1 HYDROGEOLOGY

1.1 INTRODUCTION

According to the national census of the 15.7 million total population of Madagascar (in 2001), about 75% live in rural areas and 83% of these are employed in agriculture. At that time, only 12% of the rural population had access to safe water (Table 1) (Minten, 2002). By 2015 the population may reach 23.7 million by which time Madagascar aims to improve water supply in rural areas to 80 % coverage through radical development of surface water and groundwater resources (Burgeap, Etudes et Conseils Plus et al., 2003).

	2001	2001 rural	2001 urban	2015	2015 rural	2015 urban
Antananarivo	4 585 068	2 702 286	1 882 782	6 736 380	4 669 125	2 067 255
Fianarantsoa	1 189 480	971 504	217 976	1 730 521	1 414 546	315 975
Toamasina	3 368 871	2 810 282	558 589	5 326 102	4 442 841	883 261
Toliary	1 734 119	1 373 204	360 915	2 614 327	1 998 892	615 435
Mahajanga	2 594 663	2 029 627	565 036	4 000 251	3 113 996	886 255
Antsiranana	2 229 659	1 728 472	501 177	3 298 115	2 540 040	758 075
Madagascar	**15 701 850**	**11 615 375**	**4 086 475**	**23 705 696**	**18 179 440**	**5 526 256**

Table 1 Population in urban and rural areas per province for 2001 and 2015 (minten, 2002)

Within the project area of central and northern Madagascar, where tropical to savannah type climate prevails, water supplies for domestic and agricultural use are obtained mainly from streams, rivers, shallow wells and springs. In this area, most communities in the drier Central Highlands obtain water from spring fed systems. In the wetter parts of the project area perennially flowing rivers supply rural and urban water needs. However, water quality problems can occur as domestic supplies are often drawn from untreated river or stream sources especially urban areas where traditional water sources are often contaminated by effluent. Hence groundwater is seen as a source of clean and safe water, and is increasingly used to supply rural, urban, agricultural and industrial water needs.

1.2 GROUNDWATER DEVELOPMENT IN MADAGASCAR

The French colonial administration undertook the first hydrogeological reconnaissance studies in 1910. Information on groundwater, geothermal springs and water quality was published in 1929. Geophysical exploration and borehole drilling for groundwater was begun during the 1950s. In 1960, a hydrogeology office was established as part of the Geology, Mines and Energy Department. Hydrogeological studies were conducted, especially in the more arid southern and western basins, from 1961 and of the first hydrogeological map of Madagascar was produced in 1972.

Since the World Water Decade of the 1980s, projects led by NGOs installed numerous wells and gravity spring fed systems. National water supply coverage increased from 27% to 31% between 1999 and 2003, although hand pump maintenance proved to be a problem. Current rural water supply projects and programmes are financed by the World Bank, UNDP, UNICEF, Japanese International Aid (JICA) and International NGOs including WaterAid, CARE and MEDAIR.

In 2002, the management of water supply and resources in Madagascar became the responsibility of the Department of Water Exploitation, in the Ministry of Energy and Mines (MEM). This Department is currently involved in several rural water supply projects including PAEPAR. MEM also collaborates with the Ministry of Waters and Forestry (WaterAid PRSP 2002).

In hilly and forested central Madagascar, gravity fed systems obtaining water from valley side springs supply most villages (Daw, 2004). The PAEPAR Project is currently installing 625 such systems in the central region. Traditional shallow dug wells are used where groundwater is available at a shallow depth, as in sandy alluvium along valleys and coastal dune sands. Increased numbers of handpump equipped deep wells and shallow boreholes are being installed in coastal towns using simple drilling methods such as water jetting, auger drilling, hand sludging, as in Maraontsetra in Tiamasina Province (Erpf and Gomme, 2005).

The rate of water abstraction unit installation has increased since the 1950s, 800 units being installed during the 1990's and over 1000 units during the first half of the present decade (Figure 1). Since 1995 the number of units installed per year has increased steadily, most of the units being wells and spring fed piped systems and a small, but increasing number of boreholes (Figure 2). Only limited amounts of hydrogeological data are routinely collected during unit installation.

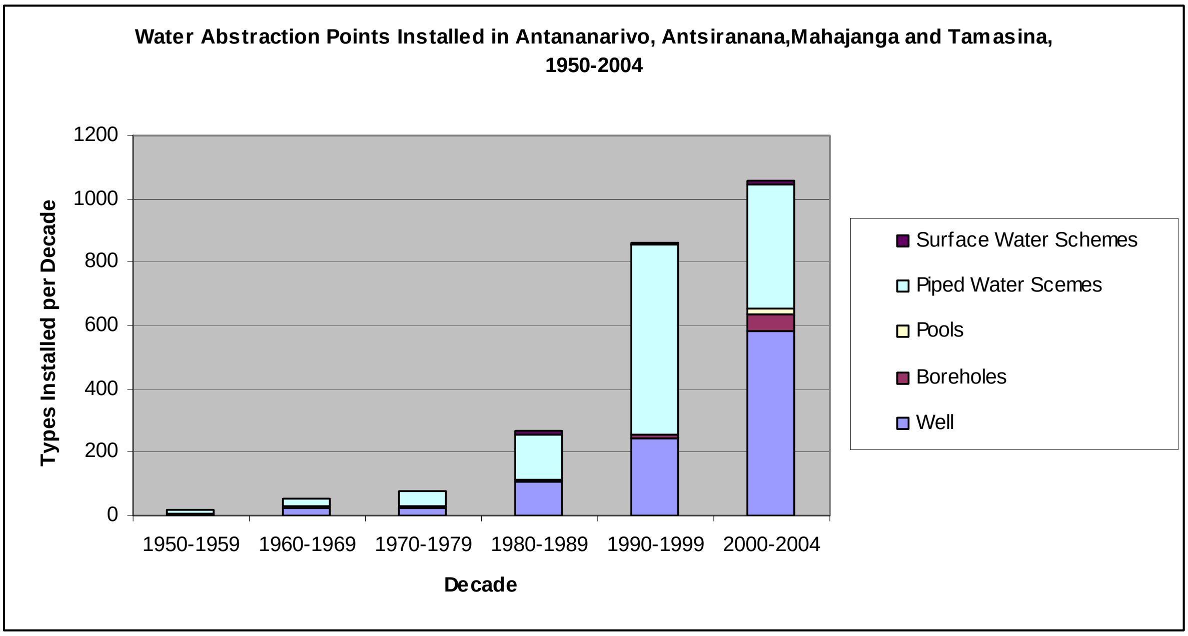


Figure 1. Water abstraction points installed per decade in the project area during 1995-2004

During the last decade, development of groundwater to meet supply needs has been concentrated in drought prone southern Madagascar (Autorite Nationale de 'Eau et de l'Assainissement, 2003). Elsewhere in Madagascar, groundwater is seen as a supply option for low-yield small-scale rural water supply. Such use has warranted only limited groundwater resource study. Consequently, although thousands of spring fed piped systems, wells and boreholes have been installed, the nature of the groundwater systems present and their resources within central and northing Madagascar remain poorly understood .

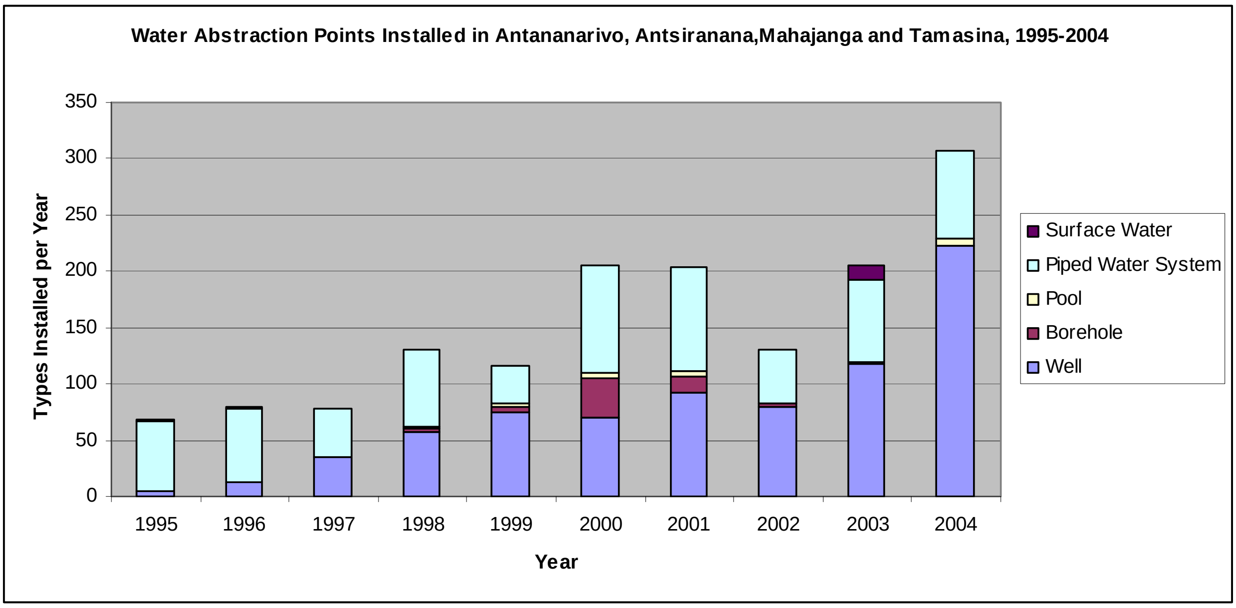


Figure 2. Water abstraction points installed per year during 1995 - 2004

A national survey of water abstraction points undertaken in 2005 by MEM, as a part of the PAEPAR Project, produced an inventory of more than 7350 georeferenced abstraction sites including boreholes, wells, ponds/lakes and spring fed piped water systems. Only site location, type, well/borehole depth, depth to water table and water quality (conductivity and pH) data were recorded at most sites. The data points are unevenly distributed, reflecting ease of access to sites located along main roads.

1.3 HYDROGEOLOGICAL MAPS

Hydrogeological maps are planning tools. They show the nature and distribution of groundwater resources and indicate how these resources may be developed. Map accuracy depends upon the availability and accuracy of hydrogeological data obtained mainly, at the time of installation and testing. However, in areas where surface water sources, springs and hand dug shallow wells predominate, little in the way of detailed hydrogeological information are available. In such areas, combinations of geological, geomorphologic, hydrologic and climatic data, informed by the current distribution of groundwater abstraction points, are used. Such methods have been used to understand hydrogeological conditions in other parts of southern and eastern Africa (Davies and Robins, 2007); by MacFarlane et al (1992) in Malawi; by Taylor and Howard (1997) in Uganda; by Vegter (1995) in South Africa, and by Interconsult (1985) in Zimbabwe. During such studies borehole data were correlated with the depth and style of weathering below erosion surfaces, as defined by King (1951) and Partridge and Maude (2000) in South Africa, Dixey (1960) in Madagascar, and Lister (1987) in Zimbabwe,.

In the absence of sufficient borehole data from the project area, a set of hydrogeological reconnaissance maps, based upon the standard UNESCO legend, are produced. The results of studies undertaken in similar hydrogeological environmentss to those present in the project area are used to indicate possible groundwater occurrence within the shallow weathered Basement Complex and Karoo sedimentary and igneous hydrogeological environments. The reconnaissance hydrogeological maps produced for the mapping areas should be used for indicative purposes only.

1.4 PHYSIOGRAPHY AND CLIMATE OF THE PROJECT AREA

The Project Area includes three physiographic zones: the Central Highland Plateau Zone, the Eastern Coastal Zone and part of the North – west Lowland Zone, each with a distinct climatic regime. Average monthly rainfall and evapotranspiration records were obtained from 43 meteorological stations (Figure 3). The Project area experiences a rainy season from November to April, influenced by the north-west monsoon; and a dry season from May to October, influenced by the south-east trade winds. Average annual rainfall is 1 700 mm. and average annual temperature 17.8 °C. The potential evapotranspiration measured by the Thornthwaite method is between 2 000 and 1 300 mm and real evapotranspiration between 1 300 and 300 mm (Donque, 1972).

