GROUNDWATER AND DROUGHT MANAGEMENT IN THE SOUTHERN AFRICAN DEVELOPMENT COMMUNITY (SADC)

COMPONENT 2

REGIONAL GROUNDWATER DROUGHT MANAGEMENT SUPPORT

Contract 003D:

Regional Groundwater Monitoring Network

Groundwater Monitoring Pilot Study

FINAL REPORT

October 2011

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1. SITE SELECTION FOR PILOT STUDY

1.1 Transboundary aquifer (TBA)

The fourteen TBAs identified in the SADC Hydrogeological Map (

Figure 1) were subjected to rigorous categorisation and ranking under a variety of theme topics (Wellfield, 2011). The most 'at risk' TBAs were identified as:

- No. 13 Southwest Kalahari/Karoo Basin,
- No. 15 Tuli Block,
- No. 20 Cuvelai, and
- No. 24 Eastern Kalahari/Karoo aquifer.

However, the cross-border Cuvelai transfer is largely by surface water and this TBA is downgraded to 'at moderate risk'. It was also recognised that the Southwest Kalahari/Karoo Basin is to be instrumented anyway within a separate programme funded by World Bank GEF. The Eastern Kalahari/Karoo was selected over the Tuli Block as current active wellfields are present on both the Botswanan and Zimbabwean sides of the border – as opposed to solely in Botswana.

1.2 Specific monitoring boreholes in the Eastern Kalahari/Karoo TBA

To save time and costs it was justified to adopt existing boreholes in both countries. To identify suitable sites and to seek permission to instrument them, the appropriate authorities were contacted through SADC initially: the Botswanan Department of Water Affairs (DWA) and the Zimbabwe National Water Authority (ZINWA). These provided details of the Maitengwe Wellfield (Botswana) and the Nyamandhlovu Wellfield (Zimbabwe), which both utilise the Eastern Kalahari/Karoo aquifer. Thereafter, Wellfield Consulting undertook a reconnaissance survey, in collaboration with the respective local authorities, to identify details about potential monitoring boreholes. This included:

- GPS location and elevation.
- Details of wellhead construction: capping, slab dimensions, upstanding casing, casing diameter.
- Details of wellhead area: slope and drainage, tree cover, line of sight to horizon, vehicle access, nearest habitation, security, feasibility of installing fencing
- Borehole condition: sealed, equipped, open/ blocked
- Current use and distance to nearest abstraction borehole to ensure there was no external influence on water level.
- Land use and ownership

In the Maitengwe Wellfield, it was deemed that the most suitable boreholes were 8887 and 8946. These boreholes were both 6.5” in diameter, in good condition, with a casing upstanding exceeding 0.5 m. They were unobstructed by vegetation, on flat topography with a relatively unrestricted view of the horizon. Borehole 8887 was located in the privately owned Maitengwe Quarantine camp, which is fenced with no nearby human habitation. Borehole 8946 was located within the secure fenced compound of currently inactive production well BH 9468; workers reside within the compound and Water Utilities Cooperation (WUC) attend site regularly. Both sites were also current monitoring boreholes with some historical data available (Table 1).Therefore, the sites were of suitable condition and completion, secure, and liable to have good satellite reception and unhindered sunlight.

Table 1 Available water level data from boreholes 8887 and 8946

Borehole	Available data	Average DTW (m)	Water level range (m)
8887	7 reading 2007; 3 readings 2011	41.2	13.8
8946	27 readings 2006-present	37.4	13.6

Note: DTW is depth to water

In the Nyamandhlovu Wellfield four out of the ten identified available boreholes contained obstructions and hence were unsuitable for monitoring. From the remaining sites, boreholes 4-UMGU-123 and Nyamandhlovu 88 were selected. Both boreholes were easily accessible from nearby tracks, were adjacent to compounds for added security and were sufficiently distant from abstraction wells.

