Groundwater Monitoring Network Design for the Tuli Karoo Transboundary Aquifer

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Acronyms

DWS-	Department of Water and Sanitation
FAO	Food and Agricultural Organization
GIS	Geographic Information System
GIS-MCDA	Geographic Information System- Multi-Criteria Decision Analysis
GPS	Global Positioning System
IWMI	International Water Management Institute
NGA	National Groundwater Archive, South Africa
SADC	Southern African Development Community
SADC-GMI	Southern African Development Community Groundwater Management Institute
ZINWA	Zimbabwe National Water Authority

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Executive Summary

Groundwater monitoring is a foundation for sustainable management of aquifers. Monitoring groundwater is fundamental to generate a full understanding of the water system in a basin or aquifer (recharge, discharge, interaction with surface water, changes in quality and quantity over time), to assess the long-term and annual changes in groundwater storage due to effects of climate and of withdrawals, and to foster sustainable management of the groundwater resources. The Tuli Karoo Transboundary Aquifer – shared among Botswana, South Africa and Zimbabwe – is not monitored in an integrated way at present. Two of the three countries undertake some monitoring within the aquifer extent for their own purposes; one of the three countries does not actively monitor the groundwater resources. The lack of spatial, temporal and integrated groundwater level data in the three countries makes it difficult to manage groundwater resources sustainably.

Report objective The main objective of this report is to design an improved groundwater level-monitoring network for the transboundary aquifer, to enable improved management of the groundwater resources. Furthermore, the overarching objective of this study is to outline a plan to install a real-time monitoring system in selected observation wells to provide near real-time data (to enable, for example, early detection of over exploitation). The advantage of real-time monitoring for Tuli Karoo is that it allows fast data sharing, provides more reliable and regular data, reduces cost of site visits and in time enables visualization of trends in key parameters. It also supports the process of collecting and sharing data and helps to build trust and cooperation among the three countries sharing the aquifer. Some of the potential drawbacks include: high initial cost (equipment and the visualization software are expensive), requirements of skilled person for configuring and installing the instrument, sensors must be calibrated carefully otherwise they could be taking the wrong readings, high maintenance costs (if the system malfunctions data could be lost) and the necessity of cellular data transmission in remote areas.

Approach The groundwater monitoring network for the Tuli Karoo Aquifer was designed using combined hydro-geological and geo-statistical approaches. A hydrogeological approach was used to map potential priority monitoring index based on Geographic Information System Multi-Criteria Decision Analysis (GIS-MCDA). A geo-statistical approach is implemented to identify the optimal number and location of monitoring wells. The premise with hydrogeological approach is that the monitoring network should enable collection of data from areas representing the full range in variation in topographic, hydrogeological, climate and land use. Based on literature review and availability of data, seven criteria including geology, lineament density, land use/land cover, soil, slope, and drainage density were selected for the GIS-MCDA. Weighted linear combination was used to combine the seven thematic maps to produce spatial priority monitoring index map. The priority monitoring index map provide a baseline information for prioritizing monitoring wells locations and provide an idea about the placement additional strategic monitoring well locations. A central concept in a geo-statistical approach is the semivariogram which describes the variance between the points in a spatial field as a function of their separation distance. The main structural parameters of the semivariogram; the sill, the correlation length (or range) and the nugget were determined by fitting empirical semivariogram model to measured water level data (Feb 20-24, 2020) using the stable semivariogram model. It is important to note that no distinction was made between the basalt and sandstone aquifers for the determination of the semvariogram parameters. The two systems are assumed to function as a single hydraulically connected system.

Results The correlation length (range) is a measure of the spatial continuity of the variable of interest and defines a distance beyond which the correlation between two measurements points is minimal, hence, critical parameter for monitoring network design. This analysis resulted in a correlation length of 19 km. Based on correlation length of 19 km and a hexagonal sampling strategy it was found that

58 optimal monitoring wells are required for the Tuli Karoo Aquifer. Among the 58 optimal monitoring well locations, four existing wells which are in close proximity to optimal well location or located at strategic locations were selected and installed with a real-time monitoring system. The real time monitoring systems were programmed to monitor water level, temperature and electrical conductivity at six hour interval and to transmit the data once in a day. UIT agreed to host the data for the project period hence data is transmitted to UIT server in Germany and visualized by online platform. Monitoring equipment is envisioned to be installed in additional sites. Ultimately, arrangements need to be made to migrate the system to the LIMCOM or SADC-GMI platform for continued use beyond the project life time.

