

Research Paper

A novel approach for providing potable water in rural Sodwana Bay, northern Kwazulu-Natal, South Africa

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ABSTRACT

Many people living in the Sodwana area of South Africa do not have access to potable water. Groundwater is the best source of fresh water for the rural community. Potable water in the Zululand coastal plain, Sodwana, South Africa can be enhanced by: (i) providing detailed information on the aquifer system using geophysics; (ii) providing information on groundwater quality and its efficient use; (iii) providing low-cost/low technology local drillers with light-weight, manoeuvrable rigs with trained teams for drilling of 6-inch diameter boreholes. The electrical resistivity geophysical method was used to study the aquifer system and define viable groundwater zones. The electrical resistivity survey increased the borehole success rate by providing information on the aquifer system suitable for water extraction. A hydrocensus was also conducted for identifying boreholes, quality of drilling and for collecting samples for water quality analysis. The result indicated that the groundwater in the area is of suitable quality. Poor quality drilling and inadequate drilling depth indicated a requirement for improved drilling rigs and suitable training. Providing the rural community with suitable drilling equipment, training and adequate information will help to solve the problem of water scarcity and also create jobs.

Key words | electrical resistivity, fresh water needs, groundwater, low-cost drilling, water quality

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INTRODUCTION

According to WHO (2015), sub-Saharan Africa is one of the regions that did not meet the Millennium Development Goals for drinking water in 2015. About 319 million people in the region do not have access to improved drinking water resources. The development of improved drinking water resources that was achieved by some countries in the region has focused exclusively on the urban areas leaving the rural areas without access to potable water. Despite massive investments in the water sector, clean drinking water is still only a dream for many of the rural poor. Piped water does not exist in 40% of the rural communities in sub-Saharan Africa and only about half of this percentage can abstract drinking water from other sources such as rivers, streams, wells and springs (UNDESA 2014). The crisis disproportionately affects rural people, denying them their fundamental rights to potable water and making them more vulnerable to diseases.

Millions of rural sub-Saharan Africans dwell on unconsolidated sediments. In such areas groundwater is located in layers of sands or gravels, is shallow in depth and therefore easier to access for drilling. When such sediments cover large areas, exploitation of substantial quantities of potable water is possible (Carter *et al.* 2001).

The major impediments to improving water access for these people include inadequate understanding of the local and regional aquifer system and the high cost of drilling the aquifers. Lack of information on the aquifer system is a major factor that can limit the accessibility to good quality fresh water.

The majority of the people living on the coastal plain, north coast of Kwazulu-Natal, South Africa have a similar daily struggle to obtain potable water to meet their basic needs. Local householders receive their water supply from

different sources, namely, a piped supply from the Mbazwana municipality, local boreholes, rainwater, and tanker transported water. The municipal supply pipeline has been over-extended with the result that flow is inadequate and households only receive about half of their water requirements. Lake Sibaya, which is the main source of fresh water in the area, is under stress due to over-abstraction and climate change. Groundwater is, therefore, the only alternate source of fresh water but is beyond their reach due to high drilling costs and also inadequate understanding of the aquifer system. Groundwater utilization in the area ranges from extraction of seasonal groundwater from shallow, hand-dug wells to drilling of boreholes for family or communal use and development of groundwater wellfields for agricultural projects. Moreover, the seasonal fluctuation of groundwater level requires deep drilling to at least 30–50 m below the water table (Vegter 1995). This is beyond the capability of the low technology drillers in the area.

Groundwater as a water resource in the coastal plain has three competitive advantages (DWS 2010, 2014):

- (a) Conjunctive resource: It can be used as an additional water resource together with surface water to meet water demands.
- (b) Rapid development: High-yielding aquifers (available in the coastal plain) can be developed at or close to the user within a short space of time.
- (c) Phased development: When developing a surface water resource, future demands need to be considered; as a result, massive capital expenditure is required for infrastructure which will only be used within the next 20 years to 30 years, whereas groundwater resources can be developed as the need arises.

Furthermore, du Toit *et al.* (2011) state that that wellfields can be rapidly developed at a cost of only R2/m³. These wellfields can be managed like any other bulk water resource using telemetry data-management systems.

