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HYDROGEOLOGICAL MAPPING OF NORTH-CENTRAL MADAGASCAR USING LIMITED DATA

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ABSTRACT

North-central Madagascar is well endowed with surface-water. Due to soil erosion and pollution, rivers can no longer provide year round clean water supplies. Shallow aquifers are being developed to provide sustainable rural and urban water supplies. A survey of water sources located 2760 boreholes, wells, ponds and springs in the area, but understanding of groundwater occurrence remains poor. The area comprises four hydrogeological zones: the dry Central High Plateau with erosion surfaces underlain by weathered and fractured Basement Complex aquifers; the wet East Coast Basin underlain by Cretaceous limestone, Neogene volcanic and Recent alluvial aquifers; and the northern Antsiranana and the western Mahajanga Basins underlain by Karoo continental and marine sedimentary and Cretaceous-Tertiary sedimentary and volcanic aquifers. Thick lateritic soils mantle much of the area. As part of the 2005-8 geological mapping of north-central Madagascar, hydrogeological mapping at 1:500 000 scale was undertaken based on hydrogeological, geological and geomorphological data layers within an Arc9 GIS format. Georeferenced groundwater data were collated with information from a weathered basement aquifer research site north of Antanarivo. Experience from studies of weathered Basement Complex, Karoo, Mezo-Tertiary and Quaternary aquifers on the mainland informed map content. Seven map sheets were produced at a scale of 1:500 000 using the UNESCO hydrogeological legend modified to show aquifer distribution. Insert maps show depth to water-table/DEM and water-quality/ geomorphological unit distributions. These maps were compiled for planning purposes in areas of limited hydrogeological data.

INTRODUCTION

Hydrogeological maps are essential planning tools for water development in rural areas of southern Africa. They indicate the nature and distribution of groundwater environments, their resources and how these resources may be developed. During the 1970s and 1980s a series of 1:1 000 000 scale hydrogeological maps of African countries, commissioned by UNESCO, were produced using a standard legend (Struckmeier and Margat, 1995). The usefulness of such maps depends on the availability and accuracy of hydrogeological data. In areas where surface water sources predominate little detailed hydrogeological data maybe available. Hydrogeological maps of such areas are produced within a GIS format using combinations of geological, geomorphologic, hydrologic and climatic data layers, informed by the distribution of groundwater abstraction points. The compilation can also be enhanced using information drawn from similar environments in adjacent regions.

The French colonial administration undertook hydrogeological studies from 1910. Geophysical exploration and borehole drilling for groundwater began in the 1950s. The Geology, Mines and Energy Department studied the hydrogeology of the arid southern and western basins from 1961. The first hydrogeological map of Madagascar was produced in 1972. Since the 1980s, NGOs have installed numerous wells and gravity spring fed systems. National water supply coverage increased from 27% to 31% between 1999 and 2003. The Department of Water Exploitation, in the Ministry of Energy and Mines (MEM) manages water supply and resources and through the PAEPAR Project is currently installing 625 gravity fed spring systems. Hand-dug wells are used where groundwater is shallow in sandy alluvium and coastal dune sands. Only limited hydrogeological data are collected. Since 1995, groundwater has been development mainly in drought-prone southern region. Elsewhere, groundwater, as a supply option for low-yield small-scale rural water supply, has received little attention. Although many springs, wells and boreholes have been installed, groundwater systems in central and northern areas remain poorly understood.

In 2001, 75% of the population of Madagascar lived in rural areas but only 12% had access to safe water (Minten et al, 2002). By 2015 the population is projected to be 23.7 million and Government aims to provide four out of five rural communities with safe water through the development of surface water and groundwater resources (Burgeap, Etudes et Conseils Plus et al., 2003). In central and northern Madagascar, water for domestic and agricultural use comes from streams, shallow wells and springs.