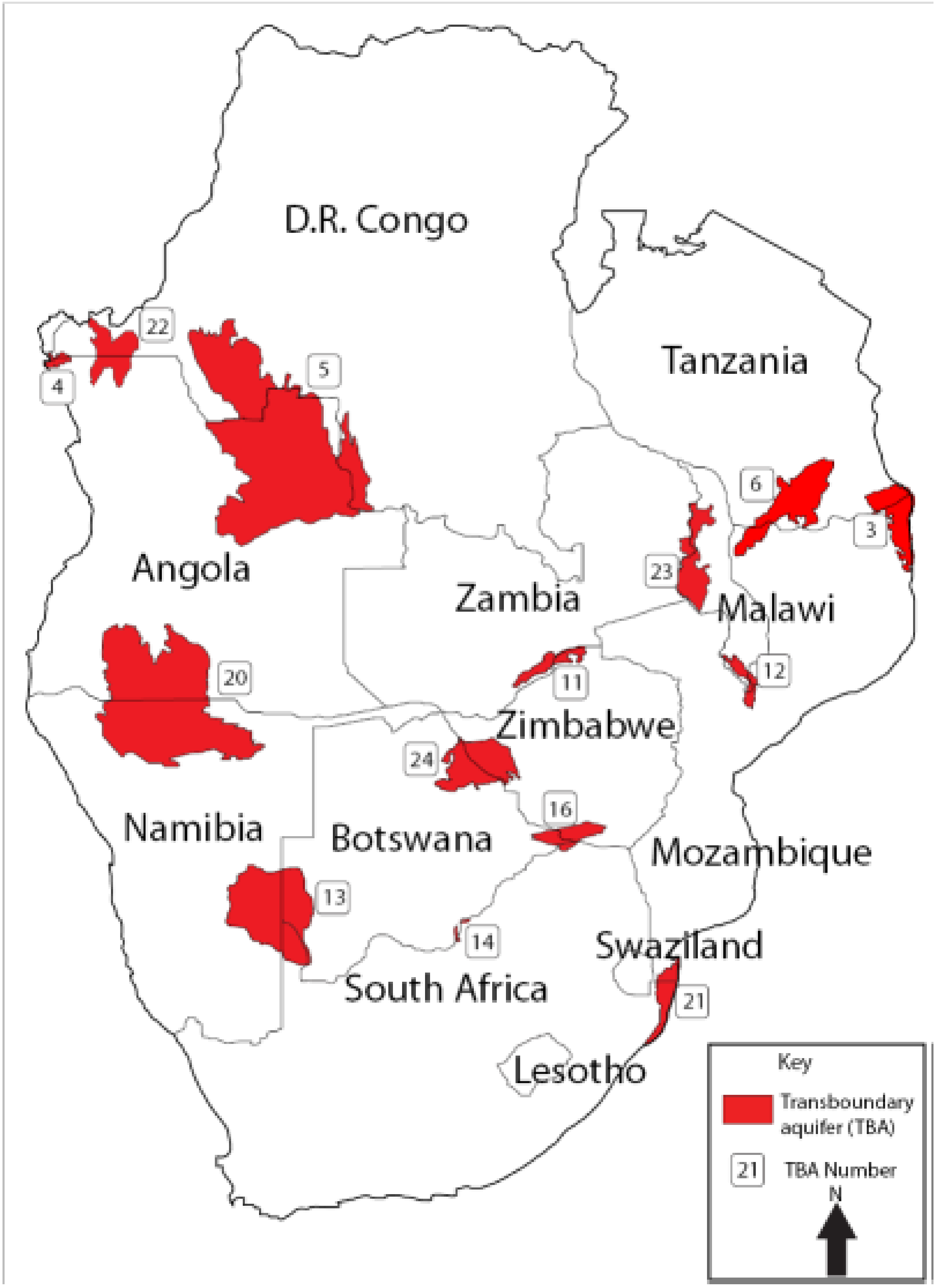

Figure 1 The SADC TBAs

2. FIELD SETUP AND MAINTENANCE

2.1 Equipment

A pilot groundwater monitoring system was designed which, due to the remoteness of the field sites, could operate independently of local services using solar power and satellite telemetry. The system was deployed in locked yellow weather-resistant and vandal-proofed cabinets which could be universally clamped to boreholes finished above ground level (Figure 2). These were labelled with 'danger high voltage' to dissuade unauthorised access to the equipment and borehole. Each cabinet enclosed the following:

- Solar regulator and charging circuit.
- 12V 7.2 Ah sealed lead acid battery.
- AST Fastconnect unit (Iridium satellite data modem 9602, antenna, logger and SDI-12 interface).
- Tamper switch to indicate when the door was open.

In addition, a 17.5V 10W solar panel was fastened to the top of the cabinet from the inside. The antenna for the satellite modem was attached below a plastic covered aperture in the top of the cabinet to increase reception. The cabinets were mounted onto square brackets affixed to the above ground level casing using a series of screws from the inside (Figure 2). Therefore all fittings could only be accessed from inside the enclosure.

(a) (b)

Figure 2 (a) attaching square base bracket to borehole casing (b) completed installation

Pressure transducers were the only subsurface equipment installed and were all interfaced with the AST Fastconnect unit using the SDI-12 communication protocol.

The AST Fastconnect unit was programmed to request data directly from the connected sensors at regular intervals and store this within its internal memory, which is cleared upon successful satellite transmission. This non-volatile memory is capable of holding 2.5 days of data in the event of communication difficulty; however, it is not possible to interrogate the unit onsite. Battery voltage and the status of the tamper switch are also read and transmitted concurrently. All data are timestamped by the AST Fastconnect unit in UTC (coordinated universal time) when logged, and the device clock is regularly synchronised with the Iridium satellite constellation to avoid drift. Communications with the AST Fastconnect unit are one-way and it is not possible to request immediate readings or change settings (e.g. measurement frequency) remotely.

A selection of submersible pressure transducers were used to allow future comparisons between sensors - Schlumberger Water Services (SWS) Micro-Diver®, and In-Situ® Rugged TROLL® 200 and Aqua TROLL® 200. These non-vented sensors were selected over more accurate vented systems as they contain internal loggers, which can store a backup dataset, and require less maintenance - vented systems require the use of desiccant which has to be replaced at regular intervals to avoid moisture ingress into the transducer and subsequent failure. Moreover, SWS and In-Situ branded transducers have been shown to be reasonably accurate and have suitable temperature compensation (Sorensen and Butcher, 2010). These transducers record total pressure – water pressure plus barometric pressure above the transducer. It is necessary to compensate this data using a separate record of barometric pressure to calculate solely the overlying water pressure.

