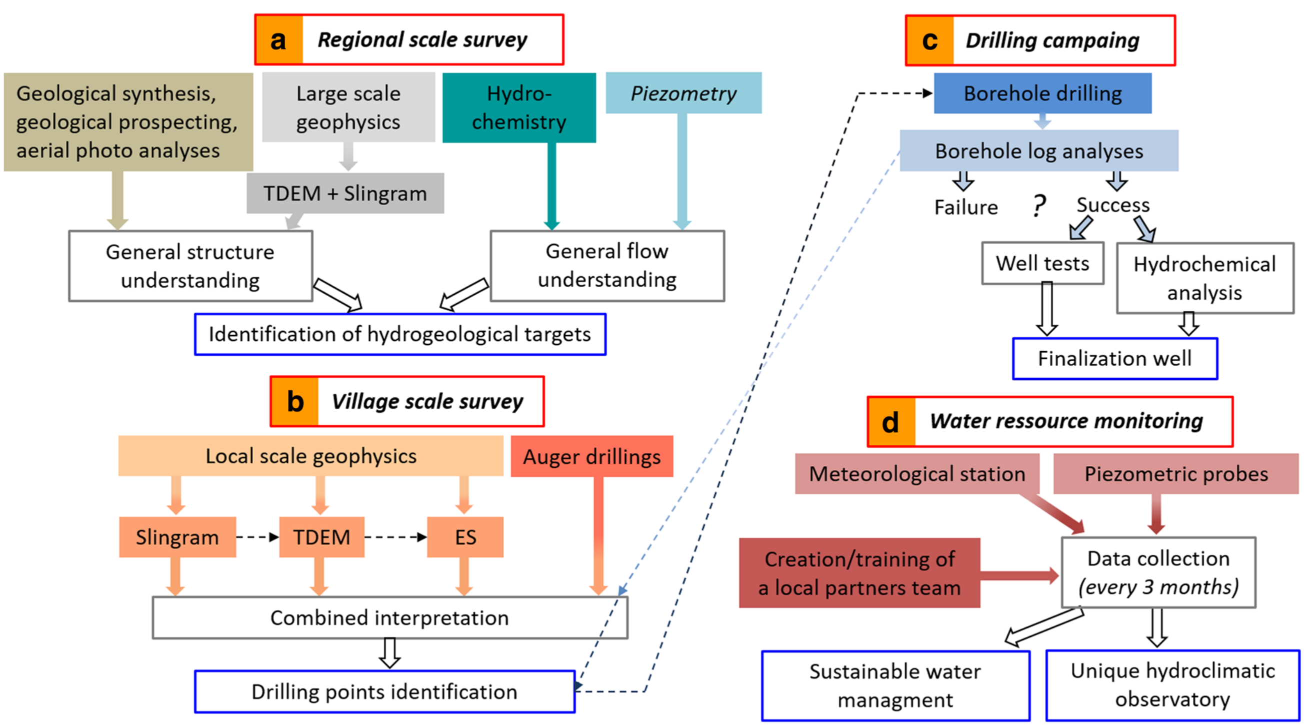

Fig. 2 Methodological approach of the project

Phase B: village scale survey

At the village scale, a multi-method geophysical survey was used to determine the location for drilling water collecting points in 11 target villages. The village scale survey (Fig. 2b) began with a Slingram survey to detect geological heterogeneities at the local scale and to determine the location of Time Domain Electromagnetism (TDEM) profiling. Electrical soundings were conducted near the TDEM surveys to compare results. Auger drillings to a depth of 8 m aided in the interpretation of the first meters of geophysical results.

Phase C: drilling campaign

Due to the lack of geological knowledge, borehole logs provide valuable information for reinterpreting geophysical results and possibly refining borehole positioning (Fig. 2c). Well productivity and hydrochemical quality were tested before the wells were completed. Consequently, the third stage of the project was the drilling campaign, which enabled validation or reinterpretation of results from previous stages.

Phase D: water resource monitoring

Due to the limited geological and hydrogeological knowledge of the study area and considering its extent, it was necessary to study the exploitation and recharge of the water resource using meteorological and piezometric monitoring (Fig. 2d). Considering the remoteness of the study area, maintenance and data collection is done by teamwork with local partners. The sensor network installed constitutes a unique hydro-climatic observatory and it improves the ability of authorities and NGOs to anticipate water stress and associated humanitarian crises due to water stress.

The results presented in the next chapters follow the same stages as the methodological approach (Fig. 2).

Equipment and tools

Geophysical methods

Slingram (EM 34)

The Slingram device used to conduct electromagnetic induction measurements (EMI) (McNeill 1980) was the EM34-3, developed by Geonics (Ontario, Canada). 2588 EMI points were measured with an approximate spacing of 20–30 m between each point. After preliminary testing and taking into account the hydrogeological target, the decision was made to conduct the survey with a spacing of 20 m between coils. This coil spacing provides a theoretical investigation depth of 15 m (McNeill 1986). The measurements were carried out in both horizontal (HD) and vertical dipole (VD). The EM34 was mainly used for village scale exploration so as to detect general structuring and to find a judicious positioning for the TDEM profile.

Time domain electromagnetism (TDEM)

The TEM-Fast 48 HPC device was used; specifications of the system can be found in the TEM-Fast manual (AEMR 2005a). The principles of the method are described by Barsukov et al. (2006). In brief, an electromagnetic signal is sent and then recorded from a cable loop deployed on the ground allow to estimate the rocks resistivity. The TDEM measurements were interpreted using a commercially available 1D inversion software packages. TEM-Researcher is designed for modeling and inversions of large TDEM sounding data sets (AEMR 2005b). TDEM was used in profiling at both the regional and village scale and a total of 262 soundings were done. At the regional scale a single square loop (100 × 100 m) was used. The profiles are sub-perpendicular to the regional faulting direction N10° (André et al. 2005) and had a reach of 15 km long. At the village scale a 50 × 50 m loop was used. The profiles are perpendicular to the general geological structures detected by EM34 and reach no more than 2 km.

