Groundwater investigation in semi-arid developing countries, using simple GIS tools to facilitate interdisciplinary decision making under poorly mapped conditions: The Boteti area of the Kalahari region in Botswana

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Abstract

Locating additional long-term groundwater resources in semi-arid regions of developing countries with growing populations is an expensive undertaking. Simple geographic information system (GIS) techniques can be utilised to facilitate efficient application of expensive geophysical techniques and test-drilling by functioning as an interdisciplinary integration and decision-making tool, especially in data-poor and poorly mapped environments where more sophisticated GIS techniques are not applicable. The paper demonstrates this in the context of the search for groundwater alternatives to the dwindling river water supply in the Boteti area of the Kalahari region in Botswana.

Keywords: Groundwater; GIS; Kalahari; Botswana

1. Introduction

The demands of growing populations in semi-arid regions feed a continual need to locate new groundwater resources and to explore other unconventional water supply options (Smakhtin et al., 2001). Locating groundwater is especially critical as such regions are normally characterised by low and highly variable rainfall, high temperatures, low humidity, high rates of potential evapotranspiration and the near absence of permanent surface water (Falkenmark, 1994). A wet season of limited duration is usually typical while droughts of several years duration may occur.

Low average rainfall in the Botswana Kalahari, combined with flat topography and deep sandy soils result in low rates of surface run-off, low to medium rates of infiltration and hence low groundwater recharge rates. Estimates of recharge from rainfall are usually given as 2–4 mm/year (Beekman et al., 1996). Under such conditions, water extraction may exceed recharge such that groundwater is effectively mined.

In regions where ample data exist, geographic information system (GIS) or remote sensing based spatial analysis and modelling techniques have been applied to groundwater searches and groundwater vulnerability modelling (Hinton, 1996; Bloomfield, 1996; Tim et al., 1996). However, in developing countries crucial gaps in available data often prohibit such advanced exercises. Nevertheless, in some developing countries, remotely sensed data have been applied

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to groundwater detection by association with geomorphic criteria (Chopra and Sharma, 1994; Krisnamurty and Srinvas, 1995), while in other countries knowledge of the terrain in conjunction with the location of domestic water sources such as hand-dug wells or shallow boreholes has led to assumptions regarding the availability of regional groundwater occurrences (Carter, 1995).

The aim of this work is to demonstrate the usefulness of simple, commercially available GIS technology as a supporting tool for groundwater exploration in large regions in developing countries with poorly mapped baseline information and low digital data availability. The purpose is to show that simple GIS applications can assist significantly toward the location of regional groundwater resources in developing countries primarily by using integrated data derived from a variety of sources – including digital satellite imagery, GPS-data collected during field explorations and 'on-screen' geomorphological interpretations – for multi-disciplinary decision making during exploration work.

2. The Boteti river study area

In the semi-arid Kalahari region of southern Africa, surface water availability, even if seasonal, has been an important factor in attracting settlement since prehistoric times (Campbell, 1977). Likewise, changing patterns of surface water have brought about major population relocations (Wilmsen, 1997; Taylor, 2000). Since the early 1990s the Boteti river (Fig. 1), a main outlet of the Okavango Delta running through the mid-Botswana Kalahari for more than 300 km before terminating in the Makgadikgadi salt pans, appears to be 'failing', raising concern over people's water supply and their livelihoods that have been intricately linked to the river from pre-historic times (Lane et al., 1998).

Massive tribal population relocations as happened in historic times in response to changes in surface water and resource availability (Tlou, 1985) are not possible today as there is no vacant land left in the region. Contemporary solutions include spontaneous rural–urban out-migration, which alleviates some of the population pressure, and changes in livelihood strategies (VanderPost, 1995).

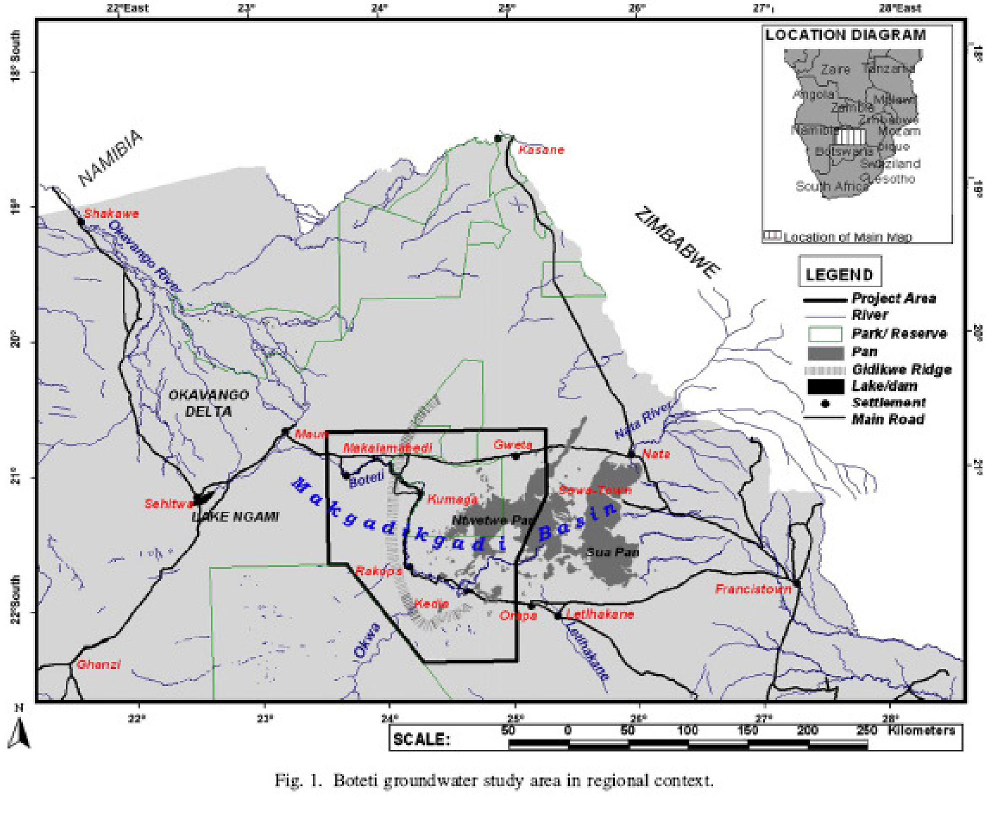


Fig. 1. Boteti groundwater study area in regional context.

Generally, however, there is a trend, often through government programmes, to facilitate the continued residence of people by locating alternative water resources (Republic of Botswana, 1991).

In the Kalahari environment of the ephemeral Boteti river where the annual average rainfall does not exceed 355 mm, water is a scarce resource of variable availability, mostly determined by erratic regional rainfall patterns (Arntzen et al., 1994). People's livelihoods historically were adapted to these variable conditions, allowing them to live along this river at low density through engagement in flood-recession based crop farming, cattle husbandry, hunting, fishing and gathering (VanderPost, 1995). Current population numbers, however, are less compatible with available traditional water resources consisting of pools of surface river water and hand-dug wells and necessitate the exploitation of deeper groundwater resources.