The University of Zululand, in conjunction with the South African Environmental Observation Network, has been seeking to develop and extend the groundwater monitoring network along the coastal plain of Kwazulu-Natal. The University of Zululand applied for funding to investigate and confirm the aquifers available and become monitoring points for the Department of Water Affairs. Low-cost

electrical resistivity geophysical method was used for the characterization of the unconsolidated sediments of the Sodwana area. This enabled the definition of the extents of the aquifers that occur in the area and for positioning 14 locations for placement of boreholes.

Historically, drilling in South Africa developed as a result of the mining industry. It has also been dominated and monopolized by predominately white drillers and owners which have increased drilling costs. This high cost of drilling boreholes has greatly limited the accessibility of rural dwellers to groundwater. The monopoly on larger drilling contracts, the ability to capitalize expensive drilling rigs and employ trained staff, gives them the competitive edge when tendering for contracts. These contracts provide the local community with neatly packaged boreholes, with little transfer of skills. Large drilling contracts are beyond the scope of low-cost, low technology drillers living in the rural areas who cannot compete at this level and depth of drilling required in the area. For this reason, three of the top drilling rig manufacturers in South Africa were contacted for help in the design and manufacture of suitable trailer-mounted drilling equipment requiring less capital investment and yet still suitable for mud rotary drilling in the area.

STUDY AREA

The northern Zululand coastal Plain, which as its name suggests, covers the coastal plain from Mtunzini in the south to Ndumo in the north. The geology consists of unconsolidated coastal deposits and the development potential is shown as low to medium (DWS 2014). The porosity of unconsolidated sands is high with a storage coefficient of 0.1 (Botha & Singh 2012). The principal groundwater occurrence is an 'intergranular aquifer', with moderate to good borehole yields of >0.5 to >3 L/s generally expected. According to Vegter (1995), borehole yields of these various semi- and unconsolidated coastal deposits are highly variable depending on grain size and thickness and are associated with drilling depths ranging between 20 and 50 m below ground level (Vegter 1995). Recharge of groundwater has been calculated at between 5% and 18% of mean annual rainfall (EMATEK-CSIR 1995).

The groundwater-associated Maputaland group is commonly of hydrochemical class 'Type D' where the groundwater is cation-dominated by Na^+ and/or K^+ and anion-dominated by Cl_- and/or SO_4 (Vegter 1995).

The Sodwana area forms part of the coastal plain and is bounded in the east by the Indian Ocean (Figure 1) and in the west by the Lebombo Mountains. Volcanic extrusion during the Jurassic period formed the basement of the Maputaland coastal plain (Hobday 1979; Watkeys *et al.* 1995; Miller 1998). This is overlain by Cretaceous sediments which in turn are overlain by unconsolidated Cenozoic sediments (Dingle *et al.* 1983; Botha 1997; Miller 1998; Botha & Porat 2008). The unconsolidated Cenozoic sediments are collectively called the Maputaland Formation. Figure 2 shows the geological succession of the Maputaland Formation.

The Maputaland coastal plain is characterized by unconsolidated sediments with aquifers forming a strong linkage between surface and groundwater. In the study area, the Mgobezeleni estuary drains a small catchment that is strongly dependent on the groundwater system. The geohydrology of the area is controlled by primary aquifer porosity. Grain sizes determine the transmissivity of the

major aquifers that occur in the study area (Kelbe *et al.* 2013). The Uloa and Umkwelane Formations constitute the deeper aquifer while the Kwambonambi Formation constitutes the shallow aquifer of the area (Figure 3).

Nearly 55% of the catchment rainfall infiltrates the soil surface to replenish the groundwater storage after accounting for evapotranspiration processes in the soil surface layers. This effective recharge and the hydraulic properties (conductivity and storage coefficient) of the aquifers and the drainage boundaries (streams, lakes, estuary and ocean) control the groundwater storage and the depth to the water table (WRC Report Sodwana 2016).