The recent BGS/USGS 'geological mapping of North and Central Madagascar through revision of the geological and mining cartography on the scales 1/100.000 and 1/500.000 of the zones' project, included a review of hydrogeological information and data and production of a set of seven 1:500 000 scale hydrogeological maps (British Geological Survey, United States Geological Survey, et al., 2008). The maps, based on standard UNESCO legend, are considered as reconnaissance planning tools in view of the scarcity of available data. During this project, data from 2760 water abstraction sites were obtained from governmental sources and collated to allow assessment of the hydrogeological domains identified.

PHYSIOGRAPHY , GEOLOGY AND GEOMORPOLOGY OF THE PROJECT AREA

Physiography

The project area comprises three physiographic zones: the Central Highland Plateau, the Eastern Coast and the North–West Lowland. Terrain form, drainage and climate collectively impact recharge to and discharge from shallow aquifer systems.

The Central Highland High Plateau zone (elevation 900-2700 masl) includes rolling plains, granite inselbergs and incised valleys. Thick red lateritic soils mantle the plains, dark brown soils the volcanic rocks, and grey alluvial soils in the valleys. The region is sub-humid to sub-arid; winters are dry (12-15°C); summers wet (19-23°C). Rainfall of between 1200-1400 mm/year mainly falls in the December to March wet season. Many rivers are ephemeral, silted up with soils eroded subsequent to deforestation. Grassland occurs on plains, rice irrigation along valleys, and woodland on valley sides.

Thick ferralitic soils mantle the Eastern Coastal zone. Coastal sand dunes and delta sediments contain shallow groundwater which is vulnerable to seawater intrusion. The region is sub-equatorial (19-27°C) with rainfall of 2000 to 3000 mm/year mainly falling during the December-March wet cyclone season. Some rain falls during the September- November dry season. Rivers flow steeply through this zone, from the Central Highlands to the coast.

In the rolling hills with thick lateritic soils of the North-Western Lowland Zone, groundwater occurs in fractured sedimentary, volcanic, limestone and alluvial aquifers. The region is dry, with rainfall of 1500 mm/year, and hot (20-27°C), being in the rain shadow of the Central Highlands. River headwater dambos (bas fonds), with clayey alluvial soils, are sites of rice cultivation during the annual monsoon.

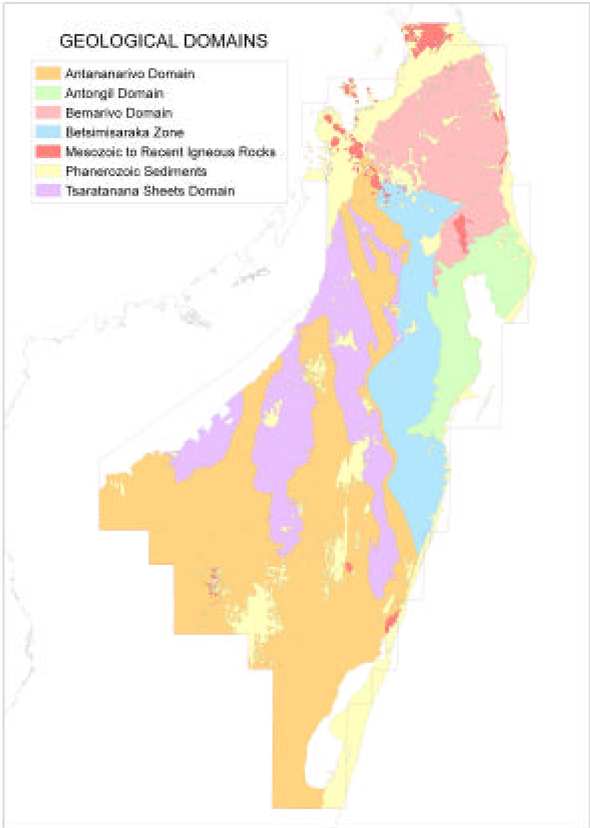

Figure 1. Map of simplified geological domains used for draft hydrogeological map compilation