Micro-Divers monitor both total overlying pressure and temperature. Each sensor was connected to a Diver-DCX at the surface via a Diver data cable (DDC). The Diver-DCX provided an SDI-12 interface to the AST Fastconnect unit and also contained a barometric sensor to automatically compensate the total pressure readings recorded by the submerged Diver. The Diver itself is powered by its internal battery which is specified by the manufacturer to last for around 10 years, whilst the Diver-DCX is powered by the surface battery. The Divers were also initiated manually to record a backup of total pressure readings internally on a 2-hourly interval. The internal memory will last for 10 years at this measurement frequency.

The Rugged TROLL 200 measures both total overlying pressure and temperature; the Aqua TROLL 200 has an additional integrated conductivity module to also record specific electrical conductance (SEC). To barometrically compensate these sensors a Rugged BaroTROLL® was deployed to determine atmospheric pressure. These pressure transducers all interface directly with the AST Fastconnect unit using direct read cables. They are powered by the battery at the surface when readings are requested by the AST Fastconnect unit. All devices were also started manually to record a 2-hourly backup dataset within their internal loggers. These readings are powered by the TROLL internal battery, which is guaranteed by the manufacturer for five years. The internal logger will hold over 14 years of data in both Rugged TROLLS and over 43 years in the Aqua TROLL 200.

Information regarding expected water table fluctuations within all monitoring boreholes (see Table 1 for Maitengwe wells) was not available before the procurement of equipment. Therefore high range submersible pressure transducers were purchased to accommodate even large water level oscillations, at the expense of sensor accuracy which is a percentage of the full scale (FS) pressure range (Table 2). To calculate the total error in water level at each site it is necessary to add the errors from both the submersible and barometric pressure transducers.

Table 2 Sensor manufacturer specifications

Sensor	Type	Range (m)	Accuracy			
			Pressure (% FS)	**Pressure** (cmH_2O)	**Temperature** (^oC)	**SEC** (µS/cm)
Rugged TROLL 200	Submersible	30	± 0.1	± 3*	± 0.3	n/a
Aqua TROLL 200	Submersible	60	± 0.05	± 3*	± 0.1	± 0.5% +1
Micro-Diver	Submersible	20	± 0.1	± 2	± 0.1	n/a
Rugged BaroTROLL	Barometric	2	± 0.1	± 0.2*	n/a	n/a
Diver DCX	Barometric	1.1	± 2.0	± 2	n/a	n/a

Note:* stated accuracy is typical at 15^{o}C and potential error could be up to a multiple of 2 and 3 of that stated for the Aqua and Rugged TROLLs, respectively.

2.2 Monitoring boreholes

Both boreholes within the Maitengwe wellfield were instrumented on 20th October 2011 (Table 3; Figure 3; Figure 4**Error! Reference source not found.**). Transducers were installed below the water table sufficient so they are not exposed during periods of drought. At borehole 8887 the Rugged TROLL 200 was installed approximately 45.8 m below RWL, and the BaroTROLL was installed around 4 metres below ground level (mbgl) to minimise air temperature fluctuations. At borehole 8946 the Aqua TROLL 200 was installed around 28.8 m below rest water level (RWL). Units 3 and 4 are still awaiting deployment in Zimbabwe.

Table 3 Monitoring sites

Unit No.	**BH No.**	**X** (m)	**Y** (m)	**Elevation** (masl)	**RWL** (mbgl)	**Pressure transducers**
1	8887	487198	7785700	975	44.15	30 m Rugged TROLL 200 (SN 193470) Rugged BaroTROLL (SN 193106)
2	8946	504270	7785789	1035	36.01	60 m Aqua TROLL 200 (SN 189394)
3						
4						

Table 4 shows the parameters monitored and transmitted from each unit. It should be stated that the actual measurement time at each site is not standardised, i.e. all sites do not take readings on the hour for example. Moreover, built-in retries from the AST Fastconnect unit may result in data being offset from the specified interval, if data are not generated initially.

Table 4 Parameters monitored and transmitted at each site

Unit No.	**Frequency** (hrs)	**Battery voltage** (V)	**Total pressure** (cm H_2O)	**Water pressure** (cm H_2O)	**Barometric pressure** (cm H_2O)	**Groundwater temperature** (^oC)	**Groundwater conductivity** (µS/cm)
1	1	✓	✓		✓	✓	
2	2	✓	✓			✓	✓
3	2	✓		✓		✓	
4	2	✓		✓		✓	

Note: all pressure transducers store a backup dataset within their internal memory.

Figure 3 Unit 1- Maitengwe Wellfield, Borehole 8887

Figure 4 Unit 2 - Maitengwe Wellfield, Borehole 8946

2.3 Site Maintenance

Despite the use of telemetry, there is still a need for site visits. Pressure transducers have been shown to drift by several centimetres over just three months; moreover, this drift can take various forms and is difficult to characterise for individual sensors (Sorensen and Butcher, 2011). Therefore it is recommended at least six-monthly dip measurements are taken to validate all automatically collected groundwater level data. All dips have to be taken from the same datum point – the top of the dip hole. These manual observations should then be reported to the data custodians for storage within the database. Access space to the monitoring boreholes is limited due to the positioning of the square mounting bracket over the dip hole, and hence only thin and flexible coaxial dip meters can be used.