The Boteti river once was a mighty stream mentioned in the journals of early travellers and explorers (Livingstone, 1857; Baines, 1973). In the 1970s this river could be crossed only by makeshift

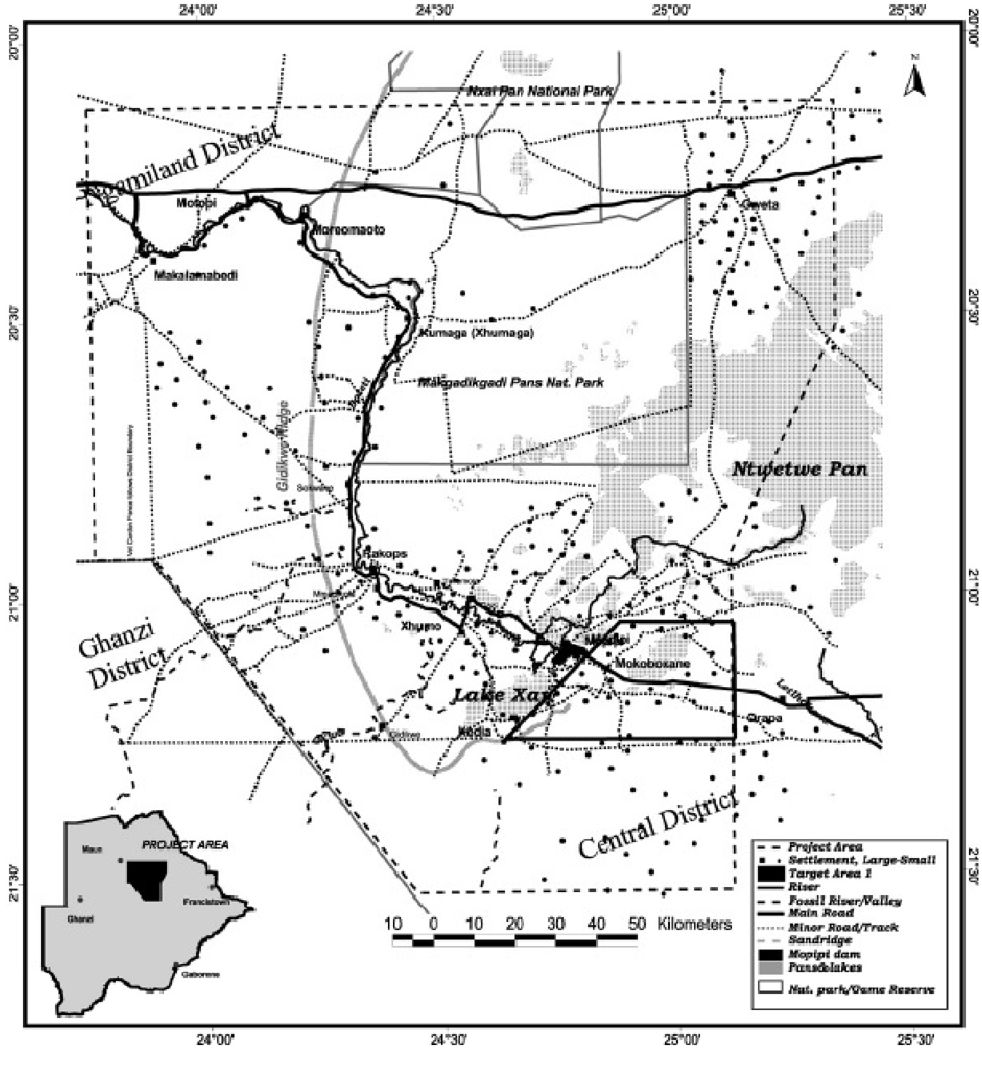


Fig. 2. Settlement pattern in study area.

ferries according to interviews with residents of Xhumo village (Fig. 2) by one of the authors in 1989. The wet 1970s are especially remembered by residents and are a benchmark for the good old (wet) days. However, south of Khumaga (Fig. 1), the river has not experienced significant flow since the early 1990s and no flow has been recorded at downstream Rakops since 1991. The flow record summarised in Table 1 is compiled from flow gauging measurements supplemented with historical records collected by Breyer (1983). Evident is that occasional years without river flow occurred throughout recent decades. For example, 1988, 1987, 1983 and 1973 were dry years and also during the sixties there were dry years. One needs to go back, however, to the 1940s to encounter a lengthy dry spell between 1929 and 1947, interrupted only by the low flow year of 1940, i.e. almost 20 years. Between 1901 and 1928, however, the river flowed consistently. In 1900 the river was dry, but it apparently flowed in the preceding years from 1849 (Table 1). In 1924/1925 heavy rains caused a very large flood, allowing Schwarz to travel the length of the Boteti in his canoes and describing swamps and lakes between present day Rakops and Mopipi (Schwartz, 1926).

Such a variable river is not a dependent water source for modern villages. After 1991, shallow wells in the river-bed had to be dug increasingly deeper, while many semi-permanent pools slowly dried out (Arntzen et al., 1994). This happened in a context of fairly rapid population growth in spite of continued out-migration especially of young adults. Boreholes, drilled through private initiative or in the context of government village water supply schemes therefore became responsible for an increasing share of water supply needs especially for the larger villages of Rakops, Xhumo and Mopipi. Such boreholes were drilled wherever conventional wisdom indicated the possibility of water or on the basis of village scale explorations. They were mostly drilled along river banks and in floodplains, abstracting groundwater from a shallow fresh water aquifer, which is recharged from river flow. Lack of river flow, however, has resulted in deterioration of the quality of the aquifer with increased groundwater salinity and declining yields adversely affecting the people and their economic activities (DWA, 2002). Without river flow and with boreholes drying up or deteriorating in quality, it became necessary to conduct a more thorough investigation of potential groundwater resources in the region and to compile an inventory of available groundwater for the period up to 2020, the time horizon used for water supply scenarios in Botswana. The Boteti groundwater resources investigation project was thus started in 2001. Because the study area was large and poorly mapped, from the start a decision was taken to use GIS to integrate the various data sources and fieldwork investigation results to support exploration decision making.

Table 1

Summarised flow record of Boteti river at Rakops, 1849–present

Year	Flow-condition
1991–present	Dry
1989–1990	Flow
1987–1988	Dry
1984–1986	Flow
1983–	Dry
1974–1982	Flow
1973–	Dry
1966–1972	Good flow
1965–	Poor flow
1961–1964	Good flow
1960–	Poor flow
1952–1959	Good flow
1948–1951	Low flow
1941–1947	Dry
1940–	Poor flow
1929–1939	Dry
1901–1928	Flow (1925: high flood)
1900–	Dry
1849–1899	Flow

Source: Breyer (1983); DWA (2002).

The location of the 29,000 km^2, irregularly shaped, study area is shown in Fig. 1 with details in Fig. 2. The area stretches along the Boteti river from Makalamabedi in the west to the Orapa mine area in the east. Boundary coordinates are 20°00′S/023°45′E for the upper left corner and 21°45′S/025°15′E for the lower right corner. The area is located in a large depression in northern Botswana, known as the Makgadikgadi basin (Fig. 1), which is an integral part of the Kalahari basin. The Makgadikgadi is dominated by two major pans, Sua (or Sowa) in the east and Ntwetwe near our study area in the west and there are many minor pans, the largest of which is Rysana pan in the study area. The present extent of the Makgadikgadi is only a fraction of the former extent of the palaeo Makgadikgadi lakes and pans systems (Cooke and Verstappen, 1984).

The resident population of the study area was recorded as 24,352 in the 2001 Population Census, an increase of 20.4% over the recorded 1991 population of 19,375 (CSO, 1991, 2002). The settlement pattern is very scattered, making the provision of drinking water a major challenge. Relatively high concentrations of people exist around Makalamabedi–Motopi–Moreomaoto–Khumaga in the north-west, in a central concentration around Rakops–Mmadikola–Xhumo–Toromoja and in a southern concentration around Mopipi–Mokoboxane (Fig. 2). The distances between these small concentrations are beyond the economic feasibility of an integrated and connected piped water system (DWA, 2002) and it is cheaper to provide water to each of the concentrations independently from sources within a 30–50 km radius. There are, in all, 12 villages and numerous minor settlements (Fig. 2), mostly small localities known as lands areas and cattle posts, which have populations ranging from less than 10 to around 500. While the present water supply is only 584,000 m^3/annum, the present estimated total domestic water demand is 650,000 m^3/annum, predicted to increase in 2020 to 1.7 million m^3/annum (DWA, 2002).