Geology

The lithostratigraphy used for hydrogeological mapping has been simplified from the 158 lithostratigraphic units defined during the geological mapping phase to the ten geological domains, shown on Figure 1. For the final hydrogeological map base geology layer, these were reduced to just seven units:

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

The geology and structure of Madagascar is complex, reflecting the break-up of the Gondwana continent during the Jurassic Period when the island of Madagascar was rifted away from continental Africa. Continental sediments and volcanic formations were deposited within and adjacent to the rift to be followed by deposition of marine sediments.

The northern and central area comprises four geological/hydrogeological regions:

The Central Highlands High Plateau is underlain by Archaean and Neoproterozoic Basement igneous and metamorphic rocks and Neoproterozoic Granites that are deeply weathered. North and south west of the Antananarivo volcanic centres occur, the basalts weathering to thick clayey soils.

The Western Mahajanga Sedimentary Basin and the Northern Antsiranana Sedimentary Basin include Karoo (Permian to Jurassic) age continental and marine carbonaceous mudstones and sandstones. In the Antsiranana Basin, Karoo continental sediments underlie Jurassic marine sediments and basalts. Overlying are Cretaceous and Eocene sediments, intruded by Oligocene volcanics. These are in turn overlain by Quaternary to Recent alluvium.

The Eastern Coast Sedimentary Basin is a narrow coastal basin that includes Cretaceous limestones, volcanic deposits, and sandstones overlain by Neogene-age basalts and clays as well as Quaternary to Recent beach, dune sands and alluvial sediments.

Geomorphology

Within areas underlain by Basement Complex rocks, groundwater mainly occurs within weathered zones, the depth of weathering reflecting the overlying erosion surface.

Water is a basic requirement for the development of lateritic soils, regolith weathering and landform development on Precambrian Basement. The thickness and lithology of weathering zones also depends upon climate, tectonic activity, groundwater temperature and chemistry, and styles of erosion. The tropical weathering profile comprises a near surface permeable nodular, vuggy or granular lateritic layer through which seasonal, lateral water flow occurs. Below, is a mottled clay layer that grades down to a fine clayey saprolite, thickest in older profiles. Little water is found within this aquiclude. The lower saprolite is permeable coarse-grained and sandy (in which groundwater is stored); the layer base being the weathering front. Limited weathering along decompression zones of horizontal fracturing can occur within the underlying bedrock. Patterns of groundwater throughflow are mainly sub-parallel to topography, groundwater discharging to local spring and stream systems.

The geomorphology of the area is dominated by five erosion surfaces developed on basement rocks within the Central Highlands, since the Dwyka glaciation (Dixey, 1960). These are:

1. The Post Gondwana/Jurassic surface at about 1850 masl with granite inselberg residuals rising above 2200 masl; groundwater discharges from springs around the inselbergs.
2. The African/Late Cretaceous Surface of mid-Cretaceous to late-Oligocene age forms plateaux at elevations of 1300 masl. Between 30 and 50m of lateritic soils rest over clayey saprolite. In areas, west of the north-south rift, the African surface is deeply eroded by numerous lavaka (gullies with basal springs) into a weathered zone 20-40 m thick. Lavaka spring zones along valley sides supply many gravity supply water schemes.
3. The Post-African Miocene-age Surface at altitudes of about 1000 masl is underlain by 15 to 30m of weathering. This surface formed in response to tectonic uplift and sea level decline; the African surface being eroded to reveal numerous rounded granite inselbergs.
4. The Pliocene-age erosion surface, at elevations below 800 masl, is deeply eroded with much outcrop and thin weathering.
5. The Quaternary-age surface is marked by alluvial sediments along rivers, in deltas and in lakes.

HYDROGEOLOGICAL INFORMATION AND DATA

Site-specific hydrogeological assessments include surveys undertaken by the Bureau de Recherches Geologiques et Miniers (Lemaire, 1963 and 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 the hydrogeological characteristics of the project area.