All pressure transducers should store a complete timeseries of data within their internal memory which could infill future gaps in the records in the event of damage or failure to the communication equipment at the surface. To maintain the available memory in the transducers the records should be downloaded annually and the data reported to the data centre. This would also identify a failure in the transducer logger or internal battery, which would otherwise go unnoticed.

Six-monthly site visits are also necessary to maintain the surface equipment:

- Check for evidence of vandalism/damage.
- Carefully clean solar panels with a damp cloth, as they lose their efficiency over time due to the build-up of dirt and debris.
- Check solar panels have an obscured view of the sun and clear nearby vegetation if necessary.
- Replace any components of the system if required.

More immediate site visits maybe required in the event of equipment failure. This could be highlighted by a communication failure, absent/anomalous reported pressure readings or a progressive or rapid decline in battery voltage. All site visits and actions should be documented.

3. DATA TRANSMISSION AND STORAGE

The field data requested and stored on the AST Fastconnect unit are transmitted using the Iridium short burst data (SBD) service (

Figure 5). The data are then relayed across the Iridium low-Earth orbit (LEO) satellite constellation using microwave cross links until they reach the nearest Iridium gateway in the USA. Subsequently, the data are automatically abstracted over the web and inserted into a SQL Server database. This is hosted in a secure data centre in Johannesburg and operated by AST in Pretoria. Each value inserted into the database is assigned a unique sequential row ID and tagged as SADC data.

A PC at Wellfield Consulting Services was configured using WampServer to act as a local web server. A MySQL database was setup on this server to receive the data from the AST database. Another MySQL database was setup on an external web hosting account.

The local server at Wellfield Consulting Services in Gaborone initiates a query (scripted in PHP) on the AST SQL Server database using open database connectivity (ODBC) on a 6-hourly basis. The server is also setup to run the query two minutes after every login, in case the server has to be rebooted following a power failure in the building. The query performs the following:

- Identifies the most recent row ID in the MySQL databases.
- Examines the SQL Server database for subsequent row IDs.
- Filters any new row IDs for SADC tags.
- Inserts any new data in both MySQL databases.
- Populates a query success or failure log file on both the local server and the remote web server.

Therefore, complete duplicate raw datasets are held in the AST SQL server database in Johannesburg, a MySQL database in Gaborone and on a remote MySQL database hosted by a UK web host. The raw dataset comprises one single data table (Table 5).

Table 5 Raw data table

Rid	Tagdate	Tagname	Tagvalue
Unique row ID	Date and time (UTC)	SADC_SADC00x_parameter	Parameter value

Note: SADC00x corresponds to borehole unit number.

In the event of the failure of the Gaborone local server, data will still be archived in Johannesburg; if insertion into the SQL server database fails then data will still be held in the USA; if the field satellite connection fails then data will be held by the onsite AST Fastconnect awaiting transmission, but only for a limited period. If there is a long-term transmission failure then the pressure transducers will still hold a backup of all groundwater and atmospheric data. These sensors can be raised to the surface and interrogated using a laptop, reader and software. These data can then be manually inserted into all databases.