3. Methodology overview

Due to the low level of available digital data for the study area, it was decided to employ a stepped approach to the groundwater investigation. Here, a general description of the methodology is offered with details and results from each stage presented in later paragraphs. First, a study area digital base-map was constructed and crucial elevation contours were added through GIS-based data comparison and interpolation. Next, using available borehole data, satellite imagery and geomorphological interpretation, the study area was divided into more and less promising groundwater areas, resulting in the identification of five terrain units with different groundwater potential. The most promising portions of these terrain units were then designated as target areas for more detailed investigation.

Throughout, the role of the GIS was to visualise the various combinations of data sets and to be an integration tool for topographic, geological, geophysical and other data. The GIS also played a crucial role in data generation and enhancement through the application of mostly simple GIS procedures such as display, GPS-data downloads, buffering, classification, overlay, query and contouring (Ormsby et al., 1998).

Within the identified target areas, the GIS was next used to visualise and overlay data that included satellite imagery and to assist various specialists, particularly the project geomorphologist, in decision making about the locations for geophysical traverses. The results obtained from these traverses were integrated with geological and borehole data to facilitate decisions about siting of exploration boreholes, the final stage of the investigation. Results from borehole drilling, test pumping and recharge estimates were used to assess the extent of groundwater resources. The GIS related activities are summarised in Table 2 and results from the different stages of the investigation process in which the GIS played a major role are described in the following paragraphs, while some of the ultimate groundwater resource assessment results are described in the final sections of the paper.

Table 2
Overview of GIS tasks/activities in Boteti groundwater exploration

1. Base map construction for study area
   - Standardise available data to common map projection and datum
   - Updating of topographic map data (roads, settlements)
   - Generating/interpolating digital contour elevation map
2. Identification of broad terrain units
   - Satellite image interpretation (visual)
   - Contour map interpretation
3. Identification of target areas for detailed investigation
   - Geomorphological interpretation (from satellite imagery, aerial photographs and fieldwork)
   - AEM interpretation
   - Borehole data interpretation
   - Geological data interpretation
   - Integrating all data into GIS
4. Siting of geophysical traverse lines and exploration boreholes within target areas
   - AEM interpretation
   - Existing borehole data interpretation
   - Geomorphological interpretation

4. Digital base map

Results of this study that are GIS associated activities such as digital base map construction, satellite image interpretation, target area identification – although subsidiary to the outcome of the groundwater exploration study – constitute the major focus of this paper because they were highly instrumental in contributing to the ultimate study purpose of assessing regional groundwater resources in the Boteti region. The production of a common digital base map was a first GIS task aimed at servicing all disciplines involved in the study.

Existing 1:50,000 (43 sheets) and 1:250,000 scale topographic maps, upon which some limited available digital map data were based, were found to be outdated (1971, 1974). However, the 1:50,000 map sheets were a useful geomorphological resource since they were constructed as photo-maps that allowed landform recognition. The current locations of settlements and alignment of roads were not available on these maps nor were these available in digital format. Even the Boteti river channel itself was not adequately digitally mapped in most parts of the study area. More seriously, elevation data were very scarce and elevation contours completely lacking.

Base-map construction involved the transformation of all available and newly generated digital data to the regional standard map-projection and datum, i.e. UTM-Zone 35, Clarke 1880/Cape Datum, even though a narrow strip west of longitude 24 east belonged technically to UTM-Zone 34. Also, all data were converted to shapefiles for use in relatively low-cost off-the-shelve GIS software acquired for the project. Existing digital data sets of some of the roads and settlements were combined with digital data generated for the study. Settlement locations, for example, were mostly updated by identifying them from the most recent population census listing and recording coordinates with hand-held global positioning system (GPS) equipment during field visits. This allowed the construction of water demand zones around settlement clusters, using a simple GIS buffer procedure. Newly constructed roads were plotted from centre-line coordinates obtained from road construction companies and older roads by driving along them with Garmin 12XL GPS equipment. GPS coordinates were downloaded and converted to shapefiles using the common map-projection and datum.

Landsat-7 satellite imagery which had been demonstrated a useful resource in other groundwater investigations in Botswana (Republic of Botswana, 1998) and – compared to other satellite products – was the most available and affordable, was acquired for the year 2000 and geo-rectified using the limited available digital map data and GPS collected control points such as road intersections. The ability of the GIS to integrate and overlay digital map data with satellite imagery was utilised to further update the base-map through on-screen digitising of sections of the Boteti river as well as abandoned and former river channels, fossil valleys, pans, important secondary tracks and fence-lines. Shapefiles were produced for all such digitised features.

A special problem concerned the lack of contour information on existing maps, such information being crucial to groundwater exploration (Tim et al., 1996). Accurate spot elevation measurements for the study area were also scarce. Survey beacons or trigonometric stations were few and some of them lacked elevation data. However, several derived elevation estimates were available from the Botswana Department of Geological Services, one based on aeromagnetic and one on gravity data. A general digital elevation model developed by the U.S. Geological Survey (USGS) was also available.

The capabilities of the GIS for interactive visualisation, using zoom and overlay functionality were utilised to compare and evaluate all elevation measurements. It was found that elevation estimates based on aeromagnetic data were not comparable to spot elevation data that were considered relatively accurate because they were based on actual field measurement. The USGS digital elevation model was found to be too coarse to represent reality on the ground. However, fairly good correspondence was established between elevation data recorded for survey beacons and estimates based on gravity data. It was therefore decided to use a combination of these data sets and compile them into one digital elevation data set. To this were added mostly recent borehole locations that possessed associated elevation data.

Visual inspection of gravity derived elevation data and trigonometric data revealed some discrepancies, apparently mostly a result of calibration. The trigonometric data were therefore used to re-calibrate the gravity-derived data. The trigonometrical network in the study area was, however, patchy and favoured relatively high elevations that are good for trigonometrical purposes but may result in overestimating elevation. The data were therefore selectively used and by incorporating the extensive local terrain knowledge of team members who had conducted previous research in the region calibration was added to the gravity data, mostly by omitting suspicious or unrepresentative points. The final data set of selected trig stations, gravity data points and borehole elevation data was submitted to a contour generating procedure, using a kriging algorithm based on a linear variogram (Fortin and Dale, 2005). Resulting contours at 10 m interval were visually examined leading to further adjustments. Final contours (Fig. 3) were exported to shapefile format and integrated with other base-map data in the GIS. The elevation data set was not considered good enough to construct a terrain model of the study region, which is characterised by subtle elevation differences not captured by contours at 10 m interval (McFarlane and Segadika, 2001), but proved to be an important asset in further exploration work.