Electrical sounding (ES)

The "Geo-Instruments" device developed by CNRS-Garchy (France) was used. 35 electrical soundings were conducted at the same place as or in the vicinity of TDEM soundings to compare the two techniques and to give more robustness to geological data and hydrogeological interpretation. TDEM is very sensitive to electrically conductive targets and ES is more accurate for electrically-resistive targets. TDEM data interpretation is also significantly less ambiguous as compared to the direct current method, and it is less sensitive to lateral heterogeneities than vertical electrical sounding (Goldman et al. 1988; Goldman and Neubauer 1994). The Schlumberger array was used with a maximum spacing of current electrodes of 200 m and maximal injected intensity was 0.3 A. IPI2Win 3.0.1 software was used to invert apparent resistivity (ρ_a) values into geo-electrical models (Bobachev 2002).

Auger drillings

The auger soundings made it possible to (1) investigate under the omnipresent red sand and (2) reach the phreatic water table to provide more points for the piezometric map. Many auger drillings were conducted during the 2 months of geophysical investigation because the near-surface underground is generally soft in the Ankazomanga basin. A hand auger 8 m in length and 10 cm in diameter was used. These hand augers were used for 79 holes with a cumulative length of 280 m and the penetrated horizons were summarily described.

Hydrochemistry

Seven sampling campaigns were carried out between 2013 and 2016 and 112 samples were collected in several water points (wells, sea, river, springs) that can be located in Fig. 1 "Hydrochemical sampling". Major ions and total organic carbon were analyzed to obtain information about geological formations present under the red sand cover and about possible anthropic pollution. The sampling was done at both old and new water collecting points in the Ankazomanga basin. Samplings were carried out beyond the Ankazomanga basin to characterize possible interactions with other water resources in the area. Sampling was also done at karst system outlets near the sea (springs, wells, and sinkholes), in the Onilahy river, and in two wells in the town of Betioky that was dug in Old Sedimentary terrains.

Piezometric survey

Piezometry and GPS survey

The study area is very flat and it has no functional topographical landmark. Differential GPS was used to obtain enough accuracy (less than 10 cm in z) to produce a piezometric map of this huge area from 135 measured water points (wells, traditional wells, and auger drillings). The Trimble GPS R10/TSC3 was used with real time correction by RTX satellite.

Piezometric probes

Ten Mini-Diver automatic piezometric probes, developed by Schlumberger, have been installed as part of this project. These devices can obtain results to a depth of 20 m under water, with an accuracy of 1 cm H_2O and a resolution of 0.4 cm. Two barometric probes (Baro) were installed in Ankazomanga and Maroarivo villages for atmospheric pressure variation compensation. In 2014, three Mini-Divers and two Baro probes were installed in already existing built wells. The remaining seven Mini-Divers were installed in the AAH wells in 2016. The measurement interval is hourly and they can acquire 1030 days of data.

Meteorological station

A BWS200 weather station developed by Campbell Scientific has been installed in the Ankazomanga Basin. The weather station is composed of four sensors that measure wind speed and direction, air relative humidity, air temperature, and rainfall. The chosen time step is 1 h. The station is commercially available with a rechargeable battery connected to a solar panel. Taking into account local security conditions it was decided to create a battery box to reduce theft risk to the solar panel and to facilitate battery replacement. The equipment is connected to a CR200X control unit. The control unit receives a scan from each sensor every minute. The autonomy of the system is 1000 days.

Results and interpretation

Regional scale survey

Geological synthesis and field exploration

The study area is at the heart of the Mahafaly plateau, which is composed of Eocene carbonate formations (Besairie 1946). Contrary to the "limestone" terminology used by André et al. (2005), the term "carbonate formation" is preferred in this document because the plateau is composed of other rock types in addition to limestone. Marl, sandstone with calcareous cement, and poorly consolidated lumachelle can be observed at the margins of the Ankazomanga basin. The Eocene formations are divided into three units (Aurouze 1957):

- E1, 300 m thick, nummulitic limestone, calcareous sandstone, and oolitic limestone,
- E2, 150 m thick, clayey limestone with orbitolinids,
- E3, 150 m thick, marly limestone, oyster marl, and gypsum marl.

Although the geological Map of Besairie (1970) showed the Ankazomanga Basin to be filled exclusively with red sand, Aurouze (1957) found some isolated metric-size blocks of black ferruginous sandstone in the field, which confirms the presence of continental Neogene (N) formation. Our geological survey and our drillings confirmed this second hypothesis. In a region more to the south, Besairie (1946) described the continental Neogene as a discontinuous and heterogeneous formation reaching a maximum thickness of 150 m and composed of:

- Compact ferruginous sandstone,
- Red sandstone with cross-bedded stratifications,
- White to pink clayey sandstone and purple clay,
- Kaolin levels 3 to 4 m thick.

According to Besairie (1946) two terrains can be distinguished surrounding the carbonate terrain of the Mahafaly plateau (Figs. 1, 3). The Old Sedimentary terrains (Cretaceous, Jurassic, and Karoo) crop out to the east and plunge under the Eocene plateau (Fig. 3). The name "Old Sedimentary" is the local term given to these rocks by geologists who have worked in the area 60 years ago. To the west, the coastal strip, composed of Quaternary sand and sandstone, is separated from the Eocene plateau by the Toliara fault. The Quaternary, 6–10 km wide, overlies on Eocene carbonate formations.

Finally, aerial photographs made it possible to identify faults inside the Ankazomanga basin. These faults are oriented approximately N°10 at the Mahafaly scale, as described by André et al. (2005). These observations will aid in the geophysical results interpretation later in this document.

Hydrogeological synthesis and piezometric mapping

Within the Mahafaly plateau two aquifers can be distinguished: (1) a near-surface water resource (< 20 m) within the sedimentary fill in the Ankazomanga depression, and (2) a deeper water resource (> 150 m) within karstified Eocene formations. The majority of water collecting points are traditional wells (Fig. 4b) (the so-called "vovo"), exploiting the near-surface aquifer at a depth of 2–4 m, through open holes in the ground, to which livestock have easy access. Certain wells exceed a depth of 10 m but they are not the most productive. The deepest well of the region reaches 19 m but is dry most of the year. The deep karst aquifer is not exploited due to its depth (more than 150 m). Near the coast, karstification features such as caves and sinkholes (Fig. 4d), or shallow wells make it possible to access the karst resource at the boundary between the coastal strip and the Mahafaly plateau (De Saint-Ours 1959; Karche 1961, 1963). In the South of Mahafaly plateau, Guyot (2002) demonstrated a strong connectivity between these wells or sinkholes and the lagoon. Several coastal discharges (Fig. 4c) are identified south of the Onilahy River (Solara and Lonvokampy). These karst discharges are highly mineralized (1000–5000 µS/cm) even at a distance of more than 1 km from the coast (Antsiliky spring near Lonvokampy). To the south, André et al. (2005) measured higher mineralization (10,000 µS/cm) in the coastal strip. Exokarst features and the presence of cave fish in some wells (Guyot 2002) indicate that the karst system is well developed.