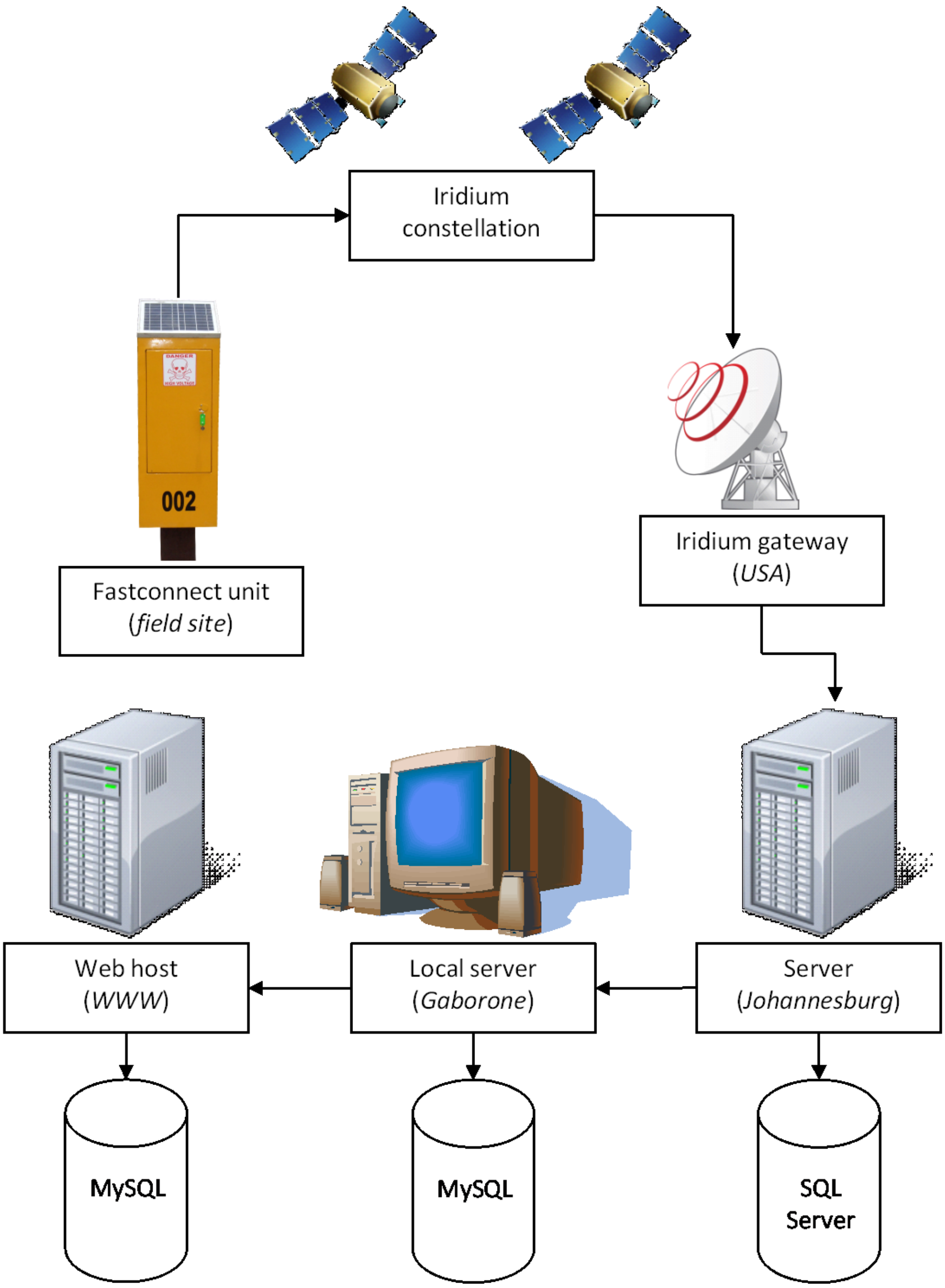

Figure 5 Data transmission and storage from field sites

4. DATA PROCESSING AND QUALITY CHECKS (QC)

4.1 Data processing

The raw values held in the MySQL databases require processing and automated checks prior to dissemination. Therefore on each request for information, either via the local server or the website, the following procedure scripted in PHP is undertaken on the respective portal. Firstly all the data is separated into individual field sites. Secondly, for each total pressure reading at site 2 the nearest barometric pressure reading is ascertained from unit 1. Thirdly, the groundwater elevation in metres above sea level (masl) is calculated according to:

$$\textit{Cable length} = DTW + (TP - BP) \qquad [1]$$

$$\textit{Groundwater elevation} = \textit{borehole elevation} - ((\textit{cable length} - (TP - BP))/100) \qquad [2]$$

Where: DTW is depth to water measured using a dip meter; TP is total pressure; BP is barometric pressure.

The length of the transducer cable (cm) is calculated by the addition of the depth to water and water pressure above the sensor (TP-BP) – both recorded on installation. The cable length is a constant hardcoded into the script and cannot be modified without recoding. The depth to water can be calculated at any point in time by subtracting the water pressure above the sensor from the known cable length. This is then corrected to mH_2O and subtracted from the appropriate borehole elevation to produce a groundwater elevation. The procedure is undertaken for each borehole separately.

4.2 QC

4.2.1 Current QC

The current automatic QC ignores both all rogue tagged data predating the site installation and anomalous spikes in groundwater elevation. The groundwater elevation PHP coded script cycles through the data and completes the following:

- Assumes the first groundwater elevation value is correct.
- Assesses whether the next value involves a step change which exceeds the typical accuracy of the submersible transducer plus barometric transducer (see Table 2).
- If the assessed value is deemed acceptable, it is regarded as the new correct value and is compared against the following value.
- If the assessed value is considered anomalous it is ignored; the previous correct value remains the same and is then compared against the value after the anomalous value.

The procedure has been tested on the current dataset and performs well. However, it assumes that the water level does not change significantly with time. Therefore if a large gap appears in the data, which corresponds with a natural change in water level greater than the typical transducer accuracy, all subsequent data will be ignored. Furthermore, if there was a sudden change in groundwater level resulting from abstraction, specifically at borehole 8946, then there may also be an issue.

4.2.2 Future QC

Automatic QC is limited by current knowledge regarding the hydrogeological regime of the field sites. For example, it is difficult to define an acceptable groundwater level, or how the groundwater level might change with time. As this becomes more apparent through the collection of data, the current threshold methodology for identifying anomalous groundwater elevation changes with time can be modified and refined. Furthermore, acceptable ranges for groundwater elevation can be defined.

An important component of future QC would also be manual checks, which would include validation of the pressure transducer data against onsite measurements of depth to water, temperature and SEC. Identification of erroneous automatic data could then feedback into the data processing. This could utilise timeseries data management software such as WISKI for correcting sensor drift. However, care needs to be exercised that all manual readings are correct. For example, there may be recording errors involving incorrect decimal places which could easily be spotted. To minimise manual errors resulting from faulty equipment, calibration should be undertaken prior to field visits.

5. DATA DISSEMINATION

5.1 Local dissemination

A PHP coded data portal is available on the Gaborone server for solely local access (Figure 6). It is available at http://localhost/transboundary and there is a shortcut on the desktop.

The following options are available:

- Manually download all new data from the AST database and populate both MySQL databases. This can be run to collate the most recent data, or if the scheduled query fails.
- Download all raw data from the local database as a CSV file.
- Download processed data from individual boreholes as a CSV file.