PROCEDURE

Vertical electrical sounding: exploration and aquifer identification

Geophysical surveying was undertaken at each of the identified locations. The purpose of the geophysical surveys was to target zones of groundwater potential and identify priority

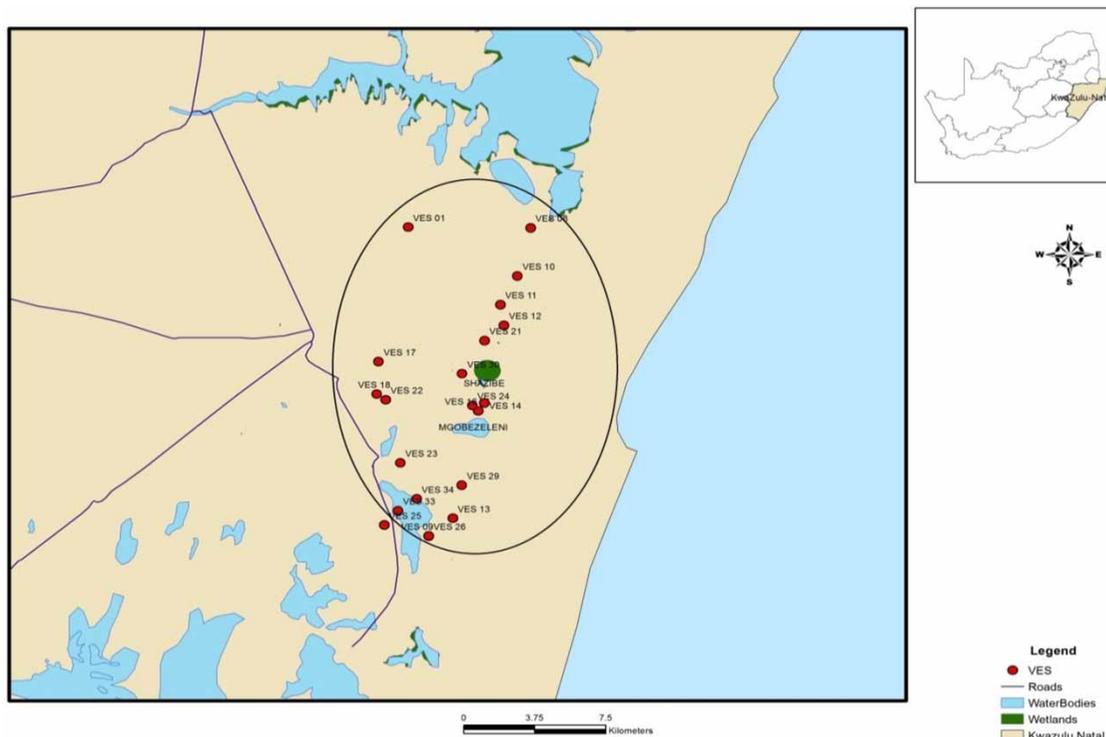


Figure 1 | Study area.