After the rainy season of 2014, an inventory of water collecting points was carried out in the Ankazomanga basin. 127 water collecting points were inventoried (Fig. 4a), but the majority are temporary. The study area is very flat and devoid of geodetic reference. The use of a differential GPS was therefore necessary. The resulting piezometric map (Fig. 4a) shows that the general flow of the near surface aquifer is towards the west, in the same direction as topographic slope. However, when measurement point density is high enough, it can be seen that at the village scale underground flows are more complex. North of Ankazomanga, flows are directed towards the east. This reflects heterogeneity and a complex morphology of the aquifer wall, which can be explained by either: (1) karst morphologies under Ankazomanga basin fill, or (2) geomorphology of sedimentary formations that fill the basin.

Connectivity between the near surface aquifer of Ankazomanga and the deeper karst hydrosystem remains completely unknown, as are the hydrogeological relationships between Eocene carbonate formations and the Old Sedimentary terrains in the east. The hydrogeological boundaries of the aquifers are poorly known and must be clarified to propose sustainable exploitation and management solutions.

Natural tracing Natural tracing made it possible to identify water masses present in the region. Five groups can be distinguished (Fig. 5):

1. The mineralization of the Ankazomanga basin water (old and new) is low [electrical conductivity is less than 300 µS/cm (see Online Appendix)]. The hydrochemi-

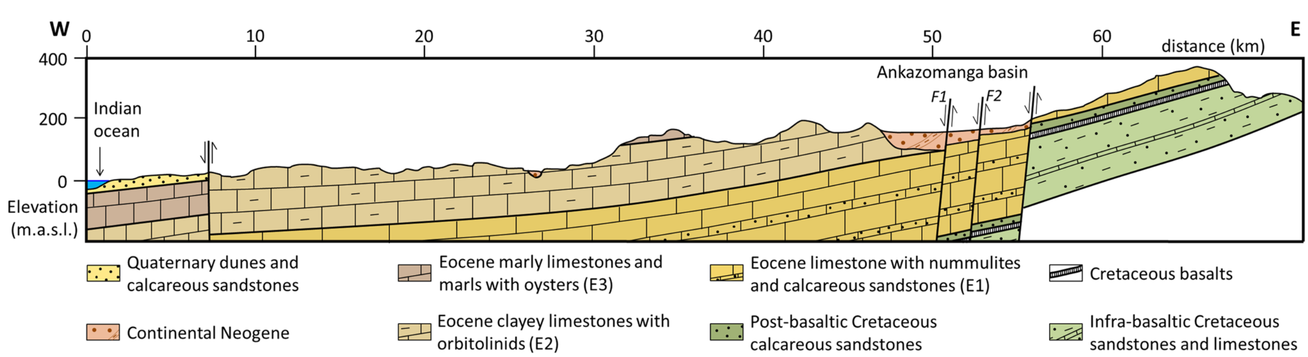

Fig. 3 Simplified geological cross-section of the study area (at latitude 23°47′00″; between Analalentika and Maroarivo villages in Fig. 1) after Aurouze (1957) modified. F_1 and F_2 are the fault identified by geophysics in Fig. 6