A national survey of water abstraction points undertaken in 2005 by the MEM PAEPAR Project located and georeferenced 7350 boreholes, wells, ponds/lakes and spring fed systems. Additional georeferenced urban groundwater abstraction units were obtained from JIRAMA (a government agency). 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 2436 sites. The bulk of these were either piped water schemes obtaining water from spring zones, or wells obtaining water from the shallow weathered zone. 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 geology and geomorphology maps within an Arc9 GIS format so that the density of sites present within each geology and geomorphology unit could be determined. Within the same data set georeferenced water table depth, specific capacity, pH and well depth data from 2029 sites were attributed to geological formations. These data were used to define the seven hydrogeological environments.

HYDROGEOLOGICAL ENVIRONMENTS

Within northern and central Madagascar, the seven hydrogeological environments were determined by attributing hydrogeological characteristics to simplified mapped geological and geomorphologic units within the UNESCO hydrogeological mapping legend for typical aquifer groups (see A, B1, B2, C1-3 and non-aquifers below) as shown on Figure 2.

A. Unconsolidated Granular Aquifers (blue)

Unconsolidated sediments including coastal dunes, alluvial deltas and fluvial valley deposits. These sedimentary aquifers normally have moderate to high yields. There are three sub-environments:

- Neogene sediments including river and delta alluvial aquifers 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 $m^3 hr^{-1} m^{-1}$ of drawdown. Water quality: SEC 50-2000 $\mu S.cm^{-1}$ with most in the range 50-500 $\mu S.cm^{-1}$; and pH range from 5-9 but most 6-8 , some high dissolved iron content.
- 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 $\mu S.cm^{-1}$ with most in the range 100-500 $\mu S.cm^{-1}$ and pH range from 5-9 but most from 6-8.
- Lake lacustrine sedimentary aquifers 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. 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 3–5 m and 9-10 m. Specific capacity range 2-3 $m^3 hr^{-1} m^{-1}$ of drawdown. Water quality: SEC 50-2000 $\mu S.cm^{-1}$ with most in the range 50-500 $\mu S.cm^{-1}$; and pH range from 5-8 but most between 7-8.

B. Fissured Aquifers (Green)

B1 (dark green) Karstic Mezozoic to Tertiary limestones, that can have moderate yields.

Little information available.

B2 (light green) Fissured Permian to Tertiary sedimentary and volcanic rocks, with weathered lateritic surface horizons. These aquifers generally have low to moderate yields and include:

- Phanerozoic sedimentary rocks include superficial sandy aquifers and 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 $\mu S.cm^{-1}$ with most in the range 100-1000 $\mu S.cm^{-1}$; and pH range from 6-9 but most about 8.
- Phanerozoic 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 $m^3\ hr^{-1}m^{-1}$ of drawdown. Water quality: SEC 50-1000 $\mu S.cm^{-1}$ with most in the range 50-100 $\mu S.cm^{-1}$; and pH range from 6-8 but most between 7-8. Warm springs, as indicated by place name, are often associated with recent tectonic and volcanic activity.