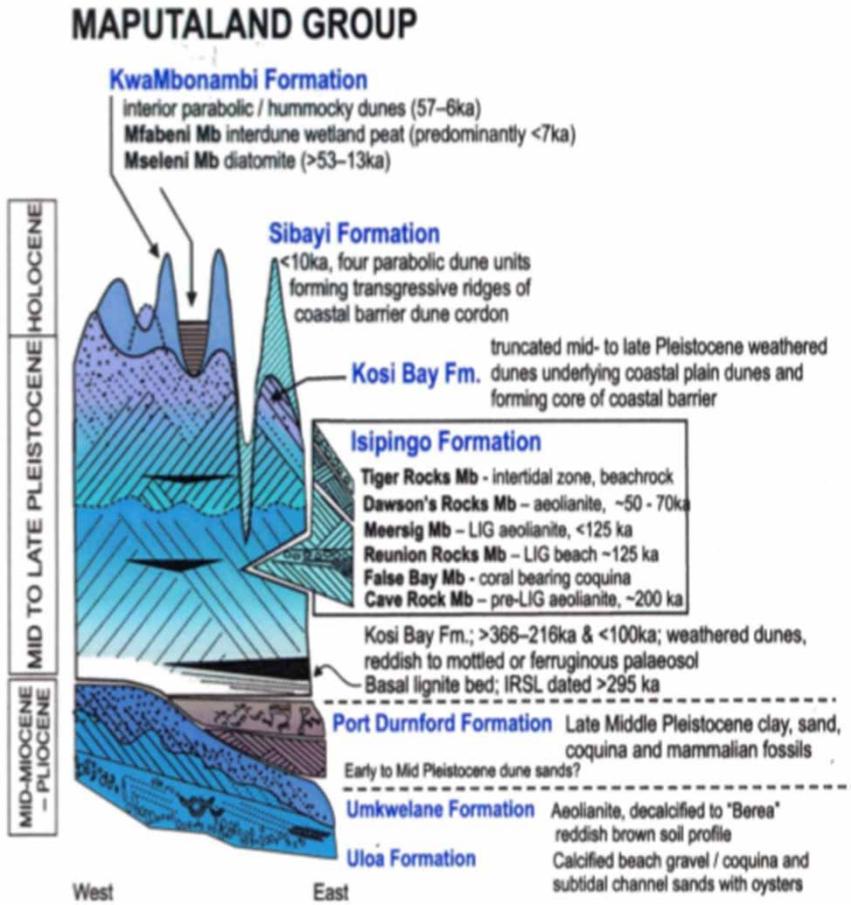


Figure 2 | Generalized lithostratigraphic profile of the Maputaland Group (Botha & Porat 2008).

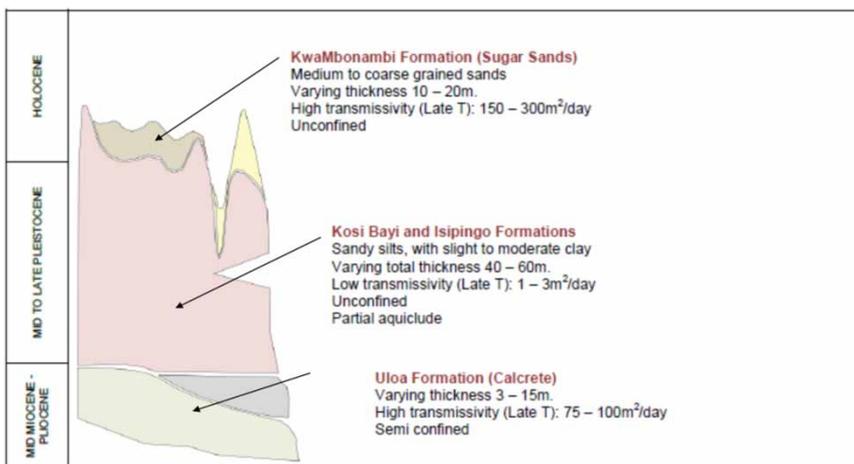


Figure 3 | The two main aquifer horizons in the study area, the shallow unconfined and the deeper confined aquifer.

areas for drilling of the monitoring boreholes. The electrical resistivity method was employed including both Wenner and Schlumberger arrays.

High apparent resistivity may be caused by grain size, porosity, or water content. Survey locations with high apparent resistivity can indicate a coarse material which is likely

to give the best potential to encounter groundwater. Therefore, areas of high apparent resistivity were marked with pegs and prioritized for drilling.

Schlumberger arrays were then conducted at peg locations to obtain a vertical electrical sounding (VES). Both methods were employed at each location with the exception of four sites (SOD 07, SOD 08, BH27, and WES 01) where Schlumberger arrays were undertaken only due to limitations regarding locating positions within the park. VES data were interpreted using IPI2win (Lite) software.

Seventeen boreholes were successfully drilled on these sites. All the boreholes had suitable amounts of water for conducting pump testing. Drilling was purposefully not extended into the Cretaceous and generally was stopped as close to it as was able to be interpreted from the geophysical result and experience of drilling in the area.

Nweze (2015) further mapped the hydraulic properties and spatial distribution of these aquifer units across the central region of the study area. VES was conducted in the area using the Schlumberger method (refer to Reynolds (2000) for detailed theory of VES by Schlumberger method) with maximum electrodes separation of 400 m. The VES surveys were purposefully conducted close to the monitoring boreholes for correlation of the VES logs with borehole logs and to enable the use of pumping test results for the estimation of hydraulic parameters where boreholes did not exist.

The smoothed values of apparent resistivity versus AB/2 were fed into IPI2Win (Lite) computer software for iteration. The software was used to generate an observed curve and a model curve. The inversion method was employed since the area of study is composed of non-homogeneous geologic materials. The model curve was iterated to fit the observed curve until the minimum percentage error possible was obtained for each VES location. The true resistivity value, the thickness and depth of each layer were determined and recorded for all VES locations. A continuously descending curve that showed a rise as current flowed into the basement rocks was observed for all VES locations. The thickness of the geoelectric layers were combined with drilling and pumping test results to estimate the hydraulic properties of the aquifers inferred for the study area.