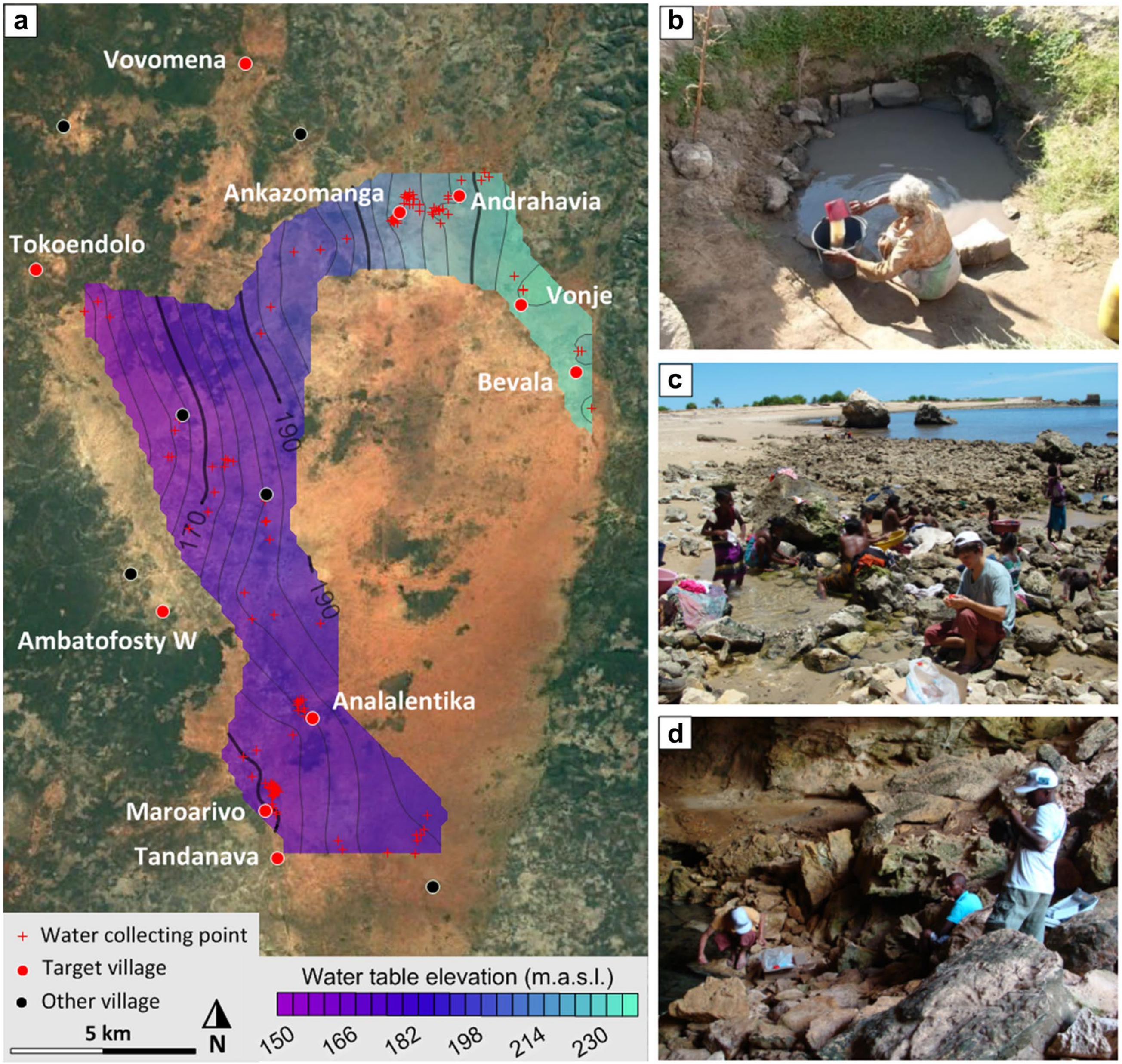

Fig. 4 **a** Piezometric map of the phreatic water table, based on 127 measurements with differential GPS after the 2014 rainy period. **b** Traditional well (so called "vovo") makes it possible to exploit water under tedious and unsanitary conditions. **c** Coastal spring, a natural karst system discharge, near Solara. **d** Hydrochemical sampling in a cave near Tsimanampetsotsa Lake at 8 km from the coast (southwestern of Fig. 1)

cal facies are variable with dominance of bicarbonates, calcium, and sodium. Some waters are affected by anthropic pollution with strong concentrations of NO_3^-, and Cl^-. The chemical variability of these waters reflects the complex and multiple geological facies of Neogene formations. Most Ankazomanga basin waters have Br^-/Cl^- ratios close to seawater, which is probably due to the influence of sea spray.

2. Water from coastal sources, wells, or sinkholes are highly mineralized (electrical conductivity is more than 3000 µS/cm); they reflect hydrochemical characteristics of the deep karst. This strong mineralization of coastal karst waters is consistent with the results of André et al. (2005). The Br^-/Cl^- ratio (Fig. 5b), commonly used in coastal hydrogeology (e.g. Alcalá and Custodio 2008; Katz et al. 2011) confirms that this salinization is due to sea water intrusion, despite the distance to the coast which may be as much as 9 km.
3. Obviously, lagoon water is highly mineralized. Figure 5 shows that this water does not have the exact composi-

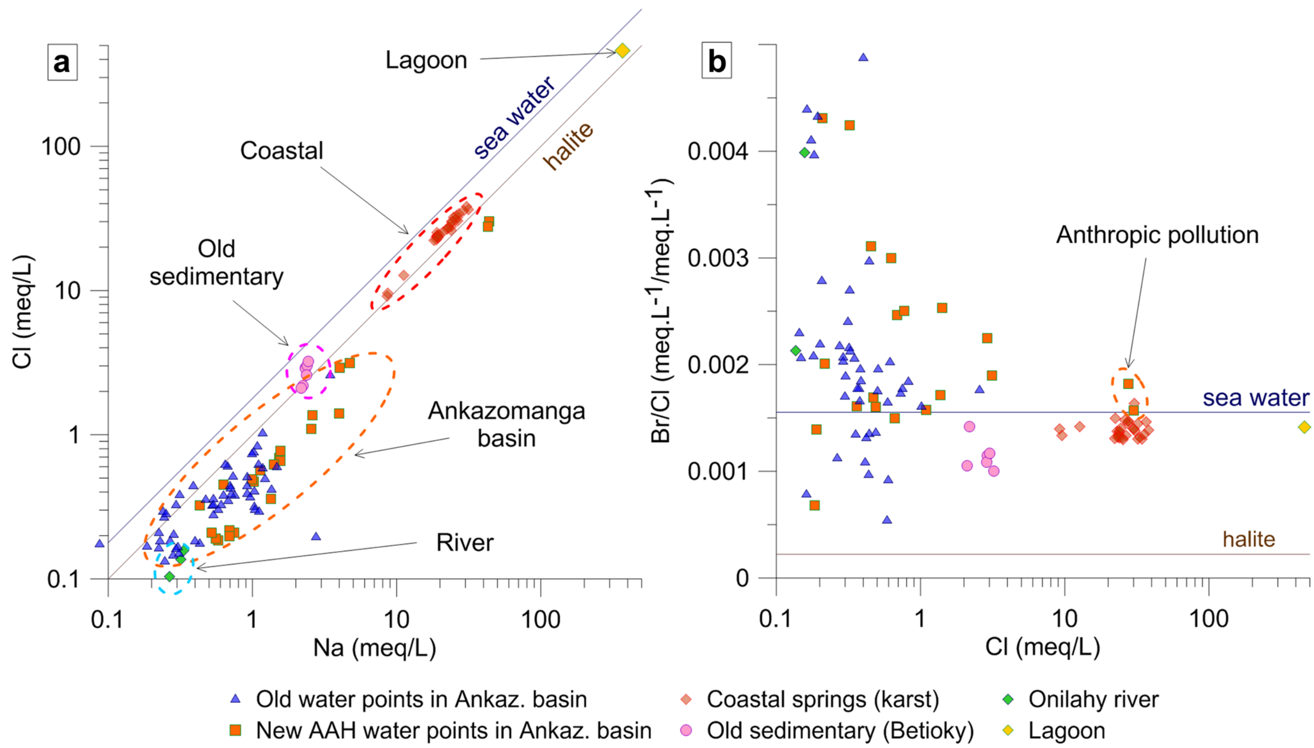

Fig. 5 Hydrochemical results for the 112 waters sampled between 2013 and 2016 (sampling points are located in Fig. 1). **a** Na vs. Cl relationship with identification of water masses. **b** Relationship Cl vs. Br/Cl. Ratio of seawater and halite lines from Fudge (1974), Fontes and Matray (1993), Copin-Montegut (1997)

tion expected for seawater. This composition is probably due to chemical reactions occurring in the lagoon. Dilution of lagoon water by the Onilahy River was suspected but the Br^-/Cl^- ratio (Fig. 5b) invalidates this hypothesis.