C. Low Permeability Formations (Brown)

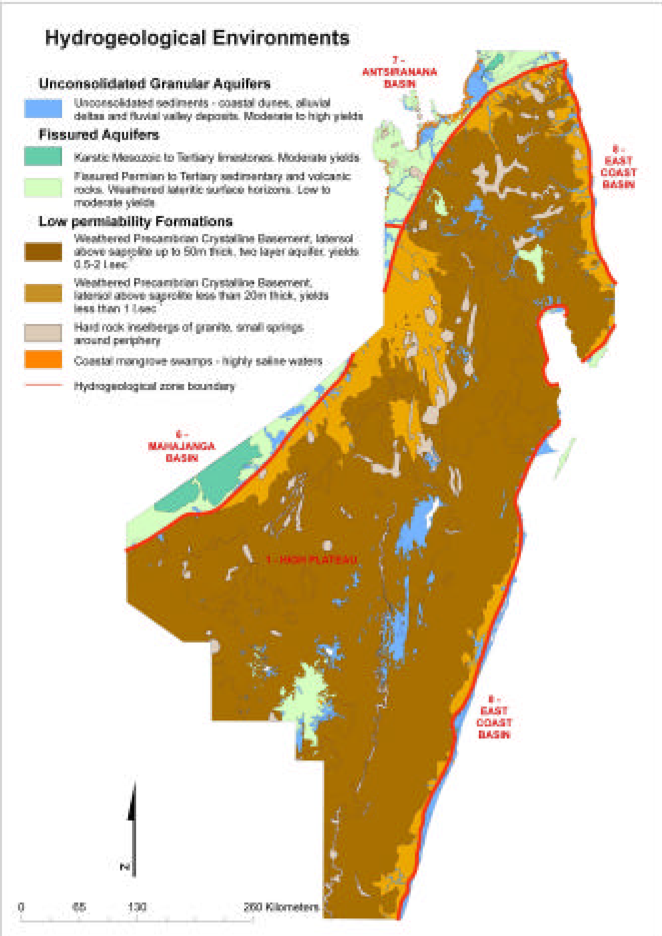

Figure 2. Hydrogeological Environment Distribution Map

C1 (dark brown). Weathered Precambrian Crystalline Basement with latersol above saprolite up to 50 m thick with two aquifer layers yielding 0.5-2.0 ls^{-1}. 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 $m^3\ hr^{-1}m^{-1}$ with most in the range 1-3 $m^3\ hr^{-1}m^{-1}$ of drawdown. Water quality: SEC 50-1000 $\mu S.cm^{-1}$ with most in the range 50-100 $\mu S.cm^{-1}$; and pH range of 6-8.

C2 (light brown). Weathered Precambrian Crystalline Basement with latersol above saprolite less than 20 m thick yielding less than 1.0 ls^{-1}. There are two sub-environments:

- 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 $\mu S.cm^{-1}$ with most in the range 100-1000 $\mu S.cm^{-1}$; and pH range from 6-9 but most from 7-9.
- 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 $m^3 hr^{-1} m^{-1}$ of drawdown. Water quality: SEC 50-2000 $\mu S.cm^{-1}$ with most in the range 50-500 $\mu S.cm^{-1}$; and pH range from 5-9 but most 6-8.

C3. Hard rock inselbergs of Precambrian and younger granite with small low yielding springs around periphery.

Non-aquifer Areas
Coastal mangrove swamps with highly saline waters.

HYDROGEOLOGICAL MAP COMPILATION.

GIS Layered Data and Information

The compilation of the hydrogeological maps and associated marginalia within an ARC9 GIS format required:

- Base map layer of simplified geological units and structures.
- Map layer of geomorphological units.
- Layers of infrastructure, topography (DTM) and drainage.
- Hydrogeological environment boundary shape files.
- Georeferenced abstraction points with attached hydrogeological parameter data, e.g. water quality (TDS) and depth to water table (mbgl) within Excel spreadsheets in dbf format.
- Understanding of likely hydrogeological conditions, especially likely groundwater resource potential, and the relationship with rainfall and drainage flow patterns.

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 have been collected. Data scarcity and the uneven distribution of the 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 used the following stages:
1 Simplification of the geological units present as a base layer with patterns of primary and secondary drainage.
2 Use of geomorphological units to define seven hydrogeological environments.
3 Location of available spring zone, well and borehole data to show their distributions within the hydrogeological environments.

4 Synthesis of the data to establish hydrogeological environments and define their limits on the maps.
5 Compilation of insert maps showing water quality on geomorphological units and depths to water table on a digital elevation model map.