Summing up and next steps Monitoring network design is an evolutionary process which needs to be evaluated and upgraded periodically. Since groundwater and surface water are part of the same hydrological system groundwater cannot be managed in isolation. Therefore, climate and surface water monitoring network must also be improved and sustained. Installation of additional real-time monitoring system and spatial and temporal analysis of measured real-time data (groundwater level, temperature and electrical conductivity) are the main next steps.

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1. Introduction

Groundwater levels are a principal source of information for the management of a basin or aquifer system. They reveal important information about changes in groundwater storage and movement in a basin, and how these are affected by climate variability and change, pumping, recharge and discharge processes. Monitoring of groundwater levels is important for various purposes (Alley, 2007; Kim et al., 1995) including: understanding trends in groundwater level, construction of potentiometric map, identification of groundwater flow direction, evaluation of the response to climate variability and change, calibration of groundwater flow models, analysis of seasonal variability, assessing the impact of groundwater pumping, estimating groundwater recharge, licencing of groundwater and understanding long-term sustainability of an aquifer. It also support drought response decisions and groundwater management activities such as water allocation planning, investigation of surface-groundwater interactions and to determine hydraulic characteristics of the groundwater system and degree of confinement. Water level measurements are also essential in the identification of recharge and discharge areas (UNESCO, 1998). Unlike surface water whereby an integrated response of surface water system can be monitored by a relatively small number of stream gauging stations due to geological heterogeneity, an aquifer system requires a distributed network of monitoring wells (Little et al., 2016).

As is the case in arid/semi-arid regions, surface water resources in Tuli Karoo System shared among Botswana, South Africa and Zimbabwe are generally scarce and unreliable and hence, groundwater is used to support agriculture, domestic and industrial water supply. Increasing water security in the face of increasing groundwater use, recurrent droughts, climate variability and change has increased the need for understanding and managing groundwater resource in the region. However, the existing groundwater level-monitoring network in the Tuli Karoo System is not adequate to enable proper groundwater resource assessment. Botswana and South Africa undertake some monitoring within the aquifer extent for their own purposes. However, there is no a single observation well in the Zimbabwe side of the aquifer which covers about 57% of the aquifer surface area. The monitoring in the two countries also lacks spatial coverage as monitoring stations are not uniformly distributed across the area. Lack of spatial and temporal information in groundwater levels makes it difficult to manage the groundwater resources sustainably in the transboundary aquifer. Furthermore, most groundwater levels are measured manually; monthly or less frequently and none of these wells[1] provides timely information to support groundwater managers to better plan and deal with potential adverse effects (e.g., over-exploitation, drought warnings).

1.1 Objectives

The main objective of this study is to design an integrated groundwater level-monitoring network for the transboundary Aquifer Area – part of the broader Tuli Karoo System – as a basis for deploying a near real-time monitoring system in selected observation wells. The monitoring network design objective is to establish a baseline groundwater level monitoring network and additional wells at strategic monitoring locations. The new monitoring network will be developed by combining an existing network with monitoring of additional wells to obtain better spatial coverage and distribution.

[1] The words “well” and “borehole” are used interchangeably throughout the report.

1.2 Scope of the study

Groundwater monitoring networks can be broadly divided into two aims: groundwater level monitoring and groundwater quality monitoring. This report focuses on groundwater level monitoring. It is clear that groundwater availability can be constrained by groundwater quality[2]. Furthermore, monitoring well instrumentations is based on existing monitoring wells and no drilling of observation borehole is attempted. Hence, the selection of monitoring well for real-time system instrumentation are constrained by the location, depth of the existing wells. Only four monitoring wells were selected to be equipped with telemetry system, as an initial pilot of the approach. The real time monitoring system collects groundwater level data, temperature and electrical conductivity and communicate these information at user defined time steps. EC is used as a partial proxy for water quality. For example it is widely used for monitoring the mixing of fresh water and saline water, separating stream hydrographs, and geophysical mapping of contaminated groundwater and as a proxy for chloride for recharge estimation using chloride mass balance (Hayashi, 2004). However, it is important to note that EC alone does not indicate all of the water quality risks associated with major forms of contamination, hence EC monitoring should not be viewed as a substitute for water quality sampling and testing.