4. The Betioky boreholes are in Old Sedimentary terrains and the water has moderate mineralization (≈ 600 µS/cm). Betioky water was sampled from only two boreholes, so these points cannot be considered representative of all Old Sedimentary terrains. However, they are more highly mineralized than the Ankazomanga basin water collecting points, which is consistent with Rabemanana et al. (2005) in the south and measurement obtained by AAH east of the town of Betioky.
5. The Onilahy River has the lowest mineralization (≈ 100 µS/cm). This was expected for surface water. Moreover, slow interactions between water and the crystalline basement where the rainiest area of the Onilahy watershed is located (in central Madagascar) may also be responsible for this low mineralization.

The hydrochemical results point to a strong marine influence on deep karst waters. Any natural tracer (e.g. Br^-/Cl^-, SO_4^{2-}, Br^-/SO_4^{2-}, K^+) would make it possible to identify another source of salinity (evaporites, thermal waters) for these karst waters. However, the tracers used do not reveal any connection between deep karst waters and waters from Old Sedimentary terrains or the Onilahy River. Therefore, it does not seem advisable to exploit the deep karst resource because the distance where sea water intrusions occur remains unknown. Guyot (2002) has shown that further south, the tides have an effect on piezometry and salinity 20 km inland from the coast. Thus, deep karst water can potentially be contaminated under the basin of Ankazomanga. In addition, two more issues need to be taken in to account: (a) exploiting this resource would probably require boreholes to depths of more than 150 m and the related manual exploitation of the water resource would not be possible, and (b) although the Mahafaly karst is highly developed (André et al. 2005) and the risk of borehole siting failure would be high because there is no way to guide a successful borehole to a cavity at such depth. Therefore, the decision was made to focus local scale exploration in the Ankazomanga basin on the near surface aquifer within the Neogene formations.

Regional scale geophysics

Slingram EM34 exploration made it possible to highlight considerable underground spatial variability (Fig. 6a). In

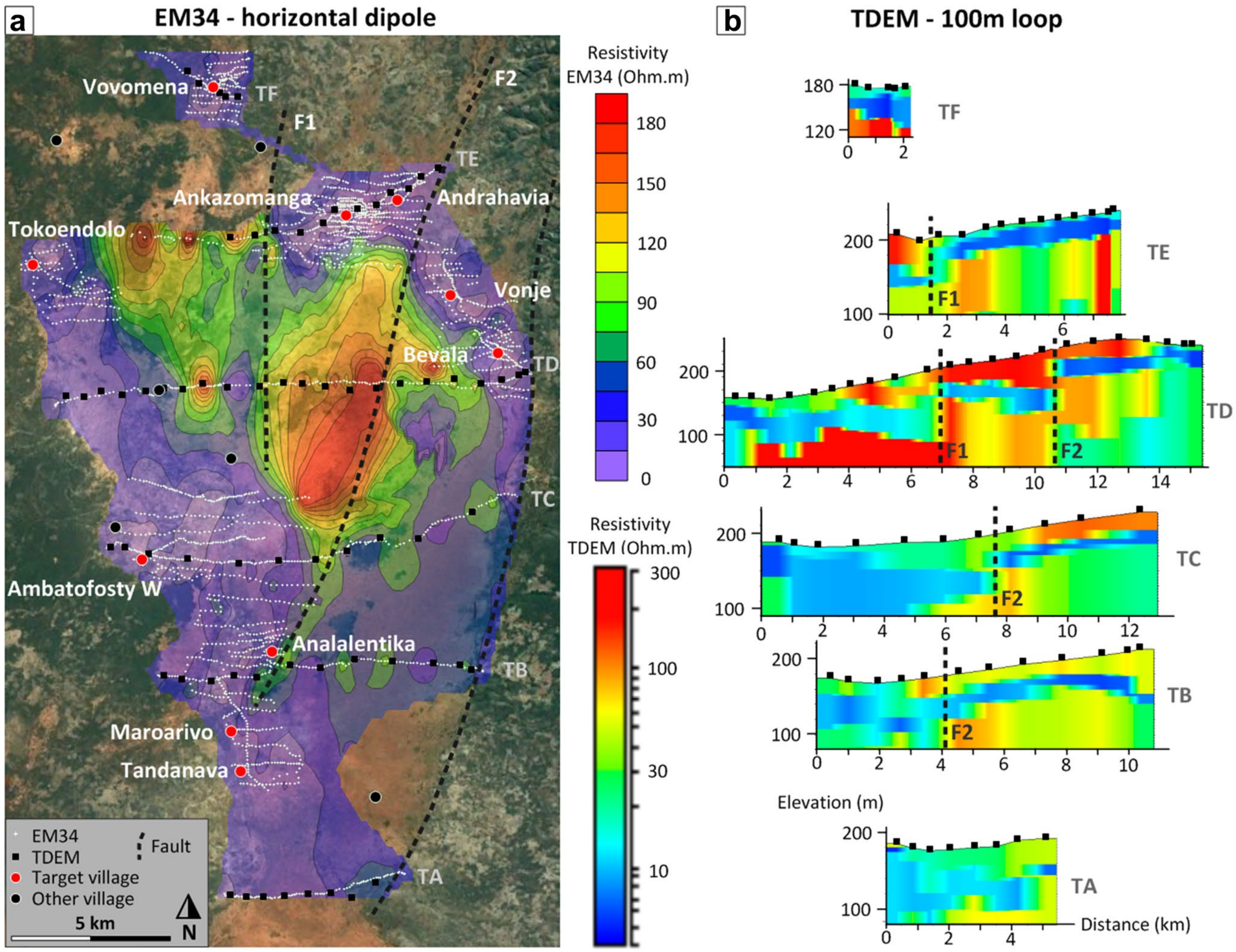

Fig. 6 Geophysical regional scale results and interpretation. **a** Slingram map for horizontal dipole and 20 m inter-coil spacing. **b** Inverted TDEM cross-section obtained by 100 × 100 m square loop

particular, in the heart of the Ankazomanga basin, a more resistant zone (> 150 Ω m) extends in the north–south direction. This direction is consistent with the major regional fracturing direction N°10 (André et al. 2005). Auger drillings revealed a significant consistency between sediment found under red sand covering and Slingram measurements. The most resistive zones correspond to coarse sand whereas more conductive zones coincide with clayey sediments. Following the example of Vouillamoz et al. (2002), different scales are used in Figs. 6 and 7 for each geophysical technique because the measurements do not exploit the same physical principles. For the same geological formation, the two techniques measure different resistivity. However, the spatial variability of a geological formation is accurately detected by both techniques.