Map Compilation

The map legend used is based on the UNESCO International Legend for Hydrogeological Maps, published in 1970 and revised in 1983 (Struckmeier and Margat, 1995). The main items of legend are:
On the main Map

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

On Insert map 1:

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

On Insert map 2:

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

The main map - Groundwater Occurrence
The main theme is groundwater occurrence within each hydrogeological environment. The legend is divided into three Classes and seven Groups (Figure 3). 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 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 - > 50 $m^3 hr^{-1}$ (0.8 – 14 $l s^{-1}$). 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 $m^3 hr^{-1}$ (0.8 – 14 $l s^{-1}$). Brown Class C represents areas with limited or local groundwater occurrence and areas with little or no groundwater resource potential. The porosity can be intergranular or fissured. Yields occur in the range of 1 – 5 $m^3 hr^{-1}$ (0.27 – 1.4 ls^{-1}).

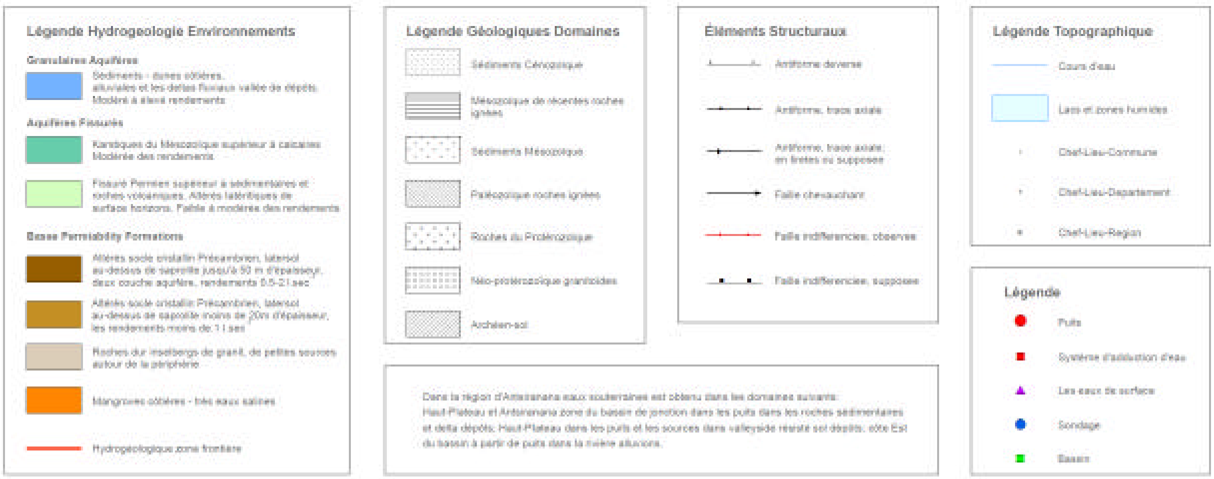

Figure 3 Hydrogeological map legend used.

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.

Group C1 has a well developed weathering mantle, 20 to 50 m thick. The land is geomorphologically defined as flat areas with few rock outcrops or lineaments. Groundwater occurrence in these areas is related to the deeply developed weathering mantle and fracture zones. The distribution of the water within the weathering profile is 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 limited extent. In the crystalline rocks, Group C1 is a complex unit with local aquifers and adjacent areas without any groundwater resources.

Group C2 has a less developed weathering mantle which is less than 20 m thick. It is characterised by undulating to flat land with rock outcrops or lineaments. Usually, groundwater resources are restricted to the secondary openings in the lower parts of the weathered rocks. Group C2 is a complex unit with areas of limited groundwater resources.

Group C3 is mountainous with little weathering mantle or groundwater resources. It is distinguished by relief and by rock outcrops. Groundwater is found along fault and fracture zones, as springs and seepage zones.