5. Terrain unit identification

Among the more important data for groundwater investigation are details of existing boreholes, data about regional geology and geomorphology as well as data collected during previous groundwater investigations carried out – in Boteti's case – for village water supply projects. During the later phase of the study, detailed airborne electromagnetic (AEM) and geophysical data were collected specifically for portions of the study area. Combining such data with base-map data in a GIS adds a geographic perspective that is lacking

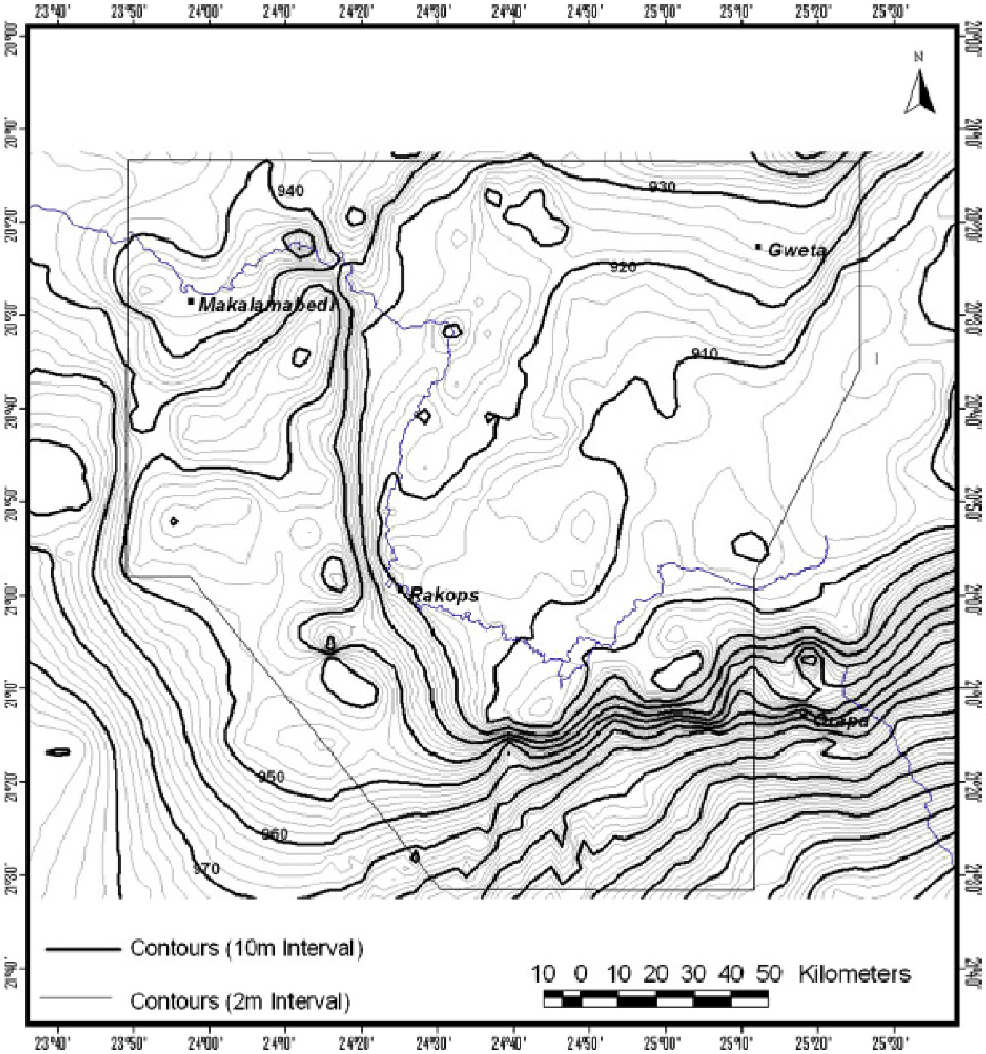


Fig. 3. Elevation contours generated for the study area.

when data sets remain with individual experts; for regional groundwater assessment such perspective is crucial.

Given the large study area, the identification of areas with promising groundwater prospects – and by implication the elimination of less promising areas – was carried out in two stages. In the first stage, GIS-based integration of all available digital information together with geomorphological interpretation by team members with extensive local terrain knowledge resulted in the division of the study area into five different terrain units with varying prospects for fresh groundwater occurrence (Fig. 5). The delineation of these terrain units was based on GIS-integrated information related to (1) geological data, including faults/dykes and geological rock formations with known groundwater characteristics, (2) borehole data and, significantly, (3) the geomorphological interpretation of elevation data with satellite imagery, supplemented by field visits that focused especially on fossil drainage patterns and contemporary pan systems. The subsequent interpretation concluded that, although the terrain had very low relief, the complexity of its geomorphological history had produced varied terrain