Pump test results

Test pumping of the boreholes was conducted using a positive displacement mono-type pump and included step and constant discharge tests at each location, with associated recovery. All boreholes were tested with the exception of the piezometer boreholes (which includes WES 01 on the western shores of Lake St. Lucia), and only a step test was undertaken at SOD 03, as fine sand was being pumped at higher yields during the step test. In general, three to five steps were specified dependent on the observed borehole response with the pumping rate during each step. Duration of steps was variable and in many cases shortened to 15 minute steps, based on aquifer responses, and the limited time frames to complete the project. The results of the step tests were analysed on site and a constant discharge test rate was specified. The constant discharge tests were run for between 8 and 12 hours. Discharge rates were often limited by the size of the pump that could fit into the casing installed in the borehole, and the preferred discharge rate to stress the aquifer was not always achievable. Test pumping results have been analysed using FC-Program to assess the characteristics of the aquifer, and to obtain an indication of the sustainable pumping rate from the boreholes.

Water quality analysis

According to Still & Nash (2002) the coastal plain of northern KwaZulu-Natal, is home to several hundred thousand people. A hydrocensus was conducted to investigate the potable water sources in the area, the presence and depth of the water levels in boreholes and sanitation practices in the area.

Water samples were collected from the hydrocensus as well as from the monitoring boreholes and analysed. The chemical, physical and biological analyses were conducted on the water samples in accordance with South African Drinking Water Quality Guidelines. The chemical analysis determined the amount of the micro and macro substances dissolved in the water. Physical analysis determined the colour, conductivity at 25 °C, odour or taste, turbidity, pH and hardness. Biological analysis was conducted to test for the presence of faecal coliform.

Drilling method requirements

Most drilling in the formal sector uses heavy, expensive, truck-mounted drilling equipment, which was developed for the mining industry. It has the capacity to drill to great depths and large diameter bores, typically in excess of 150 m and with diameters larger than 10 inches (305 mm). In practice, such equipment is mostly used for drilling boreholes to depths of 50 m or less. The replacement cost (depreciation), size, excessive capacity and large crew size makes such drilling expensive.

Furthermore, the volume of a borehole is determined by its diameter and depth. Increasing the volume requires more energy (removal of the cuttings), and the drilling rate becomes more expensive. For example an 8 inch (203 mm) diameter hole requires removal of double the volume of material that a 6 inch (152 mm) diameter borehole requires (Stephens *et al.* 1999). Drill cuttings are removed by pumping compressed air or water up the annular space. The air or water must reach a critical velocity to be able to bring cuttings to the surface. The direct relationship between borehole diameter and fluid flow implies that a 8 inch (203 mm) diameter borehole also requires double the volume of fluid compared with a 6 inch (152 mm) diameter borehole. The cost of drilling a 6 inch (152 mm) borehole will therefore be half the cost of a 8 inch (203 mm) (half the volume) diameter borehole if using trailer-mounted rigs. A further consideration is that doubling the borehole diameter only increases the volume of water extracted by 10% (Heath 1987).

The following five elements are responsible for most drilling costs:

- The drilling equipment (truck, rig and tools). The value of the capital is depreciated over the typical 5–8 year life-span of the equipment. The depreciation value is reduced to a cost per hole or a cost per metre drilled.
- Consumables (fuel and oil, guar gum, casing, gravel pack and maintenance). These costs are itemized and calculated per hole.
- Direct labour for drilling crew. These costs are itemized and calculated per hole.
- Overheads (cost of capital, interest, logistics and administration).

The total cost per metre is obtained by dividing the total cost by the annual borehole production rate (m). Drilling large-diameter boreholes using heavy, truck-mounted drilling equipment, large crew size and high fuel consumption results in a high cost per hole or per metre drilled. High-cost machinery and support equipment costs result in fewer boreholes being drilled. The relatively low production of boreholes means that fewer drilled metres are drilled. This, in turn, creates inefficiencies of equipment usage and ultimately higher overheads. This combination results in higher unnecessary cost per metre drilled.