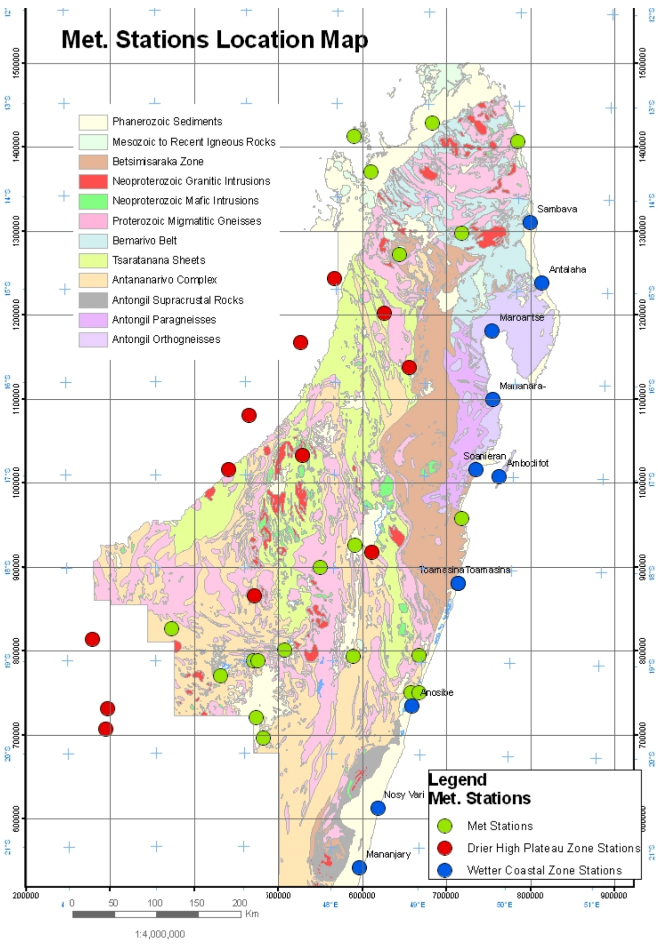


Figure 3. Meterorological Stations in northern and central Madagascar

1.4.1 The Central Highland Plateau Zone

The Central High Plateau zone, at an elevation of 900-2700 masl., includes rolling hills, wide plains, volcanic cones, granite massifs and deeply incised valleys. The plains are mantled by red lateritic soils, the volcanic areas with dark brown soils, and grey alluvial soils occur along valley bottoms.

CLIMATE

The zone experiences cool to mild dry winters (12-15°C) and, warm wet summers (19-23°C). The annual rainfall is 1200-1400mm, with a main wet season from December to March. Assessment of 12 records from meteorological stations in the Central High Plateau Dry Zone indicate a sub-humid to sub-arid zone with a distinct 5-6 month dry season (May – September) and that potential evaporation exceeds rainfall during the 8 months of April to November (Figure 4). The area could experience prolonged drought conditions.

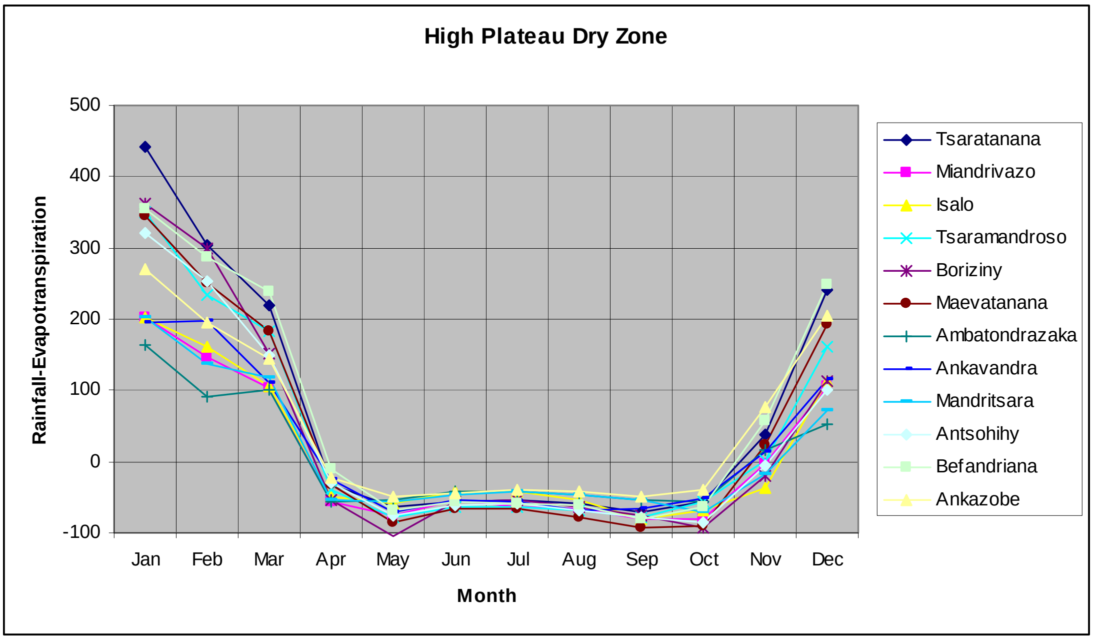


Figure 4. The distribution of potential rainfall (rainfall minus evaporation) within the Central Highland dry zone.

DRAINAGE

Formerly, many of the eastward draining streams and small rivers had clear, uncontaminated and potable flows that formed the main sources of water for rural communities. In recent years, these rivers have tended to silt up due to soils erosion caused by deforestation. Their flows are now ephemeral causing water supply to be difficult by the latter half of the dry season. The large western flowing rivers (the Mangoro and Sofia) have muddy waters unsuitable for human consumption. Stream flows are used for the irrigation of rice. Irrigation water is also obtained from the larger lakes, such as Lake Alaotra. Two large lakes, Alaotra and Itasy, are located on the central plateau. These lakes are increasing affected by pollution and silting caused by deforestation. Spring flows are also diverted along open channels for rice irrigation or to central water points through small-gauge pipes by gravity flow. Spring commonly occur in areas of lavaka style erosion, issuing from the base of lavaka style gully features. Drainage patterns tend to be dendritic or linear (fault-controlled).

LAND USE

Grazed grassland is occurs on the plains, irrigation of rice along valley bottoms, intensive agriculture in lowland areas and commercial woodlands on valley sides. The agricultural system is based on small-holdings producing rice by irrigation and a variety of rain-fed crops including maize, cassava, sweet potatoes, beans and various tree fruits. Zebu cattle graze the grasslands.

1.4.2 The Eastern Coastal Zone

The humid Eastern Coastal Wet Zone has ferralitic soils. Elongate dune deposits and shallow river delta sediments along the coast provide sources of shallow groundwater that may be vulnerable to seawater intrusion if over-pumped.

CLIMATE

The area experiences a sub-equatorial climate with an annual rainfall of 2000 to 3000 mm/year, warm temperatures (19-27°C) with a main wet season from December to March. Appreciable rainfall occurs during April to August, with some rainfall during the September to November dry season. Assessment of 12 records from meteorological stations in the Eastern Coastal Zone indicate a very humid tropical zone with a short 2-3 month dry season (September to November) with potential evaporation exceeding rainfall during the whole year (Figure 5). The area should not normally experience periods of drought.

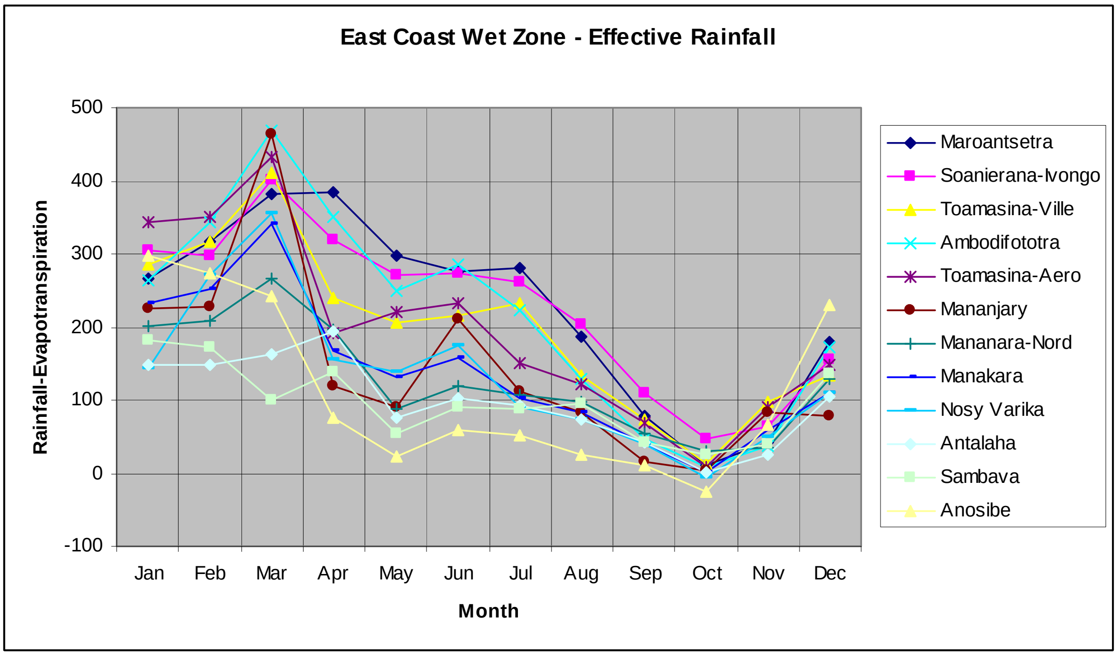


Figure 5. The distribution of potential rainfall (rainfall minus evaporation) within the Eastern Coastal humid zone.

DRAINAGE

The Mananara, Mangoro, Maningory, Bemarivo, Ivondro, and Mananjary rivers flow from the Central Highlands towards the east coast. These short rivers flow steeply, over many waterfalls, to the east coast. Within the Eastern Coastal Wet Zone water supply is only problematic during the wet season when floodwaters are heavily laden with suspended silts making abstraction difficult and which tend to block inlet pipes and pumps

LAND USE

Two thirds of rainforest has been removed. Agricultural is based on small holdings with rice as the staple crop but with tropical market gardens and tree crops including coffee, banana, citrus and cloves.

1.4.3 The North-Western Lowland Zone

The North-Western Lowland Zone has a gentle, hilly aspect being mostly underlain by sedimentary rocks mantled by a variety of soils. Appreciable quantities of groundwater occurs in the fractured sedimentary and volcanic rocks and karstic limestones in this area, and in unconsolidated river alluvium and delta deposits.

CLIMATE

The climate is drier (in the rain shadow of the Central Highlands) and hotter than the other two blocks. The annual rainfall is about 1 500 mm/year in north, around Mahajanga, and temperatures vary from 20 to 27°C.

DRAINAGE

The longer and slower rivers flowing to the west coast include the Sofia, Sambirano, Mahajamba, Betsiboka, Mania, North and South Mahavavy, Mangoky, and Onilahy. The Ikopa is a major tributary of the Betsiboka. The Mangoky River; the Ikopa River and the Betsiboka River have basin areas of 50 000, 18 550 and 11 800 km^2, respectively. The channels of many of these rivers, their tributaries and headwaters have become choked with sandy alluvium transforming them from perennial to ephemeral rivers. This process is analogous to the formation of the sand rivers of southern Africa. Groundwater occurs within the sandy infill deposits throughout the year and as such is available for irrigation and cattle watering. In the wetter areas the headwaters take on the form of dambos (bas fonds) with clayey alluvial deposits within the valley bottoms. These absorb rainwater during the annual monsoon and are sites of rice cultivation.

LAND USE

There are extensive grasslands with some dry forests and woodlands. The agricultural system is mainly pastoral with the cultivation of rice and cattle grazing on grasslands.