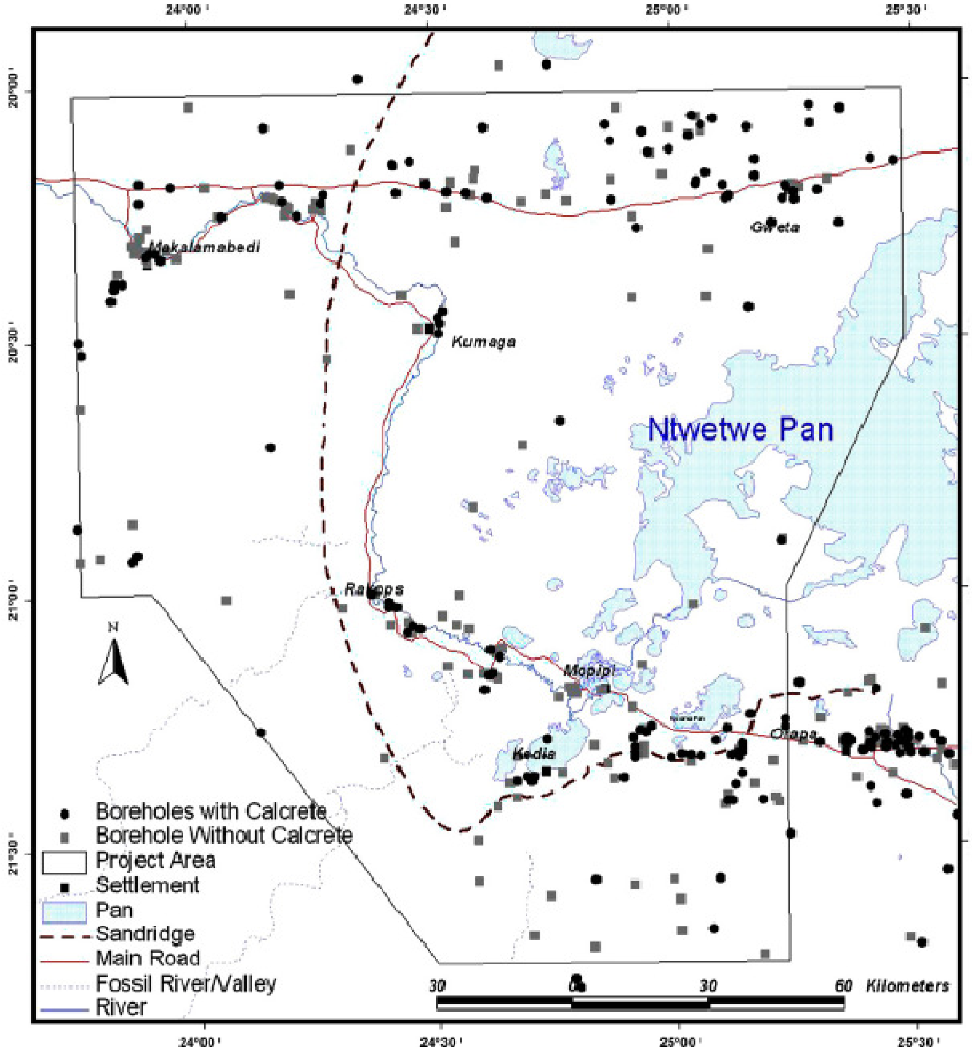


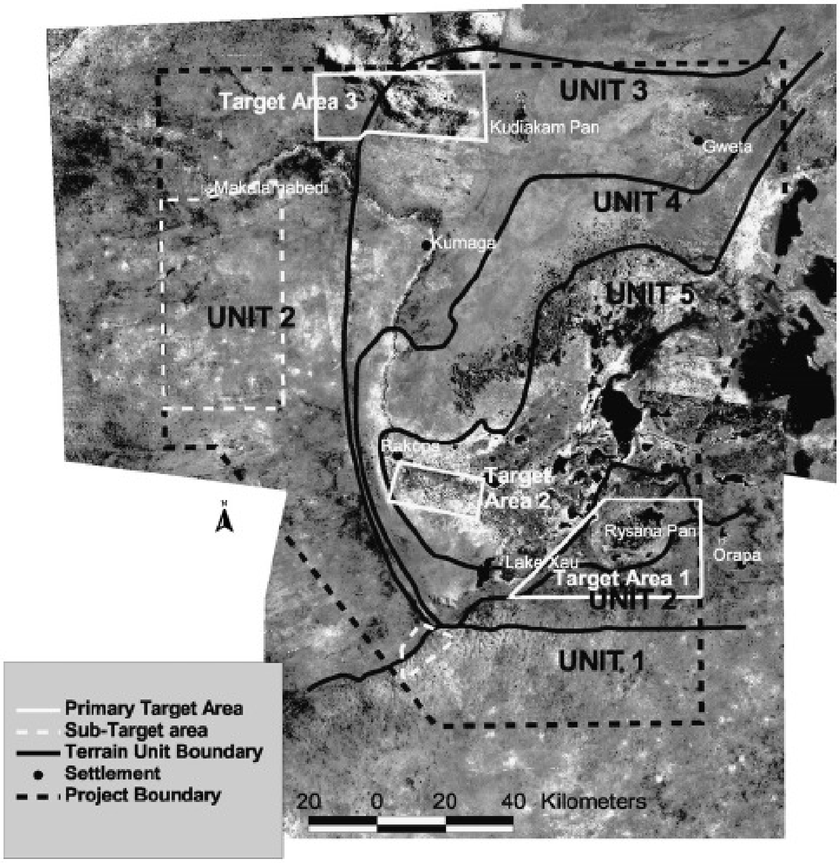
Fig. 4. Distribution of boreholes with and without calcrete in study area.

types with quite distinctive characteristics. Five main terrain units were distinguished (Fig. 5).

Unit 1 comprises the terrain above the palaeo-lake system in the south east corner of the study area, which lies above about 950 m in elevation, i.e. higher than the sequence of palaeo-lakes, which have dominated the region's geomorphological history (Cooke and Verstappen, 1984; Shaw, 1985; Thomas and Shaw, 1991).

Unit 2 represents the palaeo-lagoon of Lake Palaeo-Makgadikgadi and includes the Gidikwe ridge and the extensive, flat lagoonal area to the west of the ridge, while Unit 3 represents the surviving components of the 936 m palaeo-lake floor of Palaeolake Thamalakane (920–936 m). Unit 4 represents the surviving parts of the 920 m palaeo-lake level, the floor of which lies between about 912 and 920 m. To the north of Ntwetwe pan, it survives as a relatively narrow flat strip south east of Gweta; further to the west, the terrain at this elevation is highly varied. Unit 5, finally, represents the recent and contemporary Ntwetwe pan floor below about 912 m (see also: McFarlane and Segadika, 2001).

It was concluded that the northern part of terrain unit 1 appeared to offer some groundwater potential, particularly because, locally, recharge pans were well



TERRAIN UNITS and Groundwater PROSPECTS
UNIT 1: Terrain above the palaeolake system (>940m): poor to moderate (north)
UNIT 2: Palaeolagoon of Lake PalaeoMakgadikgadi: moderate or unknown
UNIT 3: Floor of Palaeolake Thamalakane (920-936m): fair to good
UNIT 4: Floor of the 920m palaeolake level: poor to moderate
UNIT 5: Recent and comtemporary Ntwetwe Pan floor (<912m): very poor

Fig. 5. Terrain units resulting from geomorphological interpretation and selected target area for detailed groundwater investigation on satellite image.

developed (Goudie and Wells, 1995), while the southern, higher part of this terrain unit appeared to offer poor groundwater prospects. The portion of terrain unit 2 west of the Gidikwe ridge appeared locally to offer some potential, again associated with recharge pans. A small area to the south east of Makalamabedi (Fig. 2), a major water demand centre, also appeared to offer interest in the form of structurally controlled pan systems, although groundwater quality is likely to be locally varied as it is controlled by the effectiveness of the recharge pans (Goudie and Wells, 1995).

The best potential for fresh water in the study area was considered to exist along the north side of the pan system – unfortunately located far from the main water demand centres – in terrain unit 3 lying between 920 and 936 m elevation, from the Gweta area to the Gidikwe ridge. However, the southward sweep of this strip that encompasses the terrain around the ‘elbow’ of the Boteti, where it changes direction from west–east to north–south, was considered to be of limited potential, because it appeared to be essentially an area of deltaic deposition rather than a surviving component of the

Palaeolake Makgadikgadi floor. On the south side of the pan system, the area of main demand, small surviving pockets of unit 3 appeared to have good potential, particularly around Rysana pan (Fig. 5), as suggested by the existence of a nearby group of fresh water boreholes and hand-dug wells.

Terrain unit 4 appeared hydrogeologically only of moderate interest, providing a relatively thin body of fresh water overlying more saline water (WSB, 2000). Nevertheless, on the south side of the pan system, where the water supply situation is critical and where most of the demand is, this terrain unit could be of local importance. Terrain unit 5 was considered to offer extremely poor prospects, except possibly along the Boteti river. However, even there the potential for finding sufficiently substantial fresh water bodies is poor. Rainfall and resultant flooding of this terrain unit is short lived, while high wind speeds combine with high temperatures to cause rapid evaporation. In addition, the groundwater level is close to the pan surface; in short, the situation is generally conducive to salinity.

6. Target area identification

In the second stage, more specific target areas for in-depth groundwater investigation within promising terrain units were identified through the analysis of borehole records and geological maps. Using the GIS as an integration and visualisation tool, these data were subjected to geomorphological interpretation focussing on groundwater relevant landforms. Use was made initially of satellite imagery and the contour elevation information compiled during base-map construction. Field visits provided additional insights. The GIS query facility was used to map out patterns of borehole characteristics for geomorphological interpretation and interactively display various band combinations of the satellite imagery for landform interpretation purposes (Republic of Botswana, 1998). Three primary and two secondary target areas for more detailed exploration were identified at the conclusion of this phase of the investigation (Fig. 5). Details of the GIS associated decision making procedure are given below, with particular attention to borehole data interpretation and visual satellite imagery analysis.

6.1. Borehole data interpretation

Digital borehole data, compiled in spreadsheets at the Botswana Department of Geological Survey, for the more than 600 boreholes in the study area typically included information about depth, water strike level and yield. GIS query and classification routines were applied to produce coded distribution maps such as Fig. 4 to distinguish and interpret patterns of groundwater depth and yield. A piezometric groundwater depth contour map was also produced. Contouring, however, assumes uniform conditions and the piezometric map was later found to be of limited use due to the extreme discontinuous underground geology related to the presence of numerous faults, dykes and horst/graben structures. Patterns of borehole depth and yield were nevertheless revealing about overall groundwater conditions.