Improved drilling equipment

To establish local drilling contractors in an industry dominated by high-investment drilling companies from the formal water sector, trailer-mounted rigs have to be developed or sourced locally. The important basic rig specifications that were considered required the rig to be towable by a light delivery vehicle; to be operated with a small crew using 2 m long drilling rods; capable of drilling in unconsolidated sediments; a bore size suitable for fitting a 4 inch (102 mm) PVC casing on completion of the hole and for fitting hand pumps and solar pumps.

RESULTS

Aquifers for future exploitation

The VES survey helped us to identify two dominant productive target aquifers. They were composed of the deep Umkwelane and Uloa Formation calcarenite and calcrete, and the shallow Kwambonambi Formation 'sugar sands' resulting from recent Aeolian reworking of older material. They were located and drilled to provide information about the lithostratigraphy, as well as the geohydrological characteristics of the two target aquifers (Figure 3). A four-layer model was observed for the study area by the integration of VES results and drilling logs.

The first layer is the top soil composed of vegetation and organic matter. The second layer is the shallow aquifer which is composed of medium to coarse grained sand. The

shallow aquifer has an average thickness of 15 m as observed from VES results and drilling logs.

The third layer is the high clay Kosi Bay formation which underlies the shallow aquifer and overlies the deeper aquifer. The fourth layer is the deeper aquifer which has an average thickness of 8 m in the study area.

The drilling logs confirmed that the Mgobezeleni hydrogeology is dominated by three main aquifers, comprising the unconfined Kwambonambi Formation with relatively high hydraulic properties that overlies the semi-permeable Kosi Formation that creates a leaky type aquifer overlying the deeper Uloa Formation with its relatively high permeability.

Pump test results

Pumping tests were conducted on the monitoring boreholes using Jacob's straight method. The results indicated wide variation in the transmissivity of the shallow and deeper aquifers of the study area. The shallow aquifer showed transmissivity values that ranged from 10 to 5,544 m²/day while the deeper aquifer showed transmissivity values that ranged from 5 to 587 m²/day.

Hydrocensus and water quality results

These people have traditionally collected water from shallow unprotected wells, which are dug in or near to river beds and pans. There is no waterborne sanitation in the area. All defecation is either carried out in the bush, or using pit latrines. The water table depth varies according to the topography, but is generally between 5 and 20 m below the surface. Water quality in protected family wells is found to be good, while shared community wells, particularly the older unprotected wells, show signs of contamination.

Water quality assessment indicated that all the boreholes tested showed water of acceptable drinking quality. The laboratory test results indicate that the groundwater across the project area is generally within the limits set out in [SANS 241 \(2011\)](#) for all determinants except for fluoride, iron, manganese and soluble organic carbon. Details are provided below:

- Fluoride exceeded the chronic health limit value of ≤ 1.5 mg/L in SOD 03.

- Iron exceeded the aesthetic limit value of ≤ 0.3 mg/L in nine of the 16 samples tested. The chronic health limit value for iron of ≤ 2 mg/L was exceeded in five samples.
- Manganese exceeded the aesthetic limit value of ≤ 0.1 mg/L in six of the 16 samples tested; the chronic health limit value was not exceeded.
- Soluble organic carbon exceeded the chronic health limit of ≤ 10 mg/L in SOD 06B and SOD 08.
- The closeness of sampling to the drilling process is the probable source of increase in some of the constituents and they are generally considered aesthetic properties and, as such, do not pose an unacceptable health risk if present at concentration values above those specified in [SANS 241 \(2011; Jeffares & Green 2012\)](#).

Improved suitable drilling rigs

From our hydrocensus investigation and the poor quality workmanship from low-cost/low technology drillers in the area, trailer-mounted drilling rigs were identified as the most suitable and cost-effective equipment for local drillers. Three South African drilling rig manufacturers were identified that currently manufacture heavy-duty drilling rigs for the formal water sector. The manufacturers, however, were willing to or were in a position to manufacture a trailer-mounted rig. The rigs can be manufactured with a sturdy, compact frame mounted on a single axle and able to drill 152 mm diameter holes up to 100 m deep using 2 m drilling rods. The manufacturers and the rig models that were considered for supplying trailer-mounted drilling rigs were as follows:

- (a) Audie Steel and Engineering
- (b) Super Rock Drills
- (c) Smith Capital Equipment.