1.3 Report organization

The rest of this report is organized as follows. First, we provide background of groundwater monitoring networks, which include approaches for the design of groundwater monitoring networks (Literature review). Second, we present a description of the study area. Third, we describe the hydro-census[3] conducted during this study and methods we used to design monitoring network for the Tuli Karoo Aquifer Area. Fourth, we present the results and discussion. Fifth, we summarize the challenges. Finally, we present the conclusion section.

2. Background

2.1 Types of groundwater monitoring networks

Groundwater monitoring network design is mainly divided into primary groundwater monitoring networks and secondary groundwater monitoring networks (Table 1). Primary monitoring networks – also known as reference, baseline or background networks – are large-scale monitoring networks, usually covering aquifers of large regional size (Jousma and Roelofsen, 2004; Zhou et al., 2013). Primary monitoring networks enable larger scale groundwater system assessment, hence monitoring wells are usually located at a relatively large distance but sufficiently close to provide an overall picture of the groundwater situation (Jousma and Roelofsen, 2004; Zhou et al., 2013).

Secondary groundwater monitoring networks, on the other hand, serve specific purposes, such as monitoring water level decline around pumping well fields, monitoring effects of irrigation schemes, monitoring groundwater-surface water interactions, etc. These networks are usually local networks.

[2] Monitoring of groundwater quality helps to: identify groundwater contaminants and contaminants levels, to identify trend in groundwater quality, and to assess the major factors that affect changes in groundwater quality and yield.

[3] Hydro-census is a broad term that entails gathering of data on water use, water quality and quantity. In this report the term hydro-census is manly used to represent assessing the suability and conditions of existing monitoring boreholes.

Their configuration depends on the issues to be investigated and the aquifer condition. Primary and secondary networks are often combined where primary networks designed to obtain large scale groundwater response under natural conditions is supplemented with denser spaced secondary groundwater monitoring network in areas of particular interest (Jousma and Roelofsen, 2004).

Table 1: groundwater level monitoring objective and network types (Jousma and Roelofsen, 2004)

Purpose	Type of monitoring network	
	Primary monitoring network	**Secondary monitoring network**
Investigation of aquifer characteristics and parameters	X	
Characterization of groundwater system	X	
Quantifying effects of groundwater abstraction	X	X
Quantifying effect of surface water management	X	
Quantifying effects of groundwater management measures	X	
Monitoring transboundary effects	X	
Protection of nature conservation areas	X	X

2.2 Strategic locations for groundwater monitoring

Ideally, monitoring networks should be designed to provide data representative of the various topographic, geologic, climatic and land use environments. Monitoring network should be completed in multilayer aquifer system to enable monitoring groundwater in different geologic units (Alley, 2007) and must cover the areal extent of major aquifers. Since it is not practical to monitor groundwater in all areas within all water bearing formations to the same level of detail, it is necessary that the priority aquifers of interest need to be identified. These include areas which have the greatest probability of groundwater level decline, potential for future water supply use (potential yield), and aquifer susceptibility to groundwater pumping or contamination (USGS, 2011).

Although using existing wells for monitoring purposes automatically places emphasis on areas and aquifers with the current groundwater development and use, monitoring well locations should be selected to address data gaps in spatial coverage and to protect potential future water supply areas. Hence, priority areas should be determined not only based on existing water supply potential but also based on future use and general aquifer vulnerability. The size of the area requiring monitoring determines the degree of detail to which the areas can be monitored. As the area becomes larger, greater emphasis need to be made for priority areas/hotspot regions.

Wells for such purposes are needed in relatively undeveloped recharge areas where water level fluctuations primarily reflect climatic variations rather than groundwater withdrawals or human-induced recharge (Alley, 2007). Equally important is the need to collect other types of hydrologic information. For example, meteorological data, such as precipitation data, aid in the interpretation of water level, and possibly water quality data (Alley, 2007). In order to monitor effectively, it is essential to understand the groundwater flow system and location of the recharge and discharge areas. Monitoring wells should be located in the optimal areas in order to provide this required information.

2.3 Groundwater level monitoring frequency

Determining sampling frequency is one of the critical steps in the design of groundwater monitoring network, because it affects the operation cost and data handling. The monitoring frequency should be determined based on monitoring objective, anticipated data variability and the amount of detail needed to fully characterise the hydrological behaviour of the aquifer (Alley, 2007). Shallow unconfined aquifers respond differently to climatic variability than deep confined aquifer, hence require more frequent monitoring.