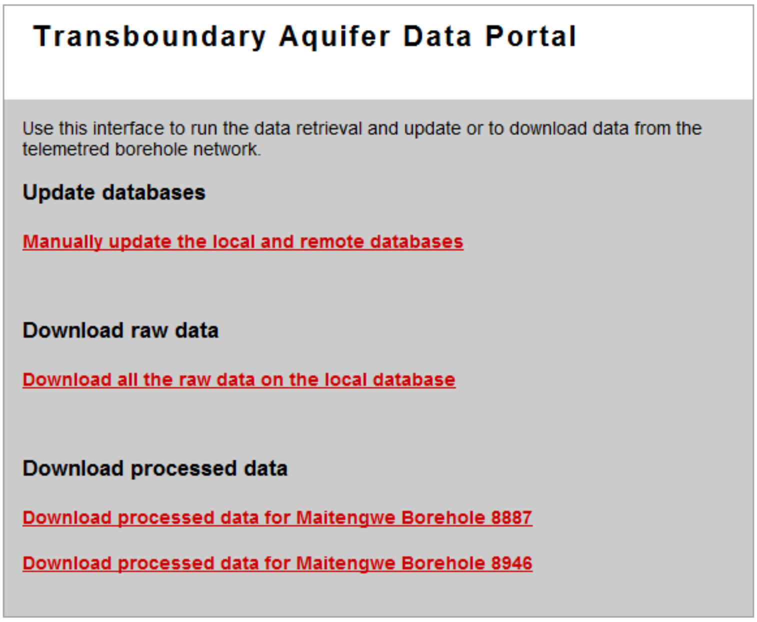

Figure 6 Data portal on the local server

5.2 Web dissemination

To demonstrate potential world-wide dissemination to any device with an internet connection a website was created using Wordpress and PHP. It is located at http://transboundary.oomodels.info (Figure 7), and is optimally viewed in a resolution of 1024x768 or greater. The homepage displays the telemetered sites in the well-known Google Maps. This allows the user to navigate to and select a borehole of interest. Boreholes can also be selected using the left-hand frame, where they are arranged by country.

The opensource dygraphs JavaScript Visualisation Library graphical package is used to display real-time data when a borehole is selected (Figure 8). The viewer works well in Internet Explorer (IE) 9, Mozilla Firefox,Google Chrome and Safari. However, there are some minor issues with IE7 and 8 which need further attention. The user can toggle between groundwater parameters and utilise the following functionality within the viewer:

- Select a time period of interest by clicking and dragging, or defining exact ranges.
- Identify a specific reading at a point in time by rolling the cursor over the graph.
- Smooth the line by using a rolling average over a defined number of points.

Furthermore, the website also contains the following features:

- A print view feature which opens the main frame in a new page for the purposes of printing graphs directly from the website.
- The ability to download fully processed data (excluding anomalous water level data) as CSV files.
- View metadata from all instrumented boreholes.
- A link to contact the future SADC Groundwater Management Institute (GMI)