2 GEOLOGY AND GEOMORPHOLOGY

2.1 GEOLOGICAL SETTING

The occurrence of groundwater is controlled by the interaction of geology and geomorphological processes. Since most of the shallow groundwater occurs within the near surface weathered and eroded zones, hydrogeological mapping units are based upon geomorphological features. The lithostratigraphic base layer, used for the hydrogeological maps, has been simplified to the following units:

- Archean Basement – includes high grade gneissic units of the Antogil strata
- Neoproterozoic Basement – includes metasedamentary rocks
- Neoproterozoic Granitoids – includes predominantly high standing granitic masses
- Phanerozoic Sediments – includes the Karoo (Permian to Jurassic continental sediments), Jurassic, Cretaceous and Eocene marine limestones and sandstones
- Phanerozoic Igneous Rocks – includes Late Jurassic, early Cretaceous and Oligocene volcanic rocks
- Neogene Sediments – includes Pliocene and Quaternary sediments
- Neogene Igneous Rocks

The detailed geology of the Basement Complex units are described in this report. The distribution of these units and their importance to groundwater occurrence are described within the four hydrogeological regions mapped (Rakotondrainibe, 205 and 206).

2.1.1 Region 1 - High Plateau

The Central Highlands area predominantly underlain by Archaean and Neoproterozoic igneous and metamorphic rocks of the Basement Complex that were deeply weathered and eroded with the formation of erosion surfaces. Within the High Plateau area, two volcanic centres mainly consisting of basalts and trachites occur north and south west of Antananarivo. Basalts weather to form thick dark clayey soils.

2.1.2 Region 6 - Mahajanga Basin - the western sedimentary basin.

The small part of the western basin included in the project area includes deposits of Karoo (Permian to Jurassic) age continental and marine sediments. The lower series of Karoo sediments are mainly very fine textured (mudstones) and may contain carbonaceous beds. The upper Karoo sediments are mainly sandstones that have weathered to form a significant area of thick sandy soils in the south-western part of the project area.

2.1.3 Region 7 - Antsiranana Basin – the northern sedimentary basin

In the northern basin thick sequences of Karoo (Permian to Jurassic) age continental and marine sediments occur. The lower series of Karoo sediments are mainly very fine-textured (mudstones) and may contain carbonaceous beds. The upper Karoo sediments include more sandstones. The Karoo continental sediments pass upwards into Jurassic marine sediments that include limestones and with basaltic flows. These are in turn are overlain by Cretaceous age marls, clays and sandstones and Eocene age limestones. In the northern basin the Phanerozoic sediments have been intruded by Oligocene age alkaline lava flows and pyroclastics. Quaternary and recent sediments include coastal sand dunes, coral reefs, mangrove swamps, and fluvial and deltaic alluvial sediments.

2.1.4 Region 8 - East Coast Basin – the eastern sedimentary basin

The elongate north-south trending Eastern basin includes Cretaceous-age limestones, volcanic deposits, and sandstones that are overlain in part by Neogene-age basaltic flows and clays. Quaternary to Recent-age deposits include beach sands, sand dunes and fluviatile and deltaic alluvial sediments.

2.2 GEOMORPHOLOGY AND EROSION SURFACES

The occurrence of groundwater within the savannah to tropical terrains of the project area is mainly controlled by the impact of the processes of weathering and erosion upon the rocks in the area. The geomorphology of the area is dominated by a series of erosion surfaces developed mainly on basement rocks within the Central Highlands within the era following the Dwyka glaciation (Dixey, 1960, Bourgeat and Petit, 1969 and Arthaud et al., 1990).

Erosional surfaces are features present in the landscape that impact upon groundwater occurrence in weathered basement terrains. Distinct landform patterns relate to erosion at specific elevation intervals noted across southern, eastern and central Africa (Lister, 1987). These surfaces result from prolonged patterns of erosion, or pediplanation, caused by sub-continent-wide patterns of uplift and tectonic activity. At a later stage, patterns of weathering at these erosion surfaces were related to variations in palaeoclimate. Six surfaces are recognised: Gondwana (Mid to end Jurassic), Post-Gondwana (Early Cretaceous), African (Mid-Cretaceous to end Oligocene), Post African (Miocene), Pliocene (Pliocene) and Quaternary (end Pliocene to the present day).

The last glaciation to affect southern and eastern African cratons was the Dwyka glaciation and its end defines the start of the weathering processes. However, the effects of palaeoclimate upon the rate and scale of rock weathering are not fully understood.

Weathering processes appear to have been at their most intense during the early Cretaceous when the atmosphere of the planet was affected by a period of volcanic activity that resulted in increased temperatures and atmospheric acidity. Deep weathering profiles were produced that have been preserved in highland areas.

2.2.1 Erosion Surfaces

Dixey (1960) and Arthaud et al., (1990) identified a Jurassic surface at about 1850 masl with residuals rising above 2 200 masl. These mainly granite inselbergs and the surrounding surface probably equate with the Post Gondwana Surface. Some groundwater discharges from spring zones and fanglomerates peripheral to these inselbergs.

They recognised the presence of extensive plateau areas within the highland area at elevations of 1 300 masl. A notable area is the Antananarivo Plateau. These areas Dixey recognised as the Late Cretaceous Surface that equates with the African erosion surface of mid-Cretaceous to end-Oligocene age and is preserved along the central north-south topograhic divide. Weathering to depths of 30-50 m has been recorded within Basement Complex rocks associated with this surface in Malawi and Uganda. Within the High Plateau region, thick lateritic soils occur above thick clayey saprolite material. Therefore, relatively deep boreholes will be needed to obtain water away from valleys. Water yields are likely to be small (0.1 – 0.5 l/s) and probably of poor quality. In the southern half of the project area and west of the north-south rift the African surface is being actively eroded as indicated by the presence of numerous lavaka or gullies. This zone of eroded and dissected areas, with a weathered zone 20-40 m thick, typically has with deep valleys with convex sides and flat, alluvium filled valley bottoms. Lavakas are common, being actively eroded into laterite and underlying saprolite layers. Surface water infiltrates down into the saprolite giving rise to spring zones along valley sides. Water wells are concentrated in alluvium along valley bottoms, and there are numerous piped water schemes fed from springs.

The Post-African erosion surface of Miocene-age occurs at altitudes of about 1 000 m asl, as it does in Zimbawe and Malawi. The thickness of weathering in those countries varies from 15 to 30m being thickest being beneath regional watersheds. The erosion surface formed in response to widespread tectonic uplift and long-term sea level fall. The African surface weathered zones were eroded to reveal the areas of rounded granite inselbergs that characterise the Post-African erosion surface.

The Pliocene-age erosion surface occurs at elevations below 800 m asl and is characterised by deep valleys, much outcrop and little weathering in interfluve areas. Along the eastern coast these areas are described as “bad lands”. This erosion surface formed in response to general landsurface uplift. In the project area this surface is represented by the dissected badland areas where much of the weathered zone (up to 20 m thick) has been removed by erosion leaving thin soils with thin sand veneers. Water is obtained from fractures and shallow bedrock, and most water is derived from alluvium along the main rivers and streams. However, streams and rivers carry a lot of suspended sediments during the wet season.

The Quaternary-age erosion surface, of end of Pliocene to Recent-age is characterised by the deposition of alluvial deposits along the middle and lower reaches of the main rivers and as lake deposits within the main rift valley, e.g. Lake Alotra.

2.2.2 Patterns of Rock Weathering

Lateritic weathering profiles as developed on Precambrian Basement have been described by Ollier and Pain (1996) and Taylor and Eggleton (2001) related patterns of regolith formation to soils and landforms in tropical and arid areas. Tropical weathering and the formation of soils were investigated by Nahon (1991) and Tardy (1997) who developed pedological weathering profiles. These studies all highlight the importance of groundwater in the processes of regolith formation.

The thickness and lithology of zone of weathering are dependent upon long term changes in climate, changes in elevation due to tectonic activity, groundwater temperature and chemistry, and the impact of erosion. The tropical weathering profile (Figure 3) can include a superficial lateritic layer (1) within which seasonal, mainly lateral, water flow occurs through a deposit with nodular, vuggy or granular texture. Below, occurs a mottled clay layer (2) that grades downward to a fine clayey saprolite (4), thickest in the older profiles. A small quantity of water may be found within this layer, the upper part between horizons 2 and 3 being the zone of water table oscillation. The base of layer 3 may be marked by a thin smectite rich zone. (Figure. 6). The water table may fall to the base of layer 4 during prolonged drought. Layer 5 is coarse-grained sandy saprolite, in which groundwater is stored, the base of which commonly marks the weathering front. Limited weathering along decompression zones of horizontal fracturing may be observed within the upper parts of the underlying bedrock. Patterns of groundwater throughflow are sub-parallel to topography, groundwater discharging to local spring and stream systems (Figure 7). Where layers 1 to 4 are very thick then recharge to a thin layer 5 will be inhibited so that it will probably contain small quantities of poor quality water.

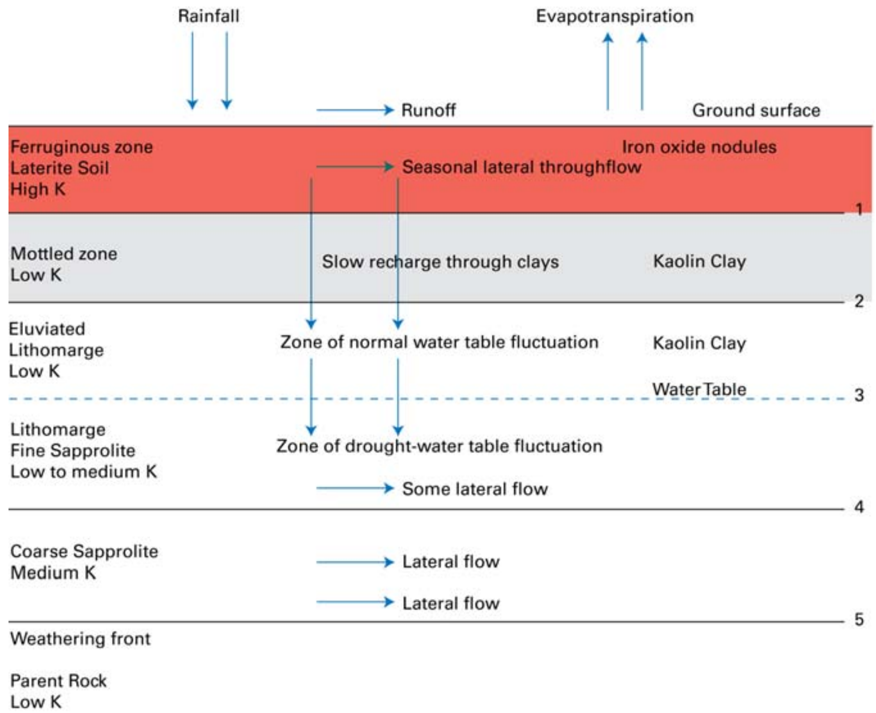


Fig. 6 Weathering profile (after Tardy, 1997; Nahon, 1991)

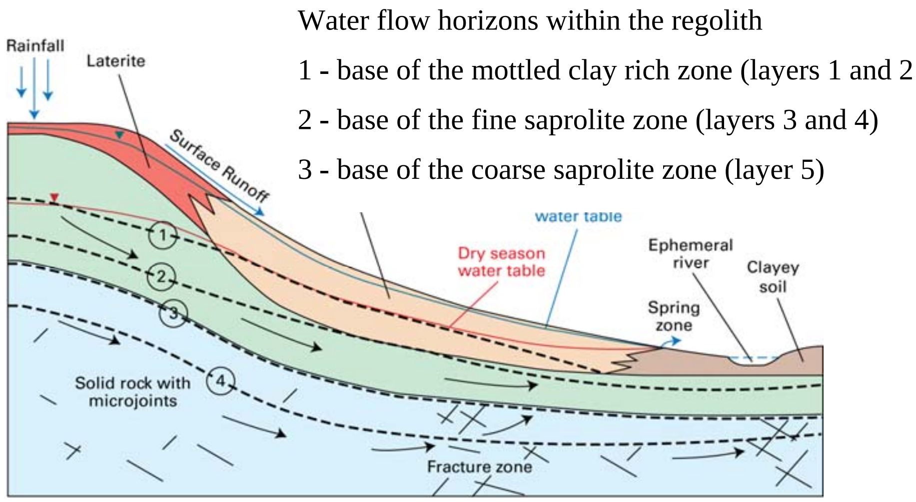


Figure. 7 Typical cross-section showing sub-parallel patterns of groundwater flow through the regolith zones

Similar lateritic weathering profiles, as developed on Precambrian Basement of the Central High plateau of Madagascar, have been described by Grillot (1990) in a hydrogeological context.