TDEM profiles were therefore oriented east–west so as to intersect: (1) the resistive anomaly observed on the Slingram results, and (2) primary regional fracturing. The TDEM results made it possible to produce 2D vertical imagery (Fig. 6b) with remarkable coherence between cross-sections, from both stratigraphical and tectonic points of view. The TDEM cross-section made it possible to locate two major faults (F_1 and F_2, Fig. 6) with overall N°10 orientation. These faults involved vertical movements of several tens of meters. They are visible on TDEM cross-sections and the Slingram map, and they are cross validated by aerial photo interpretation. Stratigraphically, the TDEM cross-sections make it possible to distinguish systematically three geological entities:

- Upper horizon with variable resistivity (between 20 and 300 Ω m),
- Intermediate horizon, highly conductive (between 3 and 10 Ω m),

- Lower horizon with variable resistivity but overall more resistive than the upper horizon (between 30 and 300 Ω m).

At this second stage of the study, without hard geological data from drilling, it was not possible to interpret these geophysical results with certainty. It was assumed that the upper horizon corresponds to loose sandy sediment, more or less clayey. It was also assumed that the lower and more resistive horizon would correspond to the Eocene carbonate formations. Eocene formations contain limestone and sandstone levels that should be resistive. The nature of the intermediate horizon remained unknown until drilling campaign results were obtained. Given the geological setting, such resistivity levels (3 and 10 Ω m) could correspond to:

- Clay,
- Salt clay,
- Sand or sandstone saturated with salt water,
- Sand or sandstone containing conductive elements (e.g. oxide, magnetite).

The nature of the intermediate geological formation was a crucial issue for the design of the drilling campaign. It was not known if the formation was an aquifer or aquiclude. This is why close cooperation was maintained during the drilling campaign (Fig. 2). Hydrogeophysical interpretations were updated daily, which led to adjustments of drilling locations and depth of the investigation targets. During the drilling campaign, it was discovered that the conductive intermediate formation is composed of a variety of lithologies dominated by marl and clay with sand and sandstone intercalations.

It should be noted that in the study area magnetic viscosity could disturb TDEM measurements. This well-known effect distorts signals for long reception times (more than 3 ms), (e.g. Krivochieva 2002; Hoareau et al. 2010). Magnetic viscosity is due to presence of magnetic materials in the vicinity of the coil. Extremely high conductivity and unrealistic values were obtained for long reception times in this study. Every time this problem was encountered, it was solved by adjusting the intensity of the injected current and the measurement was repeated until this undesirable effect disappeared.

Village scale survey: Tokoendolo example

The Tokoendolo example illustrates the strategy that was followed during this project. This example demonstrates the geological complexity and the uncertainties that persisted despite the number of measurements conducted.

At the village scale, exploration began with EM34 mapping that produced a preliminary characterization of a large area around the village (≈ 8 km^2). The general structure detected is oriented north–south overall (Fig. 7a) with alternation of conductive (10 Ω m) and resistive (more than 50 Ω m) bands. This pattern agreed with the EM34 results obtained at the regional scale (Fig. 6).

The TDEM profile was positioned as perpendicularly as possible to the structure detected by the EM34. Field conditions do not always allow for straight tracings, which is

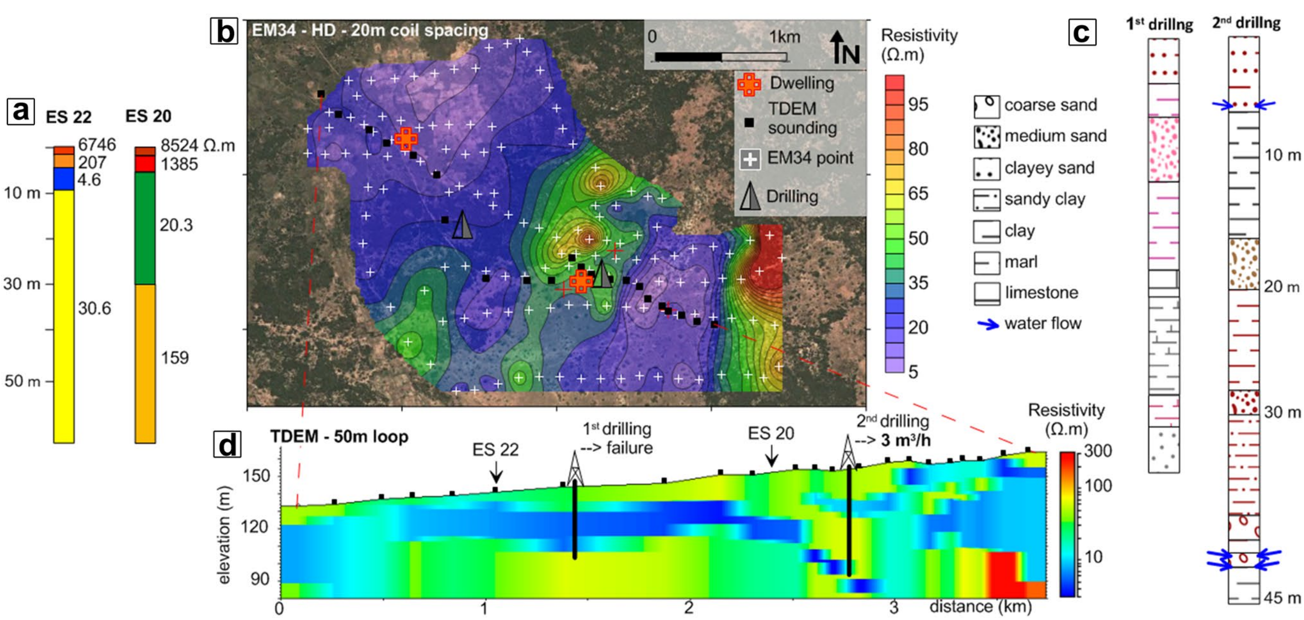

Fig. 7 Results obtained at the village scale for Tokoendolo; **a** electrical sounding (ES); **b** Slingram EM34 in horizon dipole (HD) with 20 m coil spacing; **c** borehole log with a simplified representation of colors observed on cuttings; **d** TDEM with 50 × 50 m loop

especially true when the ideal linear transect crosses a dense spiny forest. The temporal constraints of this humanitarian project did not allow for bush clearing. The village scale TDEM profile (Fig. 7c) detected the three horizons found at the regional scale. The highly conductive intermediate formation is always present but its thickness is quite variable, from a few meters to tens of meters. Moreover, this conductive formation is not tabular in shape. On the right side of the profile, there appears to be a kind of large scale cross-stratification and the conductive formation appears to be discontinuous. These observations are consistent with the presence of continental Neogene formations because continental formations often have a limited lateral continuity.