Borehole log records, as routinely recorded during drilling, include information about underground lithology. This information was not available in digital form but had to be entered into computer files from hand-written forms kept at the Department of Geological Survey. The resulting borehole lithology file was combined with the digital borehole file, using the borehole identity number as the common identifier during a simple GIS join operation. Distribution maps of lithologies at varying depths could then be produced, using simple GIS query procedures to answer questions such as ‘where do we find boreholes with Kalahari sediment in the top layer’. In this manner, for example, maps of shallow and deep silcrete and calcrete occurrences were produced as these formations provide important indicators for groundwater occurrence (Fig. 4). The borehole lithology information was also used to assess the accuracy of the existing digital 1:1,000,000 geology map of the Geological Survey Department, resulting in various corrections to this map at a number of key locations, particularly with respect to the occurrence of Ntane sandstone, a rock known as a potential aquifer. On the basis of the existing geological map and the supplementary information from borehole lithologies as combined in the GIS, extensive portions of the study area could be rated as having low prospects for fresh groundwater, given the known properties of geological formations as described in the literature (Mallick et al., 1979; DWA, 2002).

6.2. Satellite imagery based geomorphological interpretation

Another important step involved the geomorphological interpretation of the study area on the basis of visual – on screen – interpretation of Landsat-7 satellite imagery. This provided information relating to topography and landscape features, structure, geomorphology and geology, vegetation and drainage. Three image scenes (shown in background of Fig. 5) were required for both the wet (April 2000) and the dry season (October 2000) to cover the study area. While the dry season images were fairly cloud-free, some cloud-cover was evident on the wet-season images. Image files were geo-referenced, using the data in the header files and GPS ground locations collected for the project and combined, after colour-matching, into composite mosaics resulting in a wet-season and a dry season image for the study area. The wet-season mosaic was found to be of superior quality compared to the dry season mosaic which – even after colour-matching – continued to exhibit substantial contrasting between the portions making up the composite.

Because of the nature of the terrain in the study area, the extreme contrasts in reflection characteristics and lack of ground-truthing information – and lack of time and money to gather such – it was decided to concentrate the interpretation on aspects of visually interpretable landscape features and geomorphological entities and characteristics, using suitable band combinations such as the false colour composite of bands 4–5–1, known to highlight structural landscape features (Mallick et al., 1979). Imagery was studied interactively on-screen in combination with elevation contour data. Surface features visible in the image such as river channels, sand ridges, pans and fossil channels were interpreted in terms of varying prospects for the discovery of fresh groundwater (Cooke and Verstappen, 1984).

Inspection of the imagery revealed that the drainage network in the study area was very sparsely developed, indicating low runoff. This is related to the low gradient, low rainfall and soils that suppress runoff due to high field capacity (Breyer, 1983). Given the gentle gradient, the Boteti river meanders through the study area from the north-west, sharply changing direction at several structurally controlled locations such as north of Khumaga, around Rakops and in the Lake Xau-Mopipi area (DWA, 2002). Study of the imagery further revealed many old or abandoned river channels and valleys on each side of the Boteti, while many fossil rivers, such as the Okwa (Fig. 1), various former delta's and alluvial fans were also identified. The main fossil rivers and valleys were digitised from the image and saved as shape files in the GIS.

Also visible in the imagery were the stands of tall riverine forest that delineate portions of the Boteti river. These tend to be bordered by more extensive belts of very high albedo indicative of bare soil, especially during the dry season. The presence of the riverine growth and the many hand-dug wells in the Boteti channel testify to the presence of shallow groundwater. In addition to the high albedo areas adjacent to the Boteti, there are also anomalously high albedos in the eastern portion of the study area due to the presence of lake-bed deposits, including salts, without vegetation cover in Ntwetwe pan and other smaller pans. Results of the geomorphological interpretation were hand-drawn on the 1:50,000 topographic photo-maps and selected portions scanned for integration with other data through the GIS or were digitised on-screen using the satellite image as a base.

The geomorphological information gathered from satellite interpretation was interactively compared to the digital geology map. Particularly, relations were investigated between faults and dykes as shown on the digital geological map and terrain expressions as geomorphologically interpreted from the satellite imagery. In a number of locations fault lines as mapped had to modified, while additional, mostly minor fault lines were also identified. These were digitised on-screen from the imagery and added to the GIS database.

Three primary and two secondary target areas for more detailed exploration (shown in Fig. 5) were identified at the conclusion of this phase of the investigation process, their identification based on GIS-integrated information related to (1) geological data, including faults/dykes and geological rock formations with known groundwater characteristics, (2) borehole depth and yield data and, significantly, (3) geomorphological landform interpretation. Selective use was also made of borehole lithology data.

7. Within target area investigation

Within target areas, more detailed exploration work was conducted. For this, use was made in certain cases of previous geophysical work from village borehole drilling programmes. Use was also made of more detailed geomorphological interpretation, relying on hard-copy aerial photographs and digital satellite imagery as well as ground reconnaissance focussing especially on linear structures, recharge and discharge pans (Goudie and Wells, 1995; McFarlane, 1995) and other water related surface and near surface features. Use was further made of borehole data for these selected areas and information from hand-dug wells identified during field tours, where local residents had identified pockets of fresh groundwater (Carter, 1995).

As a separate component of the investigation, low level airborne electromagnetic (AEM) data were acquired at 500 m line spacing in five selected areas covering most of the target areas. Although becoming available quite late in the investigation, this was combined with other data to select the most promising portions within target areas. Specifically, the GIS supported combination of AEM-data and borehole data, while additional geomorphological interpretation was applied to site geophysical traverse lines strategically across these most promising portions. The resulting geophysical profiles were interpreted together with the geomorphological and AEM information to produce a basis for the selection of sites for the drilling of test boreholes. These were subsequently drilled, test-pumped and analysed for quality, quantity and recharge characteristics.

7.1. Target Area 1

One of the selected target areas, known as Target Area 1 (see Fig. 5), is here used as an example. As in other target areas, traverses for ground geophysics were selected through detailed examination of geomorphological characteristics, using the 1:50,000 photo-topographic maps, the elevation contour data generated for the project, digital satellite imagery, hard-copy aerial photography and field observation. The GIS was used to examine the digital geological map in detail especially with respect to the position of faults and dykes and other structural details and to relate these to the digital borehole and borehole lithology data. All data, including selected scanned aerial photographs, were integrated for visualisation and comparison into the GIS and overview maps produced (see Fig. 6). This resulted in the selection of sites for geophysical traverses to cover both promising and – to enhance knowledge of the regional picture – unknown portions of the target area. The results from the geophysical survey were subjected to further geomorphological interpretation and were compared with the data from the AEM survey. Exploration boreholes were sited on the basis of both sources of information and prioritised on the basis of geomorphological interpretation (DWA, 2002).

Target Area 1 had the advantage of having been partly subjected to previous investigations, resulting in the development of a number of wellfields (Anglo American Corporation, 1984). The Mokoboxane wellfield, for example, had seven boreholes exploiting a shallow, semi-consolidated aquifer contained in Ntane sandstone, the geographical extent of the aquifer limited by a series of WNW to ESE trending structures and by the NNE Mopipi Fault, which demarcates the western boundary of Ntane sandstone. The water quality of the upper layer of this aquifer is good, but water becomes brackish with depth. In 1997, four boreholes, drilled to supply the Setata Quarantine camp, penetrated up to