3 HYDROGEOLOGY

3.1 HYDROGEOLOGICAL STUDIES IN MADAGASCAR

Studies of groundwater occurrence in Crystalline Basement rocks of sub-Saharan Africa were consolidated in a thematic volume edited by Wright and Burgess (1992). Taylor and Howard (1997) further investigated the relationship of geomorphology and groundwater occurrence in Uganda. Groundwater flow through weathered Precambrian Basement strata has been studied in the small Ambohitrakoho catchment, located north of Antananarivo in central Madagascar, by Grillot and others during 1987-1993 (Dussarrat and Ralaimaro, 1993). These studies paralleled those being undertaken by Wright and others in Zimbabwe and Malawi during 1984-1990.

Grillot et al (1987), in their study of the 130 ha rice-growing Ambohitrakoho catchment on the crystalline basement rocks of the High Plateau region, recognised a waterbearing weathered zone comprising an unconfined aquifer in weathered laterite and a semiconfined aquifer in fissure granitic basement, separated by a clayey layer .

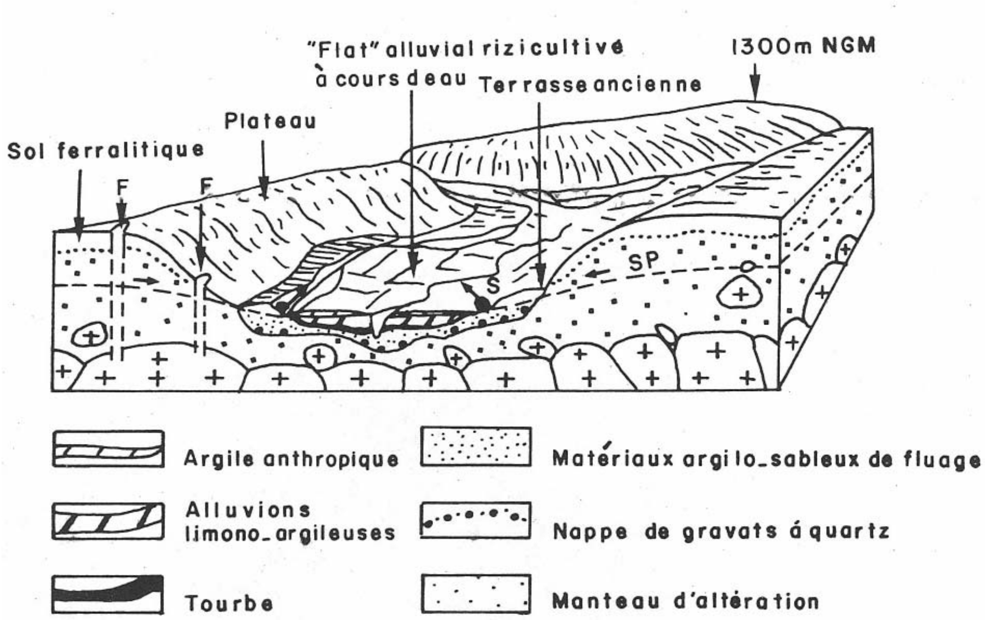


Figure 8. A 3-D diagram showing the distribution of weathering profile units within the studied catchment (Grillot and Raunet et al., 1990)

By 1989 a series of boreholes had been installed for the monitoring of water levels and water quality variations within the two aquifer units in response to seasonal rainfall (Grillot et al., 1989). As part of the ongoing study, the impact of neotectonic faulting upon groundwater occurrence and drainage was assessed (Arthaud et al., 1989). Valley incision occurs preferentially along zones of weakness due to faulting and fracturing (Arthaud et al., 1990).

In addition, an attempt was made using monitoring data, collected to estimate groundwater discharge through the catchment site. The results obtained appear to indicate that the pattern of groundwater flow present occurred, not at a local scale but, as part of a regional flow system (Grillot, 1989). Spring systems were observed to occur along the base of convex-sloping valley sides. The outflows from such springs and seepage zones are commonly channelled to feed into valley bottom rice-irrigation schemes. The discharges from such springs when monitored throughout a year showed differences in flow contributions, using isotope data, from the unconfined and confined aquifers between the wet and dry seasons (Grillot, 1990).

Grillot and Ferry (1990) investigated subsurface and surface flow patterns within a two-layer system comprising an unconfined aquifer in weathered laterite and a semiconfined aquifer in fissure granitic basement, separated by a clayey layer. Three major characteristics of surface-subsurface interaction were recognised:

1. Surface flows depend largely on the groundwater state of the unconfined aquifer within the interfluve areas.

2. Some infiltration occurs through the clayey cover of the lower ground, as recharge to the underlying semi-confined aquifer.

3. During and at the end of recharge, surface flows are maintained by the local weathered aquifer and by the rising water levels within the underlying sandy saprolite aquifer.

Recharge to the two layer weathered system preferentially occur within the interfluves, with rapid movement of water to the unconfined aquifer through which slower flow was observed to discharge points, and limited recharge through the semi-confining clayey zone to the sandy saprolite/fissured granite zone (Grillot and Blavoux et al, 1990). The findings of the study, reviewed in Grillot and Raunet et al (1990), concluded that the near surface clayey weathered aquifer discharges to valley bottoms enabling prolonged rice cultivation; the fissured and sandy weathered granitic/gneiss semi-confined aquifer is of regional occurrence discharging to major valley bottoms; and in the lowlands and major valley bottoms, water bearing sands receive upward flow from the fissured granite aquifer. Grillot et al., (1991) used analysis of water level data and the results of core sample permeability tests to demonstrate the upward leakage of water from the fissured and weathered granite aquifer into sand and peat deposits within the valley bottom.

Grillot (1992) and Grillot and Dussarrat (1992), in their reviews of project results, noted that the base of the near surface unconfined lateritic zone is clayey and not especially permeable, whereas permeability within the semi-confined saprolite is quite high vertically ($l0^{-4}$ m/s) and much lower laterally (10^{-7} m/s), according to both laboratory and field tests (Grillot et al. 1991). As a result, during the rainy season, the water level within the interfluve areas rises about 2-4 m, to fall again in the winter dry season (Grillot 1990; Grillot and Blavoux et al. 1990).

There is also significant groundwater within fissures in the underlying bedrock, which has a much slower (circa three-month) response to rainfall (Grillot and Dussarrat, 1992). In parallel with the decline during the dry season, the groundwater in the saprolite becomes warmer, richer in solutes, and isotopically heavier. Grillot and Blavoux et al. (1990) attributed this to the saprolite aquifer being fed from water coming back out of the underlying fissured bedrock, that contains older and poorer quality waters. Presumably the water circulates deeply in artesian or semiconfined fashion though fissured bedrock within the interfluves (Grillot and Dussarrat, 1992).

Rainwater infiltrates quickly without evaporation (Grillot,1992). The water that takes the deeper route moves down within the interfluves for most of the year (except during the later part of the rainy season when groundwater backs up). Then it moves down under the interfluves, within the fissured bedrock, to discharge through valley-floor sands, peats and clays. It flows up through the valley fill in sub-artesian fashion for most of the year, except the driest three months, during which water sinks below the valley (Grillot and Raunet et al., 1990; Grillot and Dussarrat, 1992). The shallow water on mid-hillside would appear to have a more complex response, flushing down under initial heavy rainfall, being drawn down during the driest months, and rising when the upslope pressure head is greatest at the end of the rainy season (Grillot and Raunet et al., 1990).

When saprolite shows different vertical and horizontal permeabilities, it presumably follows fabrics inherited from the parent rocks, whose orientations vary locally. Grillot does mention that the unconfined water in the saprolite discharges sideways along the sides of the valleys during all but the driest three months (Grillot and Raunet et al,. 1990). Nevertheless, considerable indirect evidence corroborates the inference of seepage and sapping.

In summary, the three aquifer types recognised within the weathered Basement Complex of the High Plateau by Grillot and others include:

Valley bottom alluvial sediment aquifer composed of porous clayey sands, peats and coarse-grained sands and gravels under semi-confined conditions. Static water levels tend to lie at 2-3 m below ground level (mbgl) and the depths of well/boreholes are in the range 5-20 m. The aquifer thickness is in the region of 10 m. and water quality tends to be fresh water but with occasional with high iron concentrations. Well/borehole specific capacities are in the range of 3 to 6 l/s/m (Specific Capacity in terms of yield per metre of drawdown).

The upper weathered zone aquifer occurs within the clayey and sandy saprolite below the sub-laterite clay zone. This unconfined to semi confined aquifer has water levels at 2-3 mbgl in wells and boreholes 4-15 m deep. The aquifer thickness may be about 5 m. Water quality tends to be fresh but with some mineralization. Well/borehole specific capacities are in the range of 0.2 – 0.5 l/s/m.

The lower weathered and fiissured Basement Complex rock aquifer occurs towards the base of the weathered zone. This unconfined to semi-confined layer has water-levels at 2-3 mbgl in wells and boreholes 5-20 m deep. The aquifer thickness is about 10 m. Water quality tends to be fresh with some mineralization. Well/borehole specific capacities rangefrom 0.8 to 1.4 l/s/m.

Latterly, Dussarrat and Ralaimaro (1993) attempted to apply the results of the Ambohitrakoho catchment (1.3 km^2) study to the much larger Mahitsy basin (117 km^2), with mixed results. Although the Ambohitrakoho catchment is located within the Mahitsy basin it cannot be considered representative of the whole basin.

The results of the studies of Grillot and others on the Ambohitrakoho catchment have been applied by Wells and Andriamihaja (1997) to examine the impact of groundwater flow patterns within the weathered basement in topographoically dissected areas to the genesis of lavaka formation. They understand that the process of lavaka formation is a combination of surface water erosion and groundwater outflow, primarily through seepage through the thick exposed saprolite zone that causes incision, spalling and slumping.

3.2 HYDROGEOLOGICAL INFORMATION

Within Madagascar, groundwater occurs within a series of series of eight hydrogeological regions described in United_Nations (1989) the PAEPAR programme (World_Bank, 2004), and Rakotondrainibe, (2005, 2006) (Figure 9).

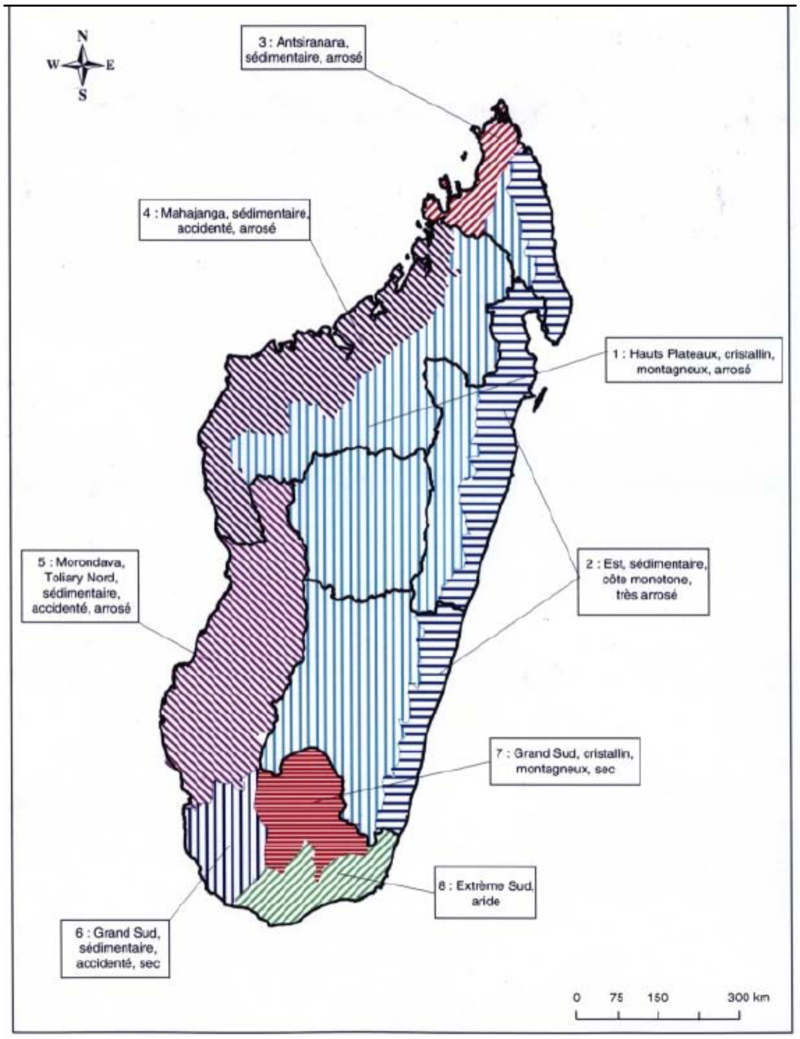


Figure 9. Location map of the eight hydrogeological regions (Rakotondrainibe, 2005)

The Project Area includes parts of the following four regions:

1. High Plateau (Precambrian basement)
2. Antsiranana Sedimentary basin
3. East Coast Sedimentary basin
4. Mahajanga Sedimentary Basin

Of the water development boreholes that have been drilled within the project area, most of those on Basement Complex are into shallow weathered zones. Some deeper boreholes have been drilled within the Phanerazoic sediments of the adjacent sedimentary basins. However, few hydrogeological data from these boreholes are availaible so that groundwater conditions are poorly understood. Groundwater occurrence within the project area is based upon the integration of geomorphologic, geologic, climatic and long-term weathering information and data to produce hydrogeological maps. Groundwater occurrence within the hydrogeological regions is summarised in table 2.