The classification and extent of hydrogeological environments on Basement Complex and Volcanic Terrains is based on the geomorphological interpretation of satellite imagery, correlated with water level and well depth records. Terrain characteristics include rock outcrops and lineaments, relief, drainage pattern, soils, lithostratigraphy and structure (see example Figure 4).

There are two insert maps, one show point groundwater quality data related to the distribution of geomorphology units in terms of total dissolved solids. The second shows point depths to water table in metres, using proportional symbols, as related to topography (DTM) and the distribution of major geological structure and fracture patterns.

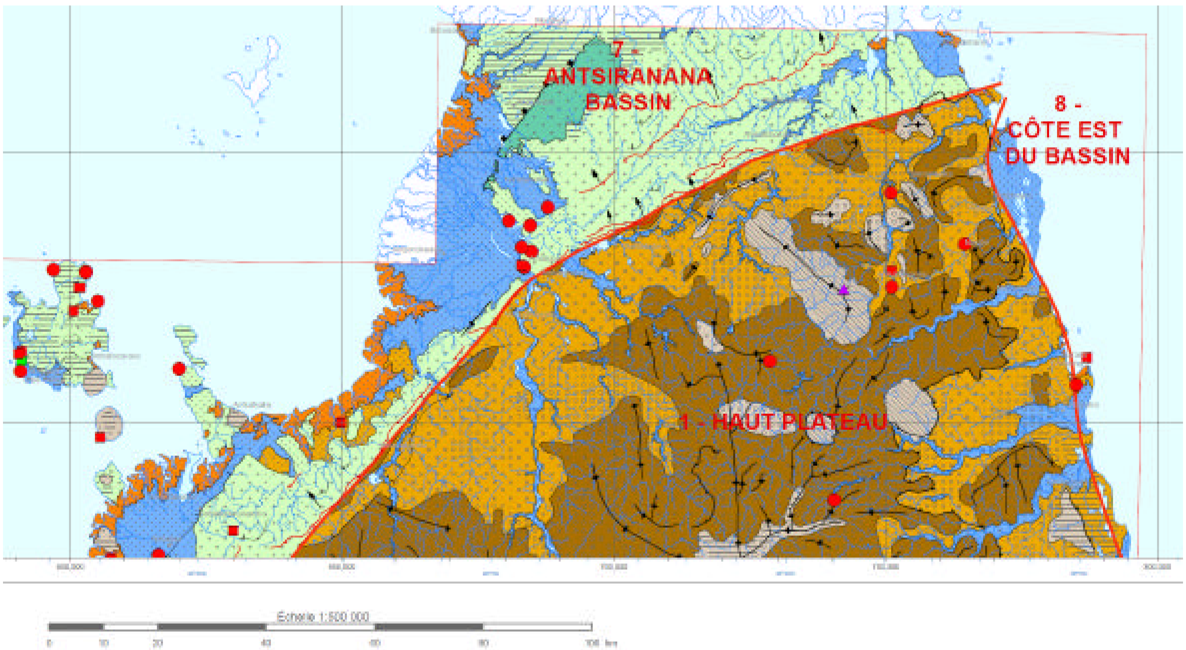

Figure 4. Sample of hydrogeological map showing the distribution of hydrogeological environments, geological formation domains and structures as well as the distribution of reported water abstraction points.

MAP LIMITATIONS, UPGRADEABILITY AND USE.

The seven hydrogeology maps demonstrate how a useful mapping tool can be produced using a combination of geological, geomorphological and limited hydrogeological data, informed by mapping of similar environments elsewhere in southern Africa. These maps at the present scale have applicability for regional long term planning of groundwater assessment, development and use.

As additional data become available from planned borehole drilling and testing as well as well and spring system installations the base spread sheet content can be expanded. Greater data density will allow the production of maps within the GIS such as groundwater resource development maps at 1:100 000 scale for planning purposes. It is, therefore, vital for an ongoing programme of basic data collection to be undertaken.

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