ES surveys (Fig. 7b) confirm the presence of the three horizons imaged by TDEM. In the near surface (1–2 m) a very resistive horizon (6500–8500 Ω m) is present. This result was consistent with red sand cover, which is not identified by TDEM due to instrumental cut-off time and because this very resistive horizon does not produce electromagnetic induction current. The resistive horizon described by TDEM is present under the sand cover. Below the resistive horizon, the highly conductive formation is present but its thickness can vary considerably compared to TDEM results (5 m for ES-22 vs. 20 m for the nearest TDEM sounding, and 15 m for ES-20 level vs. 25 m). This variability results from the fact that ES and TDEM provide estimates and not exact measurements because measurements are indirect and the raw signal needs to be inverted. The techniques are not based on the same physical principle and the investigated volumes are quite different.

Two boreholes were drilled around Tokoendolo village (Fig. 7d). The first drilling was aimed at exploiting water that could be collected within the conductive formation where the formation was thickest. During borehole drilling it was discovered that the conductive formation consisted mainly of clays and marls. This led to the failure of the first drill-hole and a second drill-hole was installed aiming at the aquifer above the marly conductive formation in a zone where this formation is deeper (43 m). This second borehole was successful and yielded around 3 m^3/h.

Drilling campaign

The drilling campaign ended with six positive and six negative boreholes. Three of the six negative boreholes reached water but aquifer thickness was not sufficient to allow the installation of a pump. For these three cases, wells were installed as replacements. The drilling campaign result is positive given the geological complexity and the lack of existing knowledge of the study area when the project began.

In such a complex and poorly understood environment, it is imperative to maintain a close cooperation between the hydrogeological team and the drilling team so as to reinterpret the data every day with new drilling information and in this way improve drillings siting.

Drilling made it possible to characterize the geology of the Ankazomanga basin and to find geological formations that are not easily found in outcrop. Drilling showed that continental Neogene formations are mainly composed of marl and clay with thin intercalations of sands and limestones. It is not possible to establish clear consistency between drilling logs because Neogene formations are of variable composition, discontinuous, and not always tabular. In addition, these discontinuous formations overlie the Eocene series, which are potentially affected by advanced karstification phenomena.

Water resource monitoring

To ensure the sustainability of the Ankazomanga basin hydro-climatic observatory, a partnership was created with local institutions (Toliara University, Regional of Meteorological Service, and Regional Direction of Water). A team was trained to maintain equipment and collect data every 3 months. The hydro-climatic observatory is composed of ten piezometric probes (distributed throughout the Ankazomanga basin) and a weather station (located in a secure area in the village of Ankazomanga). The piezometric sensors were installed to monitor zones of dissimilar conditions, so as to be as representative as possible of hydrogeological diversity.

The example of two wells monitored since 2014 near the Ankazomanga well illustrates the diversity of hydrogeological functioning (Fig. 8). These two wells are about 500 m apart and are located at similar altitude (Well 01: 225 m and Well 02: 227 m) on a flat area, however their hydraulic behavior is significantly different. First, their water levels are different, water in Well 02 is 1–4 m lower than water in Well 01 depending on the season. The recharge of Well 01 is much more reactive to rain events. Well 02 reaches its recharge peak 3 months later and in a smoother way than Well 01. This temporal shift can be explained by lateral water transfer toward the east from Well 01 to Well 02. This water movement, which is contrary to the general direction of underground flow (Fig. 4a), is probably explained by complex morphology of the base of the aquifer, which may be affected by karst morphologies in Eocene formations.

During the wet seasons 2015/2016 and 2017/2018, El Nino conditions resulted in weak rainfall. Despite 6 rainy episodes of more than 30 mm in 2015/2016, recharge was very limited. During the next dry season (autumn 2016), the well water level was very low. Extracting water for human consumption caused Well 01 to be pumped dry every day for about 2 months (green dots reaches a plateau—Fig. 8). Because Well 01 went dry, extraction for human consumption increased in Well 02. In the same way, it is always

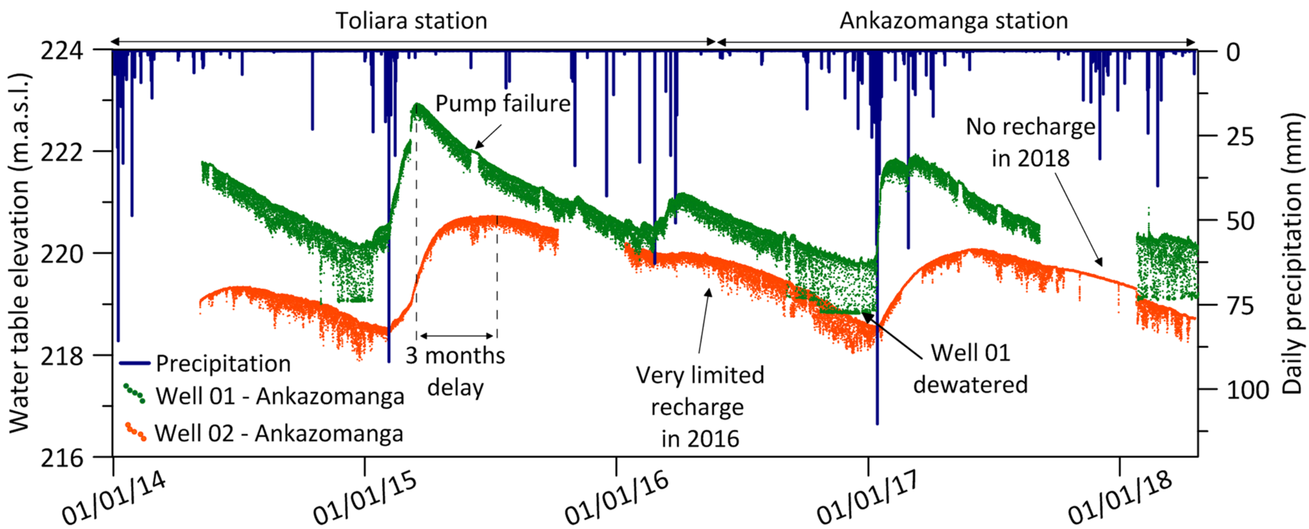

Fig. 8 Results of the hydro-climatic observatory with the example of Ankazomanga. The weather station and Well 01 (elevation 225 m) and Well 02 (elevation 227 m) are about 500 m apart