Region	Lithologies	Sources of water
High Plateau	Deep weathered deposits Sandy alluvial deposits Fractured and volcanic deposits Flow from sandy deposits	Weathered sandy sources Wells in sandy deposits Wells in alluvial deposits Surface waters Boreholes in fissured rocks
Mahajanga Sedimentary Basin	Alluvial deposits Beach sand deposits More clayey sandstone deposits	Wells in superficial deposits Wells in alluvial deposits Wells in coastal sand deposits Surface water Drilled boreholes in Eocene Limestones
Antsianana Sedimentary Basin	Alluvial deposits Beach sand deposits Quaternary volcanic deposits	Wells in alluvial deposits Wells in coastal sand deposits Surface water Sources in the volcanic deposits
Eastern Sedimentary Basin	Alluvial deposits Beach sand deposits More clayey sandstone deposits	Wells in alluvial deposits Wells in coastal sand deposits Surface water

Table 2 Aquifer lithologies and sources of water in each within in the hydrogeological environments present in the project area.

3.2.1 Available Hydrogeological Information

Site-specific hydrogeological assessments reported include surveys undertaken by the Bureau de Recherches Geologiques et Miniers at Andilamena, Fenerive, Lavaka Tsararano, Mananara, Maroantsetra, Vavatenina and Tsaratanana (Lemaire, 1963); and in Le District de Vohemar (Besairie, 1955). The aquifer properties of weathered Basement Complex strata have been studied in detail at a test catchment site north of Antananarivo (Grillot et al., 1990). Dussarrat and Ralaimaro (1993) used the results of the latter work to correlate patterns of groundwater occurrence with systems of weathering, faulting, and erosion. The present study used data and information from these and similar hydrogeological environments in Africa to outline of the hydrogeological characteristics of the project area.

3.2.2 Database

For the purposes of this study, data have been obtained from about 2760 sites located within three adjoining blocks to cover the extent of the geologically mapped areas. These include

Block 1: 1100–1600 N latitude; 500–800 E longitude

Block 2: 650–1100 N latitude; 270-800 E longitude

Block 3: 500-600 N latitude; 500-800 E longitude

Of the 2760 georeferenced sites located within the Project Area, types of water abstraction could be allocated to 2100 sites. The bulk of these sites were either piped water schemes obtaining water from spring zones, or are wells obtaining water from the shallow weathered zone (Figure 10). Only limited water level and water quality data were available from these sites. There being little or no geological data available, the sites were plotted on the project geomorphology map within ArcGIS so that the numbers of sites present within each geomorphologic unit could be determined. The results are shown on Table 3.

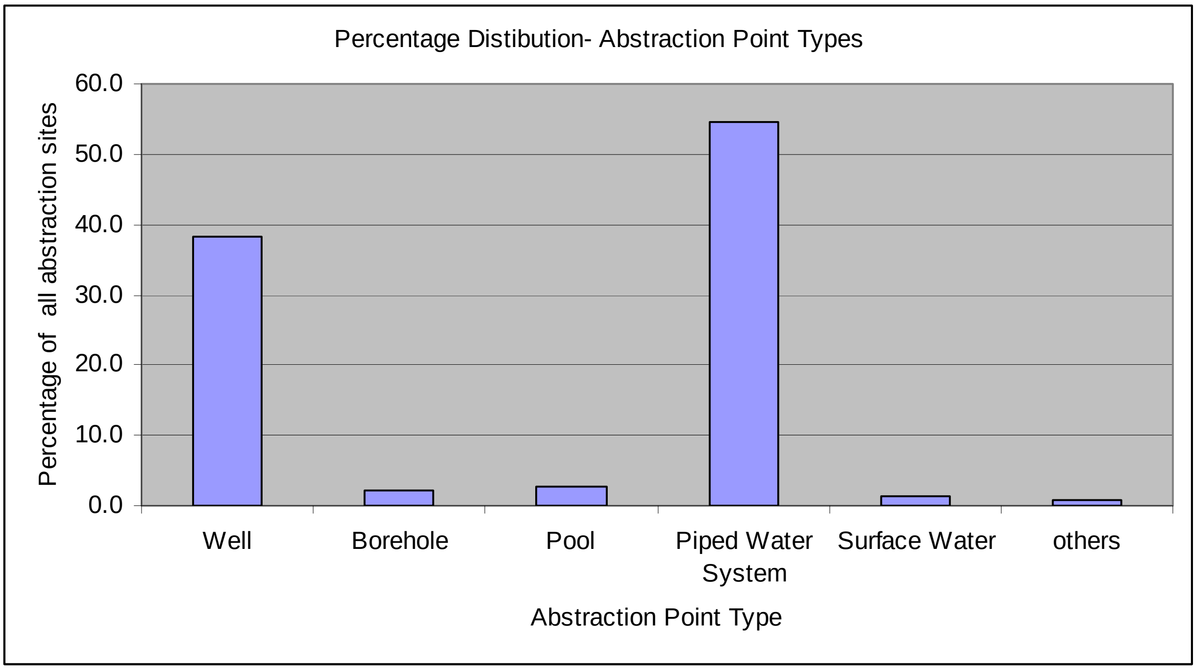


Figure 10. The percentage distribution of abstraction point types within the project area.

Key	Unit	Well	Borehole	Pool	Piped Water System
A	Alluvion anciennes (hautes terrasses)	7			3
B	Alluvions	306	10	15	103
C	Bad lands	6			3
D	Basses peneplains lateritiques	134	12	6	32
E	Carapace sableuse	44	13	27	11
F	Depots de cotiers indifference	27	2	1	4
G	Depots de plages	1			
H	Depots lacustres	27		1	15
I	Eventails alluvials	15	1		15
J	Hautes peneplaines lateritiques				11
K	Massifs et inselbergs				10
L	Relief lateritique de dissection profonde	83	7		165
M	Sables, dunes	69			8
N	Volcanites Neogene Quarernaires	2			43
O	Zone a lavaka ou lavaka dissemines	101	4	9	747
	Totals	822	49	59	1170

Table 3. The distribution of abstraction point types per geomorphologic unit in the project area

The distribution of sites indicates that significant numbers of sites are located on seven geomorphologic types.

3.2.3 Basement Complex Erosion Surfaces and Weathered Zones

ZONE A LAVAKA OU LAVAKA DISSEMINES

An area of active erosion of weathered Basement Complex rock aquifers located beneath the African late Cretaceous age erosion surface. Sites located include 101 wells, 747 piped water schemes and 4 boreholes. Water is mainly obtained from spring zones occurring at the base of lavaka gullies especially in the areas around and to the south and west of Anantanarivo.

Well depths range from 1-40 m with most being in the ranges 1-6 m and 10-20 m deep.

Depth to water table ranges from 1-20 m with most in the range 1–9 m.

Specific capacity range 1-8 m^3/hr/m of drawdown with most in the range 1-3 m^3/hr/m of drawdown.

Water quality - SEC 50-1000 µS.cm^{2-1} with most in the range 50-100 µS.cm^{2-1}; and pH range of 6-8.

RELIEF LATERITIQUE DE DISSECTION PROFONDE

Weathered Basement Complex rock aquifers located beneath the Post-African erosion surface. Sites located include 83 wells, 165 piped water schemes and 7 boreholes. Here water is obtained from valley side springs and valley bottom wells.

Well depths range from 1-15 m with most being 4-7 m deep.

Depth to water table ranges from 1-10 m with most in the range 2–5 m.

Specific capacity range 1-2 m^3/hr/m of drawdown.

Water quality - SEC 50-2000 µS.cm^{2-1} with most in the range 50-500 µS.cm^{2-1}; and pH range from 5-9 but most from 6-8.

BASSES PENEPLAINS LATERITIQUES

Weathered Basement Complex rock aquifers located beneath the Pliocene age erosion surface. Sites located include 134 wells, 32 piped water schemes and 12 boreholes. Within the lower eroded areas, greater reliance has to be placed on wells to supply water.

Well depths range from 2-40 m with most being 5-15 m deep, indicating that the depth of weathering is of the order of 15m.

Depth to water table ranges from 1-13 m with most in the range 2–8 m.

Water quality - SEC 50-2000 µS.cm^{2-1} with most in the range 100-1000 µS.cm^{2-1} ; and pH range from 6-9 but most from 7-9.

3.2.4 Phanerozoic Sedimentary Rocks

CARAPACE SABLEUSE

Superficial sandy aquifers are composed of weathered sandstones of Karoo age. Sites located include 44 wells, 11 piped water schemes and 13 boreholes. The flatter land surface and deeper aquifers are indicated by greater reliance on wells and boreholes for water abstraction.

Well and borehole depths range from 3-40 m with most being 10-35 m deep.

Depth to water table ranges from 1-13 m with most in the range 3–9 m.

Water quality - SEC 50-2000 µS.cm$^{2-1}$ with most in the range 100-1000 µS.cm$^{2-1}$; and pH range from 6-9 but most are about 8.

3.2.5 Phanerozoic Igneous Rocks

VOLCANITES NEOGENE QUARERNAIRES

Igneous volcanic aquifers are composed of basalts, trachytes and pyroclastics of Neogene to Quaternary age. Sites located include 2 wells and 43 piped water schemes. Within this unit almost all water is obtained from spring zones issuing from the lower slopes of the volcanic massifs. Hence, information is derived from spring flow sources only.

Specific capacity range 1-10 m^3/hr/m of drawdown.

Water quality - SEC 50-1000 µS.cm$^{2-1}$ with most in the range 50-100 µS.cm$^{2-1}$; and pH range from 6-8 but most from 7-8.

Warm springs, as indicated by place name, are often associated with recent tectonic and volcanic activity

3.2.6 Neogene Sedments

ALLUVIONS

River and delta alluvial aquifers are composed of unconsolidated clays silts and sands of Quaternary to Recent age. Sites located include 306 wells, 103 piped water schemes and 10 boreholes. About 75% of the sites are shallow wells located within valley floor river alluvial deposits.

Well depths range from 2-20 m with most being 4-7 m deep.

Depth to water table ranges from 1-10 m with most in the range 2–5 m.

Specific capacity range 1-2 m^3/hr/m of drawdown.

Water quality - SEC 50-2000 µS.cm$^{2-1}$ with most in the range 50-500 µS.cm$^{2-1}$; and pH range from 5-9 but most from 6-8, some problems with high dissolved iron content.

DEPOTS LACUSTRES

Lake lacustrine sediments aquifers are composed of unconsolidated clays silts and fine- to medium-grain sands of Quaternary to Recent age. Sites located include 27 wells, 15 piped water schemes and one borehole. In these flat lying finer grained silts and sands most water is obtained from shallow wells.

Well depths range from 4-25 m with most being 5-8 m deep.

Depth to water table ranges from 2-11 m with most in the ranges 3–5m and 10m.