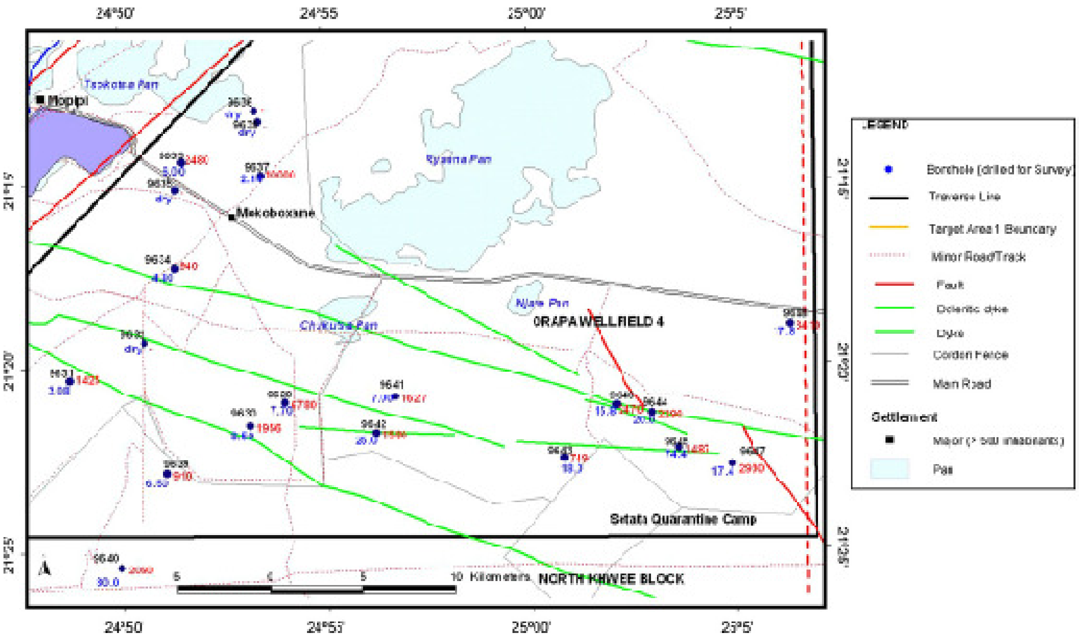


Fig. 6. Overview of Target Area 1.

135m of Ntane sandstone and major water strikes were encountered. The high yield was attributed to the intersection of secondary features (faulting, brecciation and jointing). More recently (1998–2000), an investigation to build up the dwindling water supply of Mokoboxane-Mopipi resulted in the drilling of additional boreholes southeast of the Mokoboxane wellfield both north and south of a WNW to ESE trending fault (DWA, 1998). Boreholes drilled along the fault were high yielding and saline, while boreholes drilled north of the fault were either dry or low yielding and saline. Twenty kilometres south of Mokoboxane eight additional boreholes were constructed to a depth of 33–109 m penetrating a succession of mudstones and sandstones. These boreholes were dry or low-yielding and saline. One borehole, however, terminated at 83 m, penetrated sandstone to total depth and struck fresh water at 69 and 73 m (DWA, 1998).

From these results it became apparent that structure severely affected the Karoo sediments in Target Area 1 and consequently groundwater occurrence. The most dominant structures trend WNW to ESE and have divided the area into a series of horst-graben features, 2–5 km in width, with north south step type faults occurring (DWA, 2002). Structural activity resulted in a general uplifting and consequent erosion of the Ntane sandstone in some places, leaving the relatively impermeable Mosolotsane mudstone close to the surface. In other places, protected by a cap of basalt or buried in a graben, the original thickness of Ntane sandstone was preserved; boreholes constructed in these portions are expected to obtain the highest yield, in particular where fractures are penetrated. The concept for siting exploration boreholes was thus to identify areas within the Karoo sediment sequence where the Ntane sandstone is uniform across the area, despite the complexity of faults, fractures and dykes (DWA, 2002). The integration capabilities of GIS were extensively used to combine and visualise data from existing boreholes, geomorphological field interpretation, geophysical traverses and – when this became available – AEM data.

On the basis of the interpretation of the integrated data, three portions of Target Area 1 were selected for ground geophysical work. Only one of these, the Setata location (Fig. 6), is further described below. The exact position of lines for ground geophysical traverses was mostly determined on the basis of existing digital geological data, borehole data and geomorphological interpretation as visualised in the GIS (Fig. 6). Ground geophysical surveying was intended to locate faults/fracture zones that may be water bearing and to determine lateral and vertical conductivity variations, which may signify variation in water quality. Ground magnetometry was carried out to identify magnetic dolerite dyke intrusives and fault zones. Horizontal loop electro-magnetic (HLEM) traversing was carried out to determine lateral changes in subsurface conductivity, which can indicate either groundwater occurrence in fault/fracture zones or quality variations (DWA, 2002).

In the Setata portion of Target Area 1 a total of eight lines with a general north and north-east orientation were cut, pegged and surveyed with both magnetometry and HLEM with the objective to intercept east–west trending structural lineaments identified through the GIS from the geological map and from satellite imagery. One line (line 300 in Fig. 7) was surveyed between two boreholes with known, good water quality to provide control to the survey. One line (304) was to give a general north-south picture of the area. All total magnetic field plots showed a very smooth response over the Setata Sandstone except where straddling dolerite dykes/faults or basalts in the eastern section, where noisy response was encountered (DWA, 2002).

7.2. Test boreholes in Setata

Interpretation of the geophysical results in combination with geomorphological characteristics resulted in the conclusion that this portion of Target Area 1 (Fig. 7) lies altitudinally above the palaeo-lake floor system along the southern flanks of the oldest palaeo-lake (McFarlane and Segadika, 2001). The land rises relatively steeply from the palaeo-lake, providing a northwards gradient for groundwater drainage, allowing groundwater flow to find preferential pathways. However, the situation is complicated by a dyke system which runs transverse to the generally northward flow. The dykes act as barriers behind which the generation of salinity is favoured. The situation is further complicated by NE-SW trending faults which divide the groundwater into compartments. It was concluded that the structurally controlled valley traversed by lines 303 and 305 (Fig. 7) may provide a pathway for water recharged near the edge of the thin basalt or into the sandstone bounding it. The upper parts of this valley appeared to offer the best prospects although large parts of the terrain lacked geomorphological indications of good recharge and, where recharged, water was compartmented and thus conducive to salinization (DWA, 2002).

The GIS then employed the AEM data with the geophysical/geomorphological interpretation to select

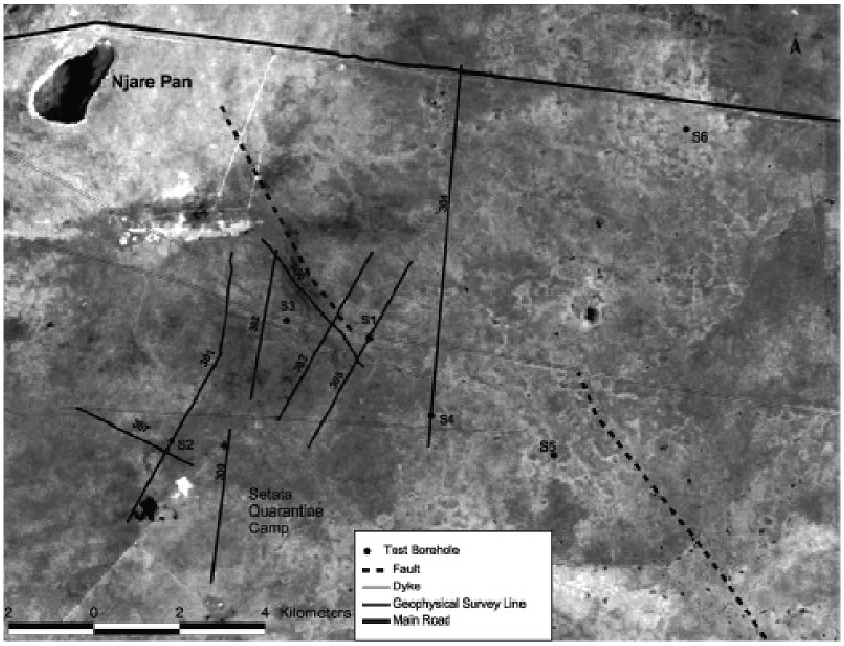


Fig. 7. Location of geophysical traverses and test boreholes in the Setata portion of Target Area 1.

sites for exploration borehole drilling. Four sites were selected as primary exploration sites and an additional two as optional (Fig. 7). Criteria behind this selection and a summary of the drilling results are presented in Table 3. While good yields were encountered, total dissolved solid levels (TDS) were in most cases above the acceptable level of 1500 mg/l (Table 3).