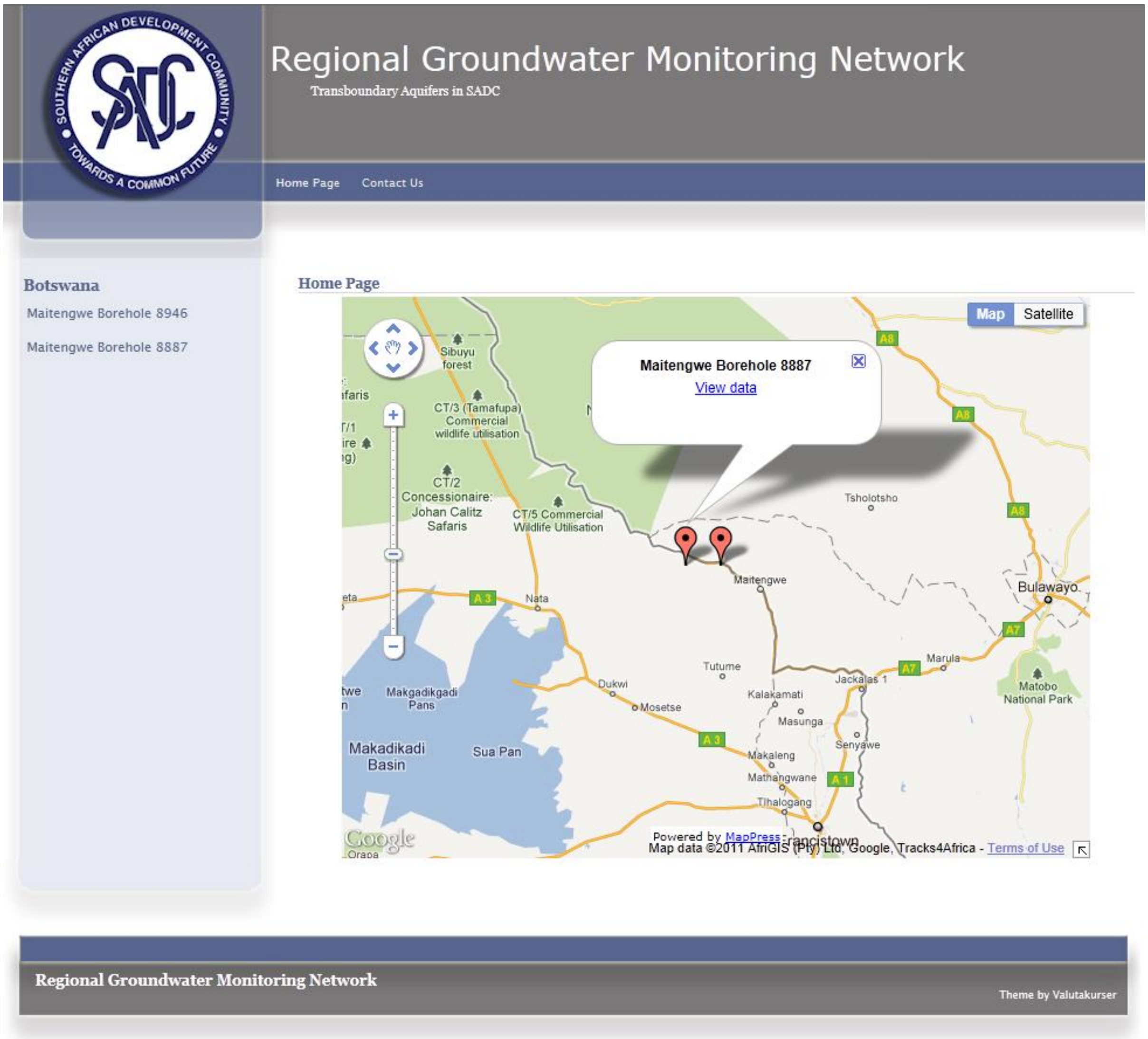

Figure 7 Website homepage showing all instrumented boreholes in Google Maps

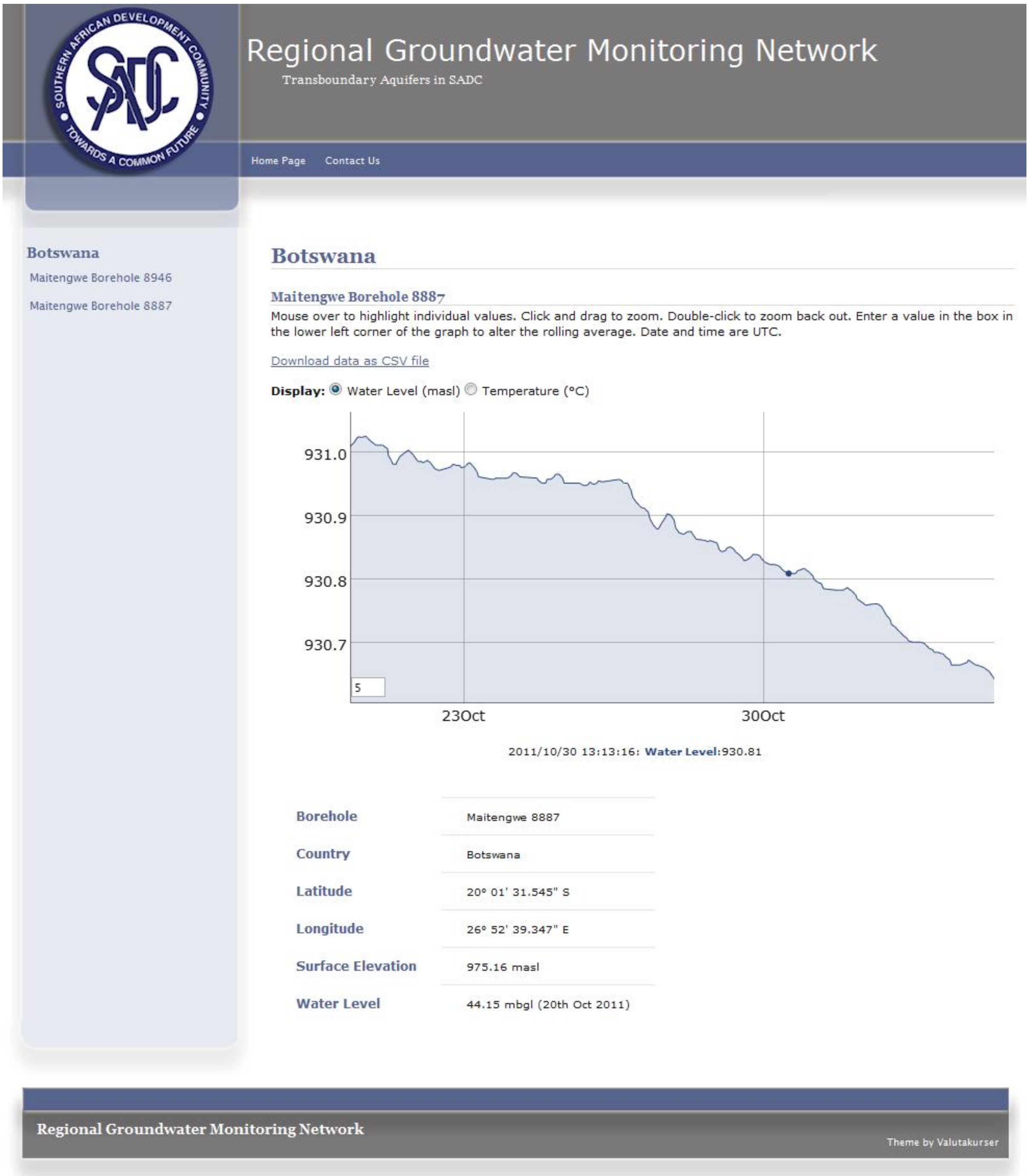

Figure 8 Viewing real-time groundwater data in a Javascript based graphical package

6. CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

The Eastern Kalahari/Karoo aquifer which traverses Botswana and Zimbabwe was chosen for the pilot monitored project. Two specific monitoring boreholes were then selected in wellfields either side of the border during a site reconnaissance trip in collaboration with the respective local water authorities. The groundwater monitoring sites in the Maitengwe Wellfield, Botswana were subsequently installed on 20th October 2011, but the remaining units are still awaiting deployment to the Nyamandhlovu Wellfield, Zimbabwe.

All units utilised a system which could be operated independently of local services using solar power and satellite telemetry. The equipment was enclosed within locked weather-resistant and vandal-proofed cabinets which were attached to the boreholes using universal clamps. Pressure transducers are incorporated into the system to measure groundwater level, temperature and, at one site, specific electrical conductance (SEC). These data are requested by a surface logger on an hourly or 2-hourly basis where they are stored whilst awaiting successful transmission using the Iridium short burst data (SBD) service. In the event of long-term communication difficulties or damage to the surface equipment, all pressure transducers were initialised manually to ensure a complete backup of all groundwater parameters onsite. The internal capacity of the transducers will hold at least 10 years data at the 2-hourly defined frequency.

The data from these sites are transmitted across the Iridium satellite constellation and eventually stored in raw format in three databases: a commercially operated SQL server in Johannesburg, a MySQL database on a local server in Wellfield Consulting (Gaborone) and a web hosted MySQL database. The data can be accessed locally using a data portal on the Gaborone server or via a project website (http://transboundary.oomodels.info), which access their respective MySQL databases. All data are processed and quality checked on each user request for information from either interface. The website includes a graphical package to allow the user to view and manipulate real-time and historical data. All raw and processed data can be downloaded from the local server or the website in CSV format. Moreover the metadata from each site are also available on the website.

The pilot project has therefore successfully demonstrated automated groundwater data collection, transmission from remote field sites to a central location, data processing and website dissemination. Thus there is the potential to use this system to monitor groundwater across the SADC region.

6.2 Recommendations

The current system is fully functional but could be improved in a number of ways if it were to be rolled out in the future. In terms of the field installations, it is recommended that the solar panel is made less accessible. This could be done by creating higher cabinets where the solar panel would be out of reach. Furthermore, it could be installed flush with the cabinet so it is not possible to force anything between the two when attempting to remove it. The cabinets are also currently yellow and hence very visible. Future cabinets should be painted in neutral muted colours.

Access to the boreholes in Maitengwe is via narrow dip holes, which is limited by the square mounting brackets deployed. Consequently, dipping the monitoring sites is difficult and bailing, to acquire a sample for checking the SEC for example, is impossible. Therefore the well caps should be completely removed if these brackets are used at future sites.

Pressure transducers were procured with no prior knowledge of expected water level fluctuations. Consequently high pressure range sensors were obtained which have lower accuracy. In the future, all available borehole water level data should be collated and examined to allow the site specific purchase of transducers to enable the most accurate possible automatic data collection.

All site data are requested and stored on the AST Fastconnect units awaiting successful transmission. However, these contain insufficient memory (only 2.5 days) and cannot be interrogated onsite in the event of communication difficulty. It is recommended that onsite interrogation is enabled to allow both the manual downloading of data and also the system and setup to be verified before leaving site. Furthermore the logger memory should be increased to allow the potential storage of least one month's worth of data and hence sufficient time to visit and correct issues at site. Currently, the transducers will provide a long-term backup of all groundwater parameters but this data would have to be obtained using specific equipment and software, and manually processed into a suitable format before insertion into the databases. Therefore it is preferable that the surface logger provides a medium-term backup which can be directly inserted into the databases with no prior manipulation. Nevertheless, the internal loggers within the pressure transducers do provide an important backup in the event of damage or theft to the battery and/or solar panel.

All sites have been setup using satellite telemetry due to their remoteness. This has high ongoing costs and power consumption. Therefore, in less remote locations, GPRS/GSM telemetry using the mobile phone network could be considered, as this would minimise data transmission costs and reduce power consumption to a level where battery operation would be feasible. However, caution should be exercised when assessing this option due to the relatively unreliable and discontinuous nature of cell phone networks over much of the SADC region.

Satellite communication with the sites is currently only one-way and it is not possible to interrogate the sites remotely. This would be useful for acquiring instant readings or changing the measurement frequency, for example. Therefore future sites should have two-way communications enabled.

Currently, all field values are obtained indirectly from the sites via a commercially operated database. This could be modified to allow direct transmission of field data to the future SADC Groundwater Management Institute (GMI). Moreover when the institute is established, it could directly host the website rather the using a commercial web hosting company.

It is also recommended that a broader trial and investigation of graphical packages for displaying timeseries data on the web should be undertaken. This would ensure the most suitable and robust is selected.

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