Specific capacity range 2-3 m^3/hr/m of drawdown.

Water quality - SEC 50-2000 µS.cm$^{2-1}$ with most in the range 50-500 µS.cm$^{2-1}$; and pH range from 5-8 but most from 7-8.

SABLES, DUNES

Coastal sand dune aquifers are composed of unconsolidated silts and fine-grained sands of Quaternary to Recent age. Sites located include 69 wells and 8 piped water schemes. Most water is obtained from shallow wells.

Well depths range from 3-9 m with most being 3-7 m deep.

Depth to water table ranges from 1-7 m with most in the range 3–5 m.

Water quality - SEC 50-500 µS.cm$^{2-1}$ with most in the range 100-500 µS.cm$^{2-1}$; and pH range from 5-9 but most from 6-8.

3.3 HYDROGEOLOGICAL ENVIRONMENTS

A series of hydrogeological environments have been recognised by applying combinations of geomorphologic units and their hydrogeological characteristics as described above within the UNESCO hydrogeological mapping legend for typical aquifer groups. In so doing the following hydrogeological environments have been identified:

3.3.1 Unconsolidated Granular Aquifers

- Unconsolidated sediments including coastal dunes, alluvial deltas and fluvial valley deposits. These sedimentary aquifers normally have moderate to high yields.

3.3.2 Fissured Aquifers

- Karstic Mezozoic to Tertiary limestones, that can have moderate yields.
- Fissured Permian to Tertiary sedimentary and volcanic rocks, with weathered lateritic surface horizons. These generally have low to moderate yields.

3.3.3 Low Permeability Formations

- Weathered Precambrian Crystalline Basement with latersol above saprolite up to 50 m thick with two aquifer layers yielding 0.5-2.0 l/s.
- Weathered Precambrian Crystalline Basement with latersol above saprolite less than 20 m thick yielding less than 1.0 l/s.
- Hard rock inselbergs of Precambrian and younger granite with small low yielding springs around periphery.
- Coastal mangrove swamps with highly saline waters.

The distribution of the main hydrogeological environments is shown on Figure 11a. The distribution of groundwater conductance and water table depth data and ranges are shown on Figures 11b and 11c.

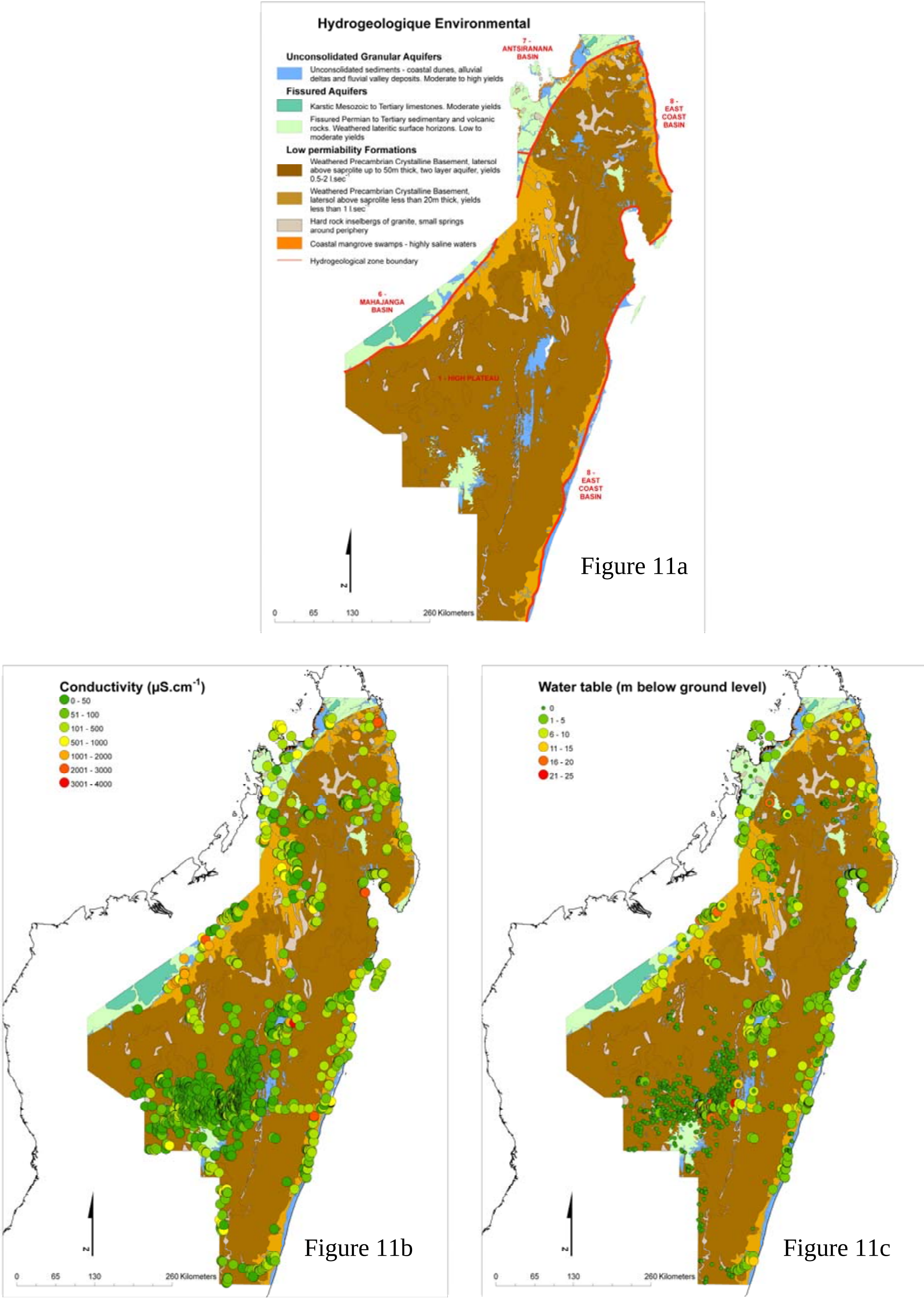


Figure 11. The distribution of mapped hydrogeological environments (11a) with groundwater conductance (11b) and depth to water table (11c) maps.

4 GOUNDWATER DEVELOPMENT

4.1 GROUNDWATER USE

Groundwater is a major source of public supply for Madagascar. Groundwater is used in conjunction with surface water to supply the towns of Fianarantsoa and Antsirabe. The towns of Majunga and Toliary use groundwater from the Eocene limestone aquifer. In the Basement Complex areas smaller quantities of groundwater occur in fractures and shallow weathered bedrock.

In the High Plateau region villagers dig wells to tap the alluvial sand aquifer. Unfortunately, these wells have not been catalogued and the volume of water drawn off is not known. The following problems have occurred during ground water use:

- The high iron concentration in alluvial aquifer groundwaters
- Intrusion of salt water in the coastal aquifers following excessive pumping.

4.2 GOVERNMENT WATER RESOURCES INSTITUTIONS

Government institutions associated with groundwater resource evaluation and development include:

- The Ministry of Energy and Mines (MEM) manages groundwater and drinking water including water quality (2002). MEM to be decentralised to six regional bodies within the DIRMEM.
- The Energy Service (Hydrogeology Division) of the Department of Mines and Energy, is responsible for groundwater prospecting, exploitation and protection; available equipment includes drilling rigs, test-pumping equipment and electrical geophysical surveying equipment.
- The Drilling and Equipment Division, a section of the Department of Mines and Energy, is responsible for deep-drilling work.
- The Meteorology Department manages surface water (2002)
- Ministry of Farm Production and Agrarian Reform
- The Hydraulics Service, responsible for irrigation.
- JIRAMA - A state enterprise responsible for water distribution in urban areas Investments and activities in the private sector are very limited, apart from the parastatal company JIRAMA which runs most of the principal urban water systems in the country (66 in all) which is responsible for electricity and water.
- The National Authority for Water and Sanitation (ANDEA) public water supplies and sanitation. ANDEA will propose priorities regarding access to water resources (after 2002).

4.3 GROUNDWATER DEVELOPMENT IN RURAL AREAS

Commonly used groundwater abstraction systems include dug wells, boreholes and gravity flow piped water from spring capture. The hydrogeological parameters that determine the choice of construction include: depth to groundwater table, depth to water bearing formation, aquifer thickness and extent, maximum acceptable drawdown and water-bearing formation development potential.

4.3.1 Dug Wells (Figure 12)

The national programme for rural water supply, PAEPER, gives priority to the construction of dug wells, lined with concrete rings, protected by concrete slabs and equipped with hand pumps. Dug wells are relatively cheap and easy to construct, provided that the water bearing formations are unconsolidated and not deeper than 15 m. Dug wells of 20 m depth are exceptional. They are rarely constructed in solid rock that needs equipment like pneumatic hammers or explosives. In almost impermeable formations, wide diameter wells can be useful, as the well can function as a storage reservoir.

Dug wells, equipped with hand pumps, have low yields of about 5 to 10 m^3/day. A typical dug wells can be equipped with a bucket, rope and windlass or a simple rope pump.

Compared to boreholes, dug wells have poor sanitary conditions and the period of construction is often limited to the dry season when the water table is deepest.

Dug wells are mainly distributed in coastal areas, around lakes and in valleys associated with the Post-African erosion surface where the weathered zone is less than 20 m thick (see map on Figure 12).

4.3.2 Boreholes (Figure 13)

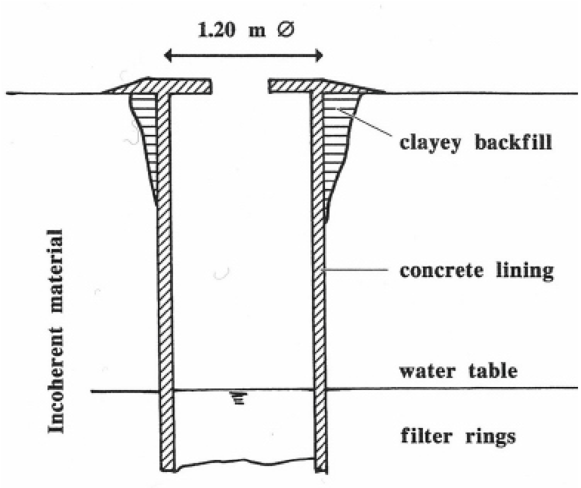
Boreholes are installed when the water table or the water bearing formation is deeper than 10 or 20 m, or located in solid rock. They are preferred if the source has to supply more than 500 persons. Most boreholes are located within the sedimentary basins to the west of the Central Highlands and in sedimentary formations along the eastern coast (see map on Figure 13).

4.3.3 Piped Water Schemes (Figure 14)

Spring protection can provide an economical and sustainable alternative to wells in areas with springs or seepage zones, especially if the water can be piped by gravity to the community. The construction method is often simpler and the contamination risk smaller than with well construction. In seepage zones, infiltration wells or galleries may need to be constructed.

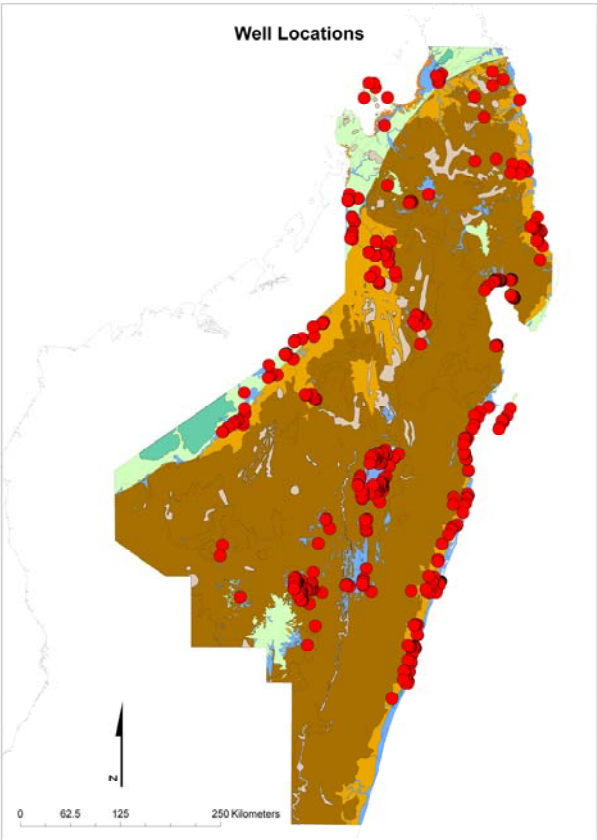
Piped spring fed water schemes are found mainly in the lavaka eroded areas around Antananarivo and to the south and west of the city, in the steep valleys along the eastern seaboard and in valleys associated with the African erosion surface in the northern parts of the project area (see map on Figure 14).