Table 3
Summary of drilling in Setata section of Target Area 1

BH (no.)	Site location	Aquifer	Depth (m)	Yield (m^3/h)	Water strike (m)	TDS (mg/l)	Comment
9643	S2/301	Sandstone	142	18	57, 123	749	Site is located on HLEM anomaly on all frequencies (fractures), south of a regional dyke, recreating the same conditions of high yielding borehole 8096 in the west of the study area, where there is lack of drilling and water quality information
9644	S1/305	Sandstone	147	20	86, 137	2290	This site is located on a NW-SE trending lineament, inferred as a fault, in a break of a regional dyke, represented on the AEM and by a magnetic anomaly
9645	S4/304	Sandstone	184	74.4	58, 82, 180	1487	Site is located on a NW-SE trending lineament inferred as a fault. The magnetic response indicates that a doleritic dyke has intruded the fault. The HLEM shows vertical conductivity on all frequencies, i.e. extending to depth
9646	S3/AEM5-4	Sandstone	140	15.8	79, 130	2470	The surface expression of this site is the junction of 2 faults/dykes, where the AEM response at approximately 110 m deep shows resistive material
9647	S5/	Sandstone	166	17.4	56, 64, 149	2700	Site based on AEM response in order to explore the eastern limits of Setata sandstone
9648	S6/AEM5-2	Sandstone	172	17.8	65, 86, 159	2572	Site based on AEM response in order to explore the north of the area, where conductivity represents sandstone

8. Water resource Setata area

The geophysical work proved very useful, mostly because the traverse lines were strategically located on the basis of geological and geomorphological evidence as combined and visualised in the GIS. The traversing lines were partly designed to provide confirmation of the geomorphological interpretation that was based on fieldwork and air photos/satellite imagery interpretation. In the very complicated structure existing in the area, both ground geophysical methods proved useful. Magnetometry revealed the existence and location of dykes and allowed discrimination of fractures from dykes. HLEM was most useful to identify and locate fault related fracture systems. The sites that were selected, and successively drilled depict a negative anomaly on all frequencies, i.e. indicating vertical conductors extending to depth (DWA, 2002). Three boreholes were also drilled on sites selected by AEM conductivity criteria, but this method appeared less able to differentiate variations in water quality and results were quite saline (Table 3).

Two criteria were found to be important in relation to the aquifer located at Setata. These were the thickness of sandstone – best yields and quality associated with thick sandstone – and structural control. The major lineaments (WNW to ESE trending dykes) and minor lineaments (NE to SW trending faults, fractures and joints) compartmentalize the area into horst and graben blocks with preservation of sandstone in the down-thrown and presence of mudstone at shallow depth in the up-thrown sections. The influence of structure is bi-fold: it preserved sandstone from erosion and also created zones of high hydraulic conductivity, where borehole yields are enhanced (DWA, 2002).

From drilling records it became clear that sandstone attains its maximum thickness in the Setata Graben, which is separated in the north from mudstones by the WNW to ESE trending fault associated with a dyke intruded at depth. In Setata the average sandstone thickness is 150 m, while north of the fault the thickness is only 70 m. The sandstone wedge thins out both east and west against mudstone. The sandstone graben was estimated to be 72 km^2 in extent and 200 m thick. Results from drilling indicated it contained a confined aquifer with water strikes at 90–180 m depth. Good yields of over 50 m^3/h were attained from the basal unit of Ntane, where the boreholes are located on fracture systems. Groundwater in storage in the graben was estimated on the basis of test pumping to amount to about 100×10^6 m^3. The average rate of recharge to the graben aquifer was estimated at 182.2×10^3 m^3/year, calculated by chloride mass balance (DWA, 2002).

Apart from water quality, which proved to be problematic in the whole of the Boteti study area, the Setata Ntane sandstone graben, as conceptualised during the study, proved to be a prospective groundwater resource, which, once developed, may supply the villages of the southern zone of the Boteti region. Water quality is, however, marginal to poor, with a tendency of deteriorating from west to east, where sodium concentration increases. Unfortunately, fluoride is present in unacceptable concentration in the less saline southwest corner of the graben. In brief, groundwater of acceptable quality is not available and prospective exploitation will have to include treatment. This in itself will not be very complicated, as, apart from fluoride, sodium and chloride, the concentration of all other ions was within the acceptable limits (DWA, 2002).

The year 2020 water demand of the southern zone of Boteti was estimated at 1250 m^3/day. If forty percent is added to this because of treatment requirements, the raw water requirement amount to 1750 m^3/day. The inferred annual contribution by recharge was 182.2×10^3 m^3 (DWA, 2002) and groundwater mining will have to provide the 464×10^3 m^3 annual balance, which, given the resource in storage, should last for the next 215 years (DWA, 2002).

9. Conclusion

Groundwater investigations are multi-disciplinary in nature. Geophysicists, geomorphologists, hydrogeologists, social scientists, remote sensing specialists and geologists all have potential roles to play. Geographic information systems, even if used at a low technical level, provide an opportunity for integrating a great variety of data sources to assist in integrated cross-discipline decision making during groundwater exploration work.

In the Boteti groundwater investigation study the GIS performed a crucial role in integrating and updating scattered and outdated base map data and was highly instrumental in the production of essential elevation contours for the study area. The ability to integrate satellite imagery and selected scanned aerial photography with base-map data, geological data and borehole data assisted during the early phase of geomorphological interpretation and the selection of terrain units and then target areas of promising groundwater prospects in the large 29,000 km^2 study area. The same approach at more detailed level and complemented by field reconnaissance proved useful in detailed geomorphological interpretation that allowed, together with AEM interpretation, the selection within the target areas of portions suitable for geophysical ground exploration and the siting of exploration traverses within these.

Plotting of geophysical traverse lines and visualisation of results together with geological, geomorphological and borehole data in comparison with results from previous surveys within the GIS environment facilitated the siting of exploration boreholes for Target Area 1. As these could be positioned accurately with the GIS in relation to geological formations and structure, inferences could be made about structure and extent of a conceptualised aquifer in Ntane sandstone, where substantial water resources were subsequently located in the Setata portion of Target Area 1.

Investigations similar to those described in this paper for the Setata area in Target Area 1 were conducted in the other target areas. In Target Area 2, known as the 'Boteti alluvium groundwater resource', cumulative total available fresh water resources amounted to a meager 5.5×10^6 m^3 as predicted by the GIS supported terrain unit analysis described in an earlier paragraph. In Target Area 3, known as the 'middle Kalahari silcrete groundwater resource', however, apart from sodium concentration, which was a potentially limiting factor to direct exploitation, groundwater resources were substantial as uniform conditions existed over about 900 km^2. The fresh to marginal quality water volume in storage was estimated at 4.7×10^6 m^3.

In each case the GIS performed a crucial role in guiding multi-disciplinary decision making for these regional groundwater investigation processes, generating cross-disciplinary added value to the study. As an overall outcome of the investigations, sufficient quantities of groundwater resources were indicated, although quality characteristics necessitate treatment in most cases. This may necessitate a rethink on current rural water supply practices, as treatment is currently not a common scenario in Botswana where it is generally assumed that groundwater can be supplied to rural populations in untreated form.

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