observed that when the pump of the Well 01 is broken, water extraction is more intense in Well 02. The wet season 2017/2018 is the driest year ever since 1982/1983 in Toliara region (Fews-Net 2018). Unfortunately, a failure of the Well 01 probe generates a gap in the data. But Well 02 shows that there was no recharge for this year. Currently, rainfall records are insufficient to determine what type of rainfall is most favorable for near-surface aquifer recharge. However, it seems that an accumulation of several rainy days is necessary to favor recharge.

At present, the piezometric and meteorological data record of Ankazomanga is still too short to conduct statistical analyses on the evolution of water resources in a climate change context. This is particularly true in a setting where climatic inter-annual variability is very strong. In a few years, the record will be sufficient to work on sustainable management scenarios of water resources for the medium and long term.

Discussion and perspectives

Geophysical measurements and drillings have shown that the Ankazomanga basin is filled with Neogene deposits whose heterogeneity and discontinuity make it a complex environment. The Neogene formations are highly diverse (sand, clay, marl, limestone, sandstone) and have weak lateral continuity. Moreover, karst morphologies (e.g. sinkholes, karren) at the base of Neogene fill impose complex constraints on flows that occur within the Neogene formations. Despite numerous investigations, the Ankazomanga basin remains poorly characterized in relation to its size and heterogeneity. At the current state of knowledge, hydrogeological modeling is impossible at the basin scale. It has been demonstrated that the Ankazomanga basin cannot be considered to contain a single aquifer, but rather many smaller aquifers that are more or less connected. For this reason, the piezometric map (Fig. 4a) needs to be interpreted cautiously at the basin scale. Indeed, at the village scale the underground hydrodynamics may be more complex, for example near Ankazomanga village where water flows locally towards the east.

If the project were extended, it would make sense to try to construct a local hydrogeological model around Ankazomanga village because the weather station and two piezometric probes there could be used to calibrate and validate the model. In addition to developing a model, it would be necessary to carry out aquifer tests to determine properties of the exploited aquifers (transmissivity, permeability). From a budgetary and temporal organization point of view, it was not possible to conduct aquifer tests during this humanitarian project. Geophysical measurements (TDEM) around the village should also be made with fairly close profiles (a few hundred meters of separation) to determine aquifer morphology with more accuracy. In this project, only 1 day of exploration was possible around each village with the three working groups (TDEM, electrical sounding, and EM34).

Several water collecting points in the Ankazomanga basin have high levels of tracers that mark anthropogenic pollution (NO_3^-, Br^-, NH_4^+). The new AAH borehole in Andrahavia exploits an aquifer at a depth of 19 m with a high NO_3^- content (≈ 3000 mg/L, see Online Appendix). It is thought that a zebu park was formerly located upstream of this borehole. This water is currently used for agriculture and livestock and renewal of aquifer water could reduce its salinity. In the future, it would be useful to evaluate the connectivity between surface and groundwater by analyzing ^3H and possibly ^{14}C if ^{3}H activity is zero. Parameters such as pH and dissolved oxygen should also be measured. This monitoring would aid in pollution prevention (protection perimeter around wells) and in estimation of water resource renewal.

The hydro-climatic observatory that has been created with a weather station and a network of piezometric sensors, makes it possible to produce a unique dataset. In an extremely remote area, it is essential to collaborate with a local institution (University, Water Direction, Meteorological Direction) to ensure the durability of the monitoring system and knowledge transfer. It is now possible to assess the evolution of seasonal water storage and to estimate aquifer recharge. It was decided not to over-instrument this site to be able to adhere to a limited maintenance budget and in this way maintain it over time. However, a problem of spatial representativeness could arise in future interpretations, given the subsoil and precipitation heterogeneity and the size of the study area. The rainfall amount in Ankazomanga is not necessarily the same as in Andremba (Fig. 1), depending on weather conditions. This uncertainty should not be overlooked in future hydrogeological interpretations.

Conclusions

From an operational point of view, this integrated hydrogeological study successfully determined locations for nine borings at a cost of 40 k€. However, the contributions of this study do not stop there.

The methodological approach developed in this paper is not site specific. At the regional level, this approach will promote implementation of new wells across the Eocene Mahafaly plateau and its geological equivalent that continues into northern Onilahy. Many inhabited areas are present in the same geological setting on the west coast of Madagascar and maybe elsewhere in the world.

The geophysical knowledge acquired was essential for working in sustainable resource management scenarios. The geophysical results made it possible to implement the piezometric probe network in a judicious manner. This information aids in the selection of wells that are representative of study area heterogeneity. Moreover, the previously acquired hydrogeological knowledge is essential for interpreting piezometric monitoring of each water collecting point because different geological settings result in widely varying piezometric responses.

The network of piezometric sensors and the meteorological station make the Ankazomanga basin a unique hydro-climatic observatory that should produce data for at least 10 years. Industrial or urban pollution is non-existent because inhabitants have a very low per capita water consumption. The hydrogeological comparison with the urban area of Toliara, which is in a similar geological setting and is currently experiencing a serious water shortage, would be very relevant. Because southwestern Madagascar is a global change hotspot (Dai 2013), this hydrogeological observatory will be unique for studying the effects of global change on groundwater resources. Operationally, this observatory will be an early-warning network for monitoring groundwater shortage. It will make it possible to work on scenarios of sustainable water resource management with local partners. As an example, the year 2018 promises to be extremely dry as early as March. This situation allows more time prior to the beginning of a humanitarian crisis to mobilize authorities to implement preventive actions and to seek funds to install additional and deeper drillings, to advise inhabitants to use less irrigation on their crops, and to organize water trucking.

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