Figure 12 - Hand Dug Wells - Installation and Distribution



Well design for construction in soft alluvium

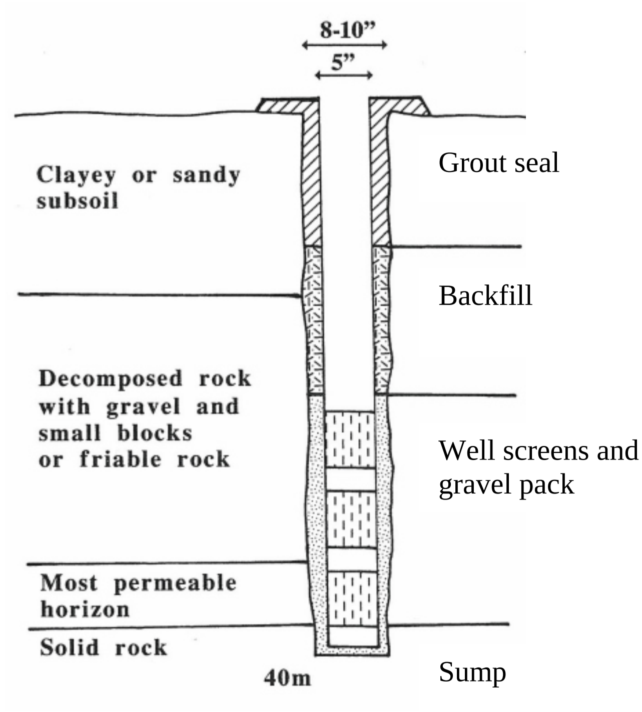
Well being dug through latasol weathered material



Map showing the distribution of wells within the project area

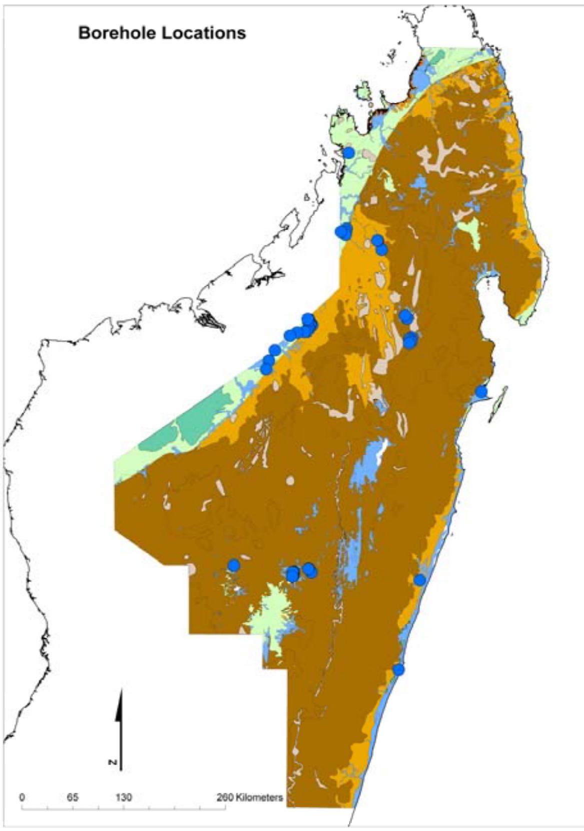
Hand Dug Wells
Depths – 15 to 20 m, 3 to 4 m below water table
Diameter -1.2 to 2m in permeable formations
Completion – concrete rings and surface surround with wall (lower photograph)
Lifting device – bucket and rope or hand pump

Figure 13 - Boreholes – Installation and Distribution



Borehole design for weathered layer over decomposed rock

Borehole being drilled with down the hole hammer drilling rig



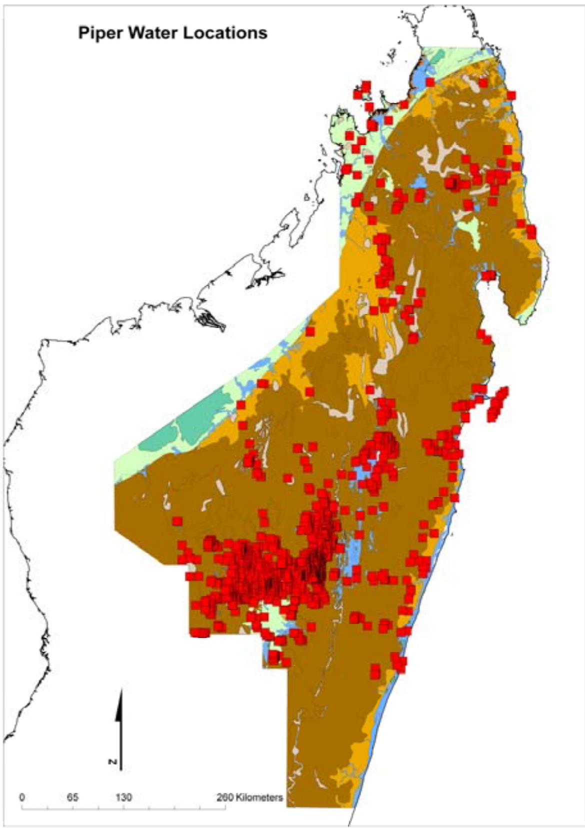
Map showing the distribution of boreholes within the project area

Boreholes
Drilling – down the hole hammer
Casing – pvc, Screens – 1 mm slots
Gravel pack – 2-5 mm diameter gravel
Pump – Afridev, India Mk II or Mk III
Completion – surface concrete surround with channel to soak-away

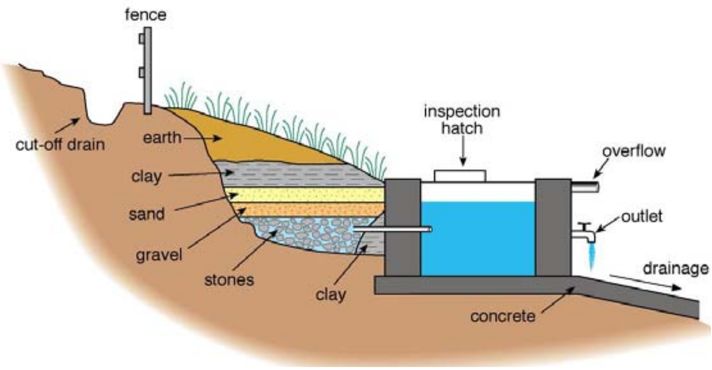
Figure 14 - Spring-fed Piped Water Supply Systems – Installation and Distribution

Unprotected spring

Spring outflow collection system with reservoir and outflow pipe



Map showing the distribution of spring-fed piped water supply systems



Spring outflow collection system design

Protected area and outflow box with wing walls

Piped Water Supply Systems

Location - many tap spring seepage zones at the base of lavakas

Water distribution – gravity flow through open channels to fields for irrigation or piped to village compounds for domestic supply

5 HYDROGEOLOGY MAPS

5.1 METHODOLOGY

A series of seven hydrogeological maps of Northern and Central Madagascar have been produced at 1:500,000 scale. These were compiled using the analysis of limited existing information and data made available. These data and information include:

- general descriptions of the hydrogeology of Madagascar that include the definition of eight hydrogeological areas,
- an Excel spreadsheet of water abstraction point data compiled for the PAEPAR Project providing the georeferenced distribution of surface-water and groundwater abstraction units with hydrogeological data,
- an Excel spreadsheet of urban groundwater abstraction units compiled by JIRAMA that includes hydrogeological data obtained from wells and boreholes located by site name with no grid reference,
- early BRGM reports describing specific hydrogeological studies,
- papers by Grillot and others describing groundwater occurrence within weathered crystalline basement rocks at an experimental catchment site located north of Antananarivo.

Additional information was obtained from studies undertaken in similar hydrogeological environments elsewhere in eastern and southern Africa.

Compilation of a hydrogeological map within a GIS required:

- base map layer of simplified geological units,
- map layer of geomorphological units,
- layers of topography (DEM) and drainage,
- Available georeferenced abstraction points with attached hydrogeological parameter data, e.g. water quality (in terms of TDS) and depth to water table (mbgl),
- understanding of hydrogeological conditions probably present, especially possible groundwater resources, their relationship with rainfall and drainage flow patterns.

Hydrogeological conditions probably present have been informed by comparison with similar hydrogeological environments in adjacent areas of mainland Africa.

Previous regional hydrogeological studies have been simple inventories of groundwater abstraction units, accompanied by thematic maps, based on some of the following data:

- Site X and Y coordinates; Borehole/well number; Borehole/well name,
- Region; District; Town; Village; Site; Population total ; Number of families,
- Nature of water abstraction point; Make of pump; Year completed,
- Height of water table above borehole/well base; Static water level (below ground level),
- Borehole/well total depth; Specific yield (m^3/hr/m of drawdown); Well diameter,
- Specific Electrical Conductance; pH.

Much of the shallow groundwater resources of the mapped area occur within a thick weathered zone mantled by lateritic soils and associated clay deposits. These groundwater deposits have in general been accessed via spring zones and shallow wells as only a few boreholes have been installed. Consequently little basic hydrogeological data needed to describe the groundwater systems have been collected. This lack of data and the uneven distribution of available data made it necessary to apply surrogate information to define probable hydrogeological units and to indicate their possible distribution. The approach used to locate and define the hydrogeological units within an Arc GIS employed the following stages:

Stage 1 – simplification of the geological units present as a base layer with patterns of primary and secondary drainage

Stage 2 – use of geomorphological units to define seven hydrogeological environments

Stage 3 – location of available spring zone, well and borehole data to show their distributions within the hydrogeological environments

Stage 4 – synthesis of the above data to establish hydrogeological units of the legend and define their limits on the maps

Stage 5 – compilation of insert maps showing water quality (in terms of specific electrical conductance) on geomorphological units and depths to water table on a digital elevation model map

5.2 THE LEGEND

The Legend of the Map is in accordance with the UNESCO “International Legend for Hydrogeological Maps”, published in 1970 and revised in 1983.

The main items of legend are:

5.2.1 On the main Map

- Hydrogeological environments
- Summary Lithstratigraphic Units
- Structural Elements
- Surface water drainage (primary and secondary)
- Groundwater abstraction units

5.2.2 On Insert map 1:

- Geomorphology units
- water quality (in terms of specific electrical conductance)

5.2.3 On Insert map 2:

- Depth to water table
- Topography (Digital Elevation Model)
- Structural lineations

5.2.4 The main map - Groundwater Occurrence

Groundwater occurrence within hydrogeological environments is the Legend's main theme. The legend is divided into 3 Classes and 7 Groups. The Classes are represented by colours (A - blue, B - green and C - brown) and the Groups by the tone of the respective colour. The units are depicted by summary lithostratigraphic ornaments.

The division into Classes (A,B,C) is based on porosity type, aquifer extent and formation productivity.

The blue coloured Class A represents aquifers comprising continuous unconsolidated or semi-consolidated sediments, with water present in connected intergranular pores. Yield range 3 - > $50m^3/h$ (0.8 – 14 l/sec).

Green Class B represents aquifers comprising aquifers where water flows mainly through fractures and fissures. These are mainly discontinuous in consolidated rocks including cemented sandstones and karstic limestones. Yields range from 3 to > 50 m^3/hr (0.8 – 14 l/s).

Brown Class C represents areas with limited or local groundwater occurrences and areas with little or no groundwater resources. The porosity can be intergranular or fissured. Yields occur in the range of 1 – 5 $m^3/hour$ (0.27 – 1.4 l/sec)

The subdivision of each class into three respective groups (A1-A3, B1-B3, C1-C3) is mainly based on prospects of boreholes, assuming a standard drawdown of 10m. The classification of a water-bearing formation is based on statistical analysis of observed specific capacity. Where insufficient data are available, the classification has been made on the basis of comparison with known formations with similar geology and morphology.