DISCUSSION OF RESULTS

The VES survey helped us to extend the identification of the two dominant productive target aquifers. The method is suitable for future exploration on the coastal plain and maybe in other similar areas in sub-Saharan Africa. The 100% success rate obtaining water in the drilling of the monitoring

boreholes all intersecting both aquifers proves that electrical resistivity is the method of choice.

Drilling confirmed the geophysics that two aquifers are available for exploitation: the deeper Umkwelane and Uloa Formation calcarenite and calcrete, and the shallower Kwambonambi Formation 'sugar sands'.

The deeper calcarenite and calcrete aquifer is not reachable by the low technology/low-cost drillers. Moreover, the seasonal fluctuation of groundwater level requires deeper drilling than the shallow, more reachable sugar sand. The 'Intergranular Aquifer' with moderate to good borehole yields of >0.5 to >3 L/s is available for large-scale exploitation.

The hydrocensus assessment showed that there was no evidence of faecal contamination. Water quality assessment indicated that all the boreholes tested showed water of acceptable drinking quality. The laboratory test results indicate that the groundwater across the project area is generally within the limits set out in *SANS 241 (2011)* for most of the determinants.

It was clear that the current drilling equipment used by the low-cost/low technology type drillers was unsuitable and inadequate for drilling into the deeper aquifer. Most of such boreholes collapsed after a short time, indicating inadequate borehole construction depth, expertise and the use of inferior quality products.

Bit size determines hole size, which in turn affects volume of water or air needed (water haulage and storage), mud pump rating, drilling rig size, weight, transport type and number of crew. Reducing the borehole size therefore translates into a major cost saving.

Suitable manufacturers were identified that are willing to manufacture, supply and maintain drilling equipment both suitable for the area and familiar to the low-cost/low technology type drillers working there. Such trailer-mounted rigs would enable the drillers to invest less capital, require less support vehicles, labour and consumables compared with the standard heavy-duty drilling rigs currently sold on the market and used by formal drilling companies.

CONCLUSIONS

A detailed geophysical survey was conducted in the study area to delineate groundwater viable zones using the electrical resistivity method. Fourteen boreholes were successfully

drilled in the identified groundwater viable zones using formal drilling equipment. From the drilling logs and VES results two main aquifers were identified: the shallow aquifer (medium to coarse sand), which is mostly tapped by the low-cost/low technology type drillers in the area, and a deeper aquifer (slightly cemented calcereous sand), which is only tapped by formal drilling companies and is also the more sustainable of the two aquifers.

The use of trailer-mounted rigs and equipment and the development of new, well-trained, contractor units, based in rural areas can result in a dramatic increase in water supply in southern Africa. Furthermore, this alternative technology of drilling small-diameter boreholes with lightweight rigs dramatically reduces the drilling costs and quantity of supply water for drilling. Due to much lower capital investment and lower operating costs these enterprises will be able to drill boreholes at 50% the cost of formal drillers.

Drilling requires skillful operations based on sound knowledge. Experience from the study area showed that unregulated, inadequately trained, unprofessional low-cost drillers have installed poor quality wells that give a bad reputation to low-cost drilling in the area.

Once a low-cost drilling capacity building programme is initiated and drillers are equipped and given training, it could open the door for inspiring the quality and expanding the work of locally based drillers, operating lightweight rigs to supply clean drinking water in rural areas. Such businesses could expand into new avenues such as groundwater exploration, pump testing, borehole rehabilitation, pump installations, monitoring and maintenance.

We suggest six elements for providing an enabling environment for low-cost drilling:

- (a) provide adequate geohydrological information;
- (b) provide drilling technology options and advice;
- (c) establish supportive financial input;
- (d) build facilitative government policies;
- (e) monitor progress and quality;
- (f) strengthen the low-cost drilling sector.

RECOMMENDATIONS

To serve rural populations without a source of potable water adequately, a different approach is needed. First,

detailed information on the aquifer system should be made available to the rural communities in the language they would understand. Such information should include target areas for drilling, the quantity of groundwater that can be abstracted from the aquifer, and also water quality control measures. Second, access by the rural population to local contractors with affordable drilling equipment and exploration techniques on unconsolidated sediments can be a tipping point for groundwater use in rural areas. Third, such quality trailer-mounted rigs could be an effective solution to increase the availability of potable water in southern Africa and to create jobs.

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