In addition to the productivity criteria, the subdivision of Class C is based upon geological and morphological characteristics. Group C1 (dark brown) consists of areas with local continuous or discontinuous aquifers, that are unconsolidated towards the surface. Yield prospects are generally below 5 m^3/hr. Group C2 (medium brown) comprises areas with fissured formations of very low productivity and yield prospects below 3 m^3/h. Group C3 (light brown) represents areas with hardly any groundwater resources and is morphologically defined as mountainous.

For crystalline rocks, the subdivision of class C is mainly based upon how the thickness, degree and texture of weathering is related to borehole/well yield .

The areas of Group C1 have a well developed weathering mantle, which can reach a thickness of 20 to 50 m. These areas are geomorphologically defined as flat areas with hardly any rock outcrops or lineaments. The groundwater occurrence in these areas is related to the deeply developed weathering mantle and/or to the associated fracture zones. The distribution of the water within the weathering profile is rather complex, but the main circulation is related to the more permeable transition zone from the weathering saprolite to the parent rock. Normally the aquifers are of a local character and of limited extent. In the crystalline rocks, Group C1 is a complex unit with local aquifers and adjacent areas with limited or without any groundwater resources.

The areas of Group C2 have a less developed weathering mantle with a thickness that only rarely reaches 20 m. Geomorphologically, they are characterised by undulating to flat areas with common rock outcrops or lineaments. Usually, groundwater resources in these areas are restricted to the secondary openings in the lower parts of the weathered rocks. Group C2 is a complex unit with areas of very limited groundwater resources and some linear aquifers.

The areas of Group C3 are mountainous and have no significant weathering mantle or groundwater resources. They are geomorphologically distinguished by their relief and by dominant rock outcrops. The only possibility of finding groundwater in these regions is along fault and fracture zones, often associated with springs and seepage zones.

The classification and extent of hydrogeological environments on Basement Complex and Volcanic Terrains are based on the geomorphological interpretation of satellite images, correlated with water level and well depth records. Relevant terrain characteristics include rock outcrops and lineaments, relief, drainage pattern, vegetation, soils, lithostratigraphy and structure.

5.2.5 Signs, symbols and additional information

In addition to the classification of water-bearing formations, described in the previous section, the Maps provide a variety of other information concerning groundwater occurrence. Most of the symbols can be readily interpreted by reference to the Legend, but some require further explanation.

The representation of springs on the main map is not systematic due to the absence of a country-wide inventory.

Insert Map 1 indicates water quality in terms of total dissolved solids shown on the map by proportional symbols (Table 4).

Maximum TDS Limit	Purpose
500 mg/l	Limit of good quality water for all purposes
1000 mg/l	Limit for irrigation of most crops
1500 mg/l	Limit of acceptable water for domestic use
5000 mg/l	Limit for livestock in semi-arid areas

Table 4 . TDS concentrations related to water use.

Insert Map 2 indicates depth to the groundwater table from the surface, in order to facilitate practical applications: 20m corresponds to the maximum limit of dug wells.

6 REFERENCES

Arthaud, F., J. C. Grillot, et al. (1989). "Controle neotectonique des directions de drainage sur les hauts plateaux de Madagascar." C. R. Acad. Sci. Paris 308(Serie II): 527-530.

Arthaud, F., J. C. Grillot, et al. (1990). "La tectonique cassante a Madagascar: son incidence sur la geomophologie et sur les ecoulements." Canadian Journal of Earth Sciences 27: 1394-1407.

Autorite Nationale de 'Eau et de l,Assainissement. (2003). Schema Directeur de Mise en Valeur des Ressources en Eau du Grand Sud de Madagascar: pp 212.

Besairie, H , 1955. Documentation Geologique Miniere et Hydrogeologique sur Le District de Vohemar. Haut Commissariat de Madagascar et Dependances, Documentation du Bureau Geologique, Numero 98.

Bourgeat, F. and M. Petit (1969). "Contribution a l'etude des surfaces d'aplanissement sur les Hautes Terres centrales malgaches." Annales De Geographie: 157-188.

BURGEAP, Etudes_et_Conseils_Plus, et al. (2003). Assistance for the elaboration of development policy of Water and Sanitation in Rural Areas. Report R1: Temporary Report on Analysis of the Actual Situation and Future Needs, Water and Sanitation Department Project Bureau Paepar. Ministry of Energy and Mines.

Davies, J. and Robins, N.S. , 2007. Groundwater Occurrence North of the Limpopo: Are Erosion Surfaces the Key? Geological Society of South Africa, Groundwater Conference, Bloemfontein, South Africa, 8-10 October 2007. 13 pages.

Daw, R. K. (2004). Manually operated pumps for drinking water supply in Madagascar, UNICEF, RWSN and SKAT. September 2004.

Dixey, F. (1960). "The geology and geomorphology of Madagascar, and a comparison with Eastern Africa." Quarterly Journal of the Geological Society of London 116: 255-268.

Donque, G. (1972). The Climatology of Madagascar. Biogeography and Ecology in Madagascar. R. Battistini and Richard-Vindard. The Hague, Junk: 87-144.

Dussarrat, B. and Ralaimaro, J. , 1993. Hydrogeological characterisation of drainage basins in weathered basement of a high altitude tropical zone: Hautes Terres, Madagascar. Hydrogeologie, vol 1, pp 53-64.

Erpf, K. and J. Gomme (2005). Mission Report on the evaluation of rapid well jetting and the CANZEE Handpump. Programme of MEDAIR in the regions of Maroantsetra and Manantenina, RWSN: 95.

Grillot, J. C. (1989). "Analysis of groundwater discharges estimation in weathered medium (high plateaux of Madagascar)." Journal of African Earth Sciences 8(1): 51-55.

Grillot, J. C. (1990). "Caracteristiques d'emergences en milieu alteritique d'altitude: leur apport a la comprehension de l'aquifere bicouche arenes-socle (Hauts Plateaux de Madagascar)." Comptes_Rendus_de_L'Acadamie_des_Sciences_Paris_Hydrogeoloie 311(Serie II): 227-232.

Grillot, J. C. (1992). "Regime des eaux souterraines en milieu critallin altere: un exemple en zone intertropicale humide d'altitude (Madagascar)." Hydrological Sciences Journal 37(2): 105-117.

Grillot, J. C., B. Blavoux, et al. (1987). "A propos des aquiferes d'alterites sur les hauts plateaux cristallophylliens de Madagascar." Comptes Rendus de L'Acadamie des Sciences Paris Hydrogeoloie 305(Serie II): 1471-1476.

Grillot, J. C., B. Blavoux, et al. (1989). "Dynamique en hautes eaux des aquiferes d'alterites sur les hauts plateaux cristallophylliens de Madagascar." Journal of Africal Earth Sciences 9(3/4): 599-607.

Grillot, J. C., B. Blavoux, et al. (1990). "Recharge des aquiferes de type bicouche en zone tropicale d'altitude: Exemple des hauts plateaux gneissique alteres de Madagascar." Geodinamica Acta (Paris) 4(4): 227-235.

Grillot, J-C and Ferry, L. 1990. Approche des échanges surface-souterrain en milieu cristallin altéré aquifère. Hydrol. Continent. 5(1): 3-12.

Grillot, J. C., M. Raunet, et al. (1990). "Comportement piezometrique des nappes d'alteruites en zone intertropicale humide d'altitude (hauts palteaux de Madagascar)." Journal of Hydrology 120: 271-282.

Grillot, J. C., D. de_Endolenko, et al. (1991). "Permeabilites de materiaux reposant sur socle cristallin: un example en zone intertropicale (Madagascar)." Comptes_Rendus_de_L'Acadamie_des_Sciences_Paris_Hydrogeoloie 313(Serie II): 959-964.

Grillot, J. C. and B. Dussarrat (1992). "Hydraulique des unites d'interfluves et de bas-fond tourbeux: un example en zone de socle altere (Madagascar)." Journal of Hydrology 135: 321-340.

Interconsult (1985) *National Master Plan for Rural Water Supply and Sanitation: Hydrogeology.* Ministry of Energy and Water Resources and Development, Republic of Zimbabwe.

King L C (1967) *The Morphology of the Earth.* 2nd Edition, Edinburgh, Oliver and Boyd.

Lemaire, B. , 1963/1964. Rapport Hydrogeologique sur l'alimentation en eau de la ville de: at Andilamena (TAN 64 – A/16), Fenerive (TAN 64 – A/11), Lavaka Tsararano (TAN 64 – A/16), Mananara (TAN 64 – A/9), Maroantsetra (TAN 64 – A/2), Vavatenina (TAN 64 – A/12) and Tsaratanana (TAN 63 – A/19). Bureau de Recherches Geologiques et Miniers.

Lister, L. A. (1987). The Erosion Surfaces of Zimbabwe., Zimbabwe Geological Survey.

McFarlane M J , Chilton P J and Lewis M A (1992) Geomorphological controls on borehole yields; a statistical study in the area of Basement rocks in central Malawi. In: Wright E P and Burgess W G (eds) *Hydrogeology of Crystalline Basement Aquifers in Africa.* Geological Society Special Publication, No 66, pp 131-154.

Minten, B. , Razafindralambo, R. , Randriamiarana, Z. and Larson, B. , 2002. Water Pricing, the New Water Law, and the Poor: An Estimation of Demand for Improved Water Services in Madagascar. USAID - Ilo program - Cornell University, Report S12 - February 2002

Nahon D B (1991) *Introduction to the Petrology of Soils and Chemical Weathering.* London and New York, Wiley.

Ollier C and Pain C (1996) *Regolith, Soils and landforms.* London and New York, Wiley.

Partridge, T.C. and Maud, R.R. , 2000. Macro-scale Geomorphic Evolution of Southern Africa. In:Partridge, T.C. and Maud, R.R. , editors. The Cenozoic of Southern Africa. Oxford Monographs on Geology and Geophysics No. 40, Oxford University Press, pp 3-18.

Rakotondrainibe, J. H. (2005). Les 8 zones hydrogeologiques et les principales nappes aquifers de Madagascar.

Rakotondrainibe, J.H. , 2006. Synthesis de La Geologie et de L'hydrogeologie de Madagascar.

Struckmeier, W.F. and Margat, J. , 1995. Hydrogeological Maps: A Guide and Standard Legend.. International Association of Hydrologists, Volume 17.

Tardy Y (1997) *Petrology of Laterites and Tropical Soils* (Translated from Petrologie des Laterites et des Sols Tropicaux, 1993). Rotterdam, Balkema.

Taylor G and Eggleton R A (2001) *Regolith Geology and Geomorphology in Australia*. London and New York, Wiley.

Taylor R G and Howard K W F (1996) Groundwater Recharge in the Victoria Nile Basin of East Africa: Support for the Soil Moisture Balance Approach Using Stable Isotope Tracers and Flow Modelling. *Journal of Hydrology*, vol 1996, pp 31-53

United_Nations (1989). Madagascar. Groundwater in Eastern, Central and Southern Africa, Department of Technical Co-operation for Development. No. 19, ST/TCD/6: 132-149.

Vegter J R (2001) *Groundwater Development in South Africa and an Introduction to the Hydrology of Groundwater Regions*. Water Research Commission Report no TT134/00.

WaterAid_Madagascar (2002). Poverty Reduction Stratergies in Madagascar: Water Supply and Sanitation., WaterAid/Ministry of Energy and Mines.

Wells, N.A. and Andriamihaja, B.R. , 1997. 2 Extreme gully erosion in Madagascar and its natural and anthropogenic causes. In: Goodman, S.M. and Patterson, B.D. (editors). Natural Change and Human Impact in Madagascar. Smithsonian Institution Press, Washington, pp 44-74.

World_Bank (2004) Project-pilote d'Alimentation en Eau Potable et d'Assainissement en milieu Rural (PAEPAR) Credit 3025-MAG. Ensemble, Reduire La Pauvrete: Madagascar - Banque Mondiale 2004 **Volume**, 43-45 DOI:

Wright E P and Burgess W G (1992) *Hydrogeology of Crystalline Basement Aquifers in Africa*. Geological Society Special Publication, No 66, pp 1-27.