As shown in Figure 1 unconfined aquifers, aquifers with rapid groundwater flow and recharge, aquifers with greater withdrawal and aquifers located in more variable climatic regions require more frequent groundwater level measurement. On the other hand, deep confined aquafers, aquifers with slow change in groundwater flow and recharge rate, and aquifer with less variable climatic conditions require less frequent groundwater level measurements. The frequency of water level measurement is also critical for understanding groundwater-surface water- interactions. For example, for quantifying flux exchange between surface water and groundwater during storm events temporal resolution of hourly or higher is required (Ebrahim et al., 2013). In addition to frequency of monitoring the length of measurement or period of measurement is important to obtain information relevant for trend analysis, to assess impact of climate change on groundwater and information relevant for assessing annual changes in levels and direction of flows, and ensure proper quantification of groundwater quantity (e.g. model calibration and validation).

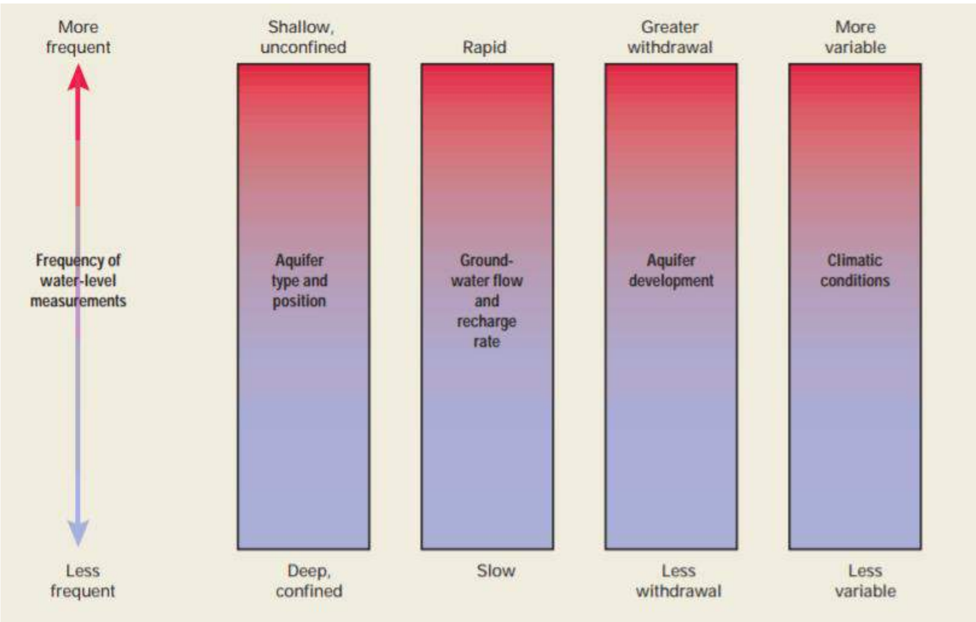

Figure 1: Factors that influence the choice of frequency of Monitoring (Source: Taylor and Alley (2002))

Table 2: Frequency of monitoring as a function of the intended use of the data (Source: Taylor and Alley (2002)

Intended use of groundwater level data	**Frequency of motioning**			
	Days/weeks	**Months**	**Year**	**Decades**
To determined aquifer properties (aquifer tests)	✓	✓ (red)		
Mapping groundwater level or potentiometric surface	✓	✓ (red)		
Monitoring short-term change in groundwater recharge or storage	✓	✓	✓ (red)	
Monitoring long-term change in groundwater recharge or storage			✓	✓
Monitoring the effect of climate variability			✓	✓
Monitoring regional effect of groundwater development			✓	✓
Statistical analysis of groundwater level trends			✓	✓
Monitoring change in groundwater flow directions	✓ (red)	✓	✓	✓
Monitoring groundwater –surface water interactions	✓	✓	✓	✓
Numerical modelling of groundwater flow and contaminant transport	✓ (red)	✓	✓	✓

Key
✓ =most applicable for intended use
✓ (red) = Sometimes applicable for intended use

2.4 Real time groundwater monitoring

In the face of increasing demand, recurrent drought and climate variability and change, timely information on groundwater is needed by water managers. Timely information on groundwater is important to assess groundwater conditions, to manage adverse situations such as drought and loss of pumpage in agriculture and domestic water supply (Prinos et al., 2002). In most cases water level measurement is carried out monthly or less frequently using dip meter. Even if wells are equipped with a data loggers, the data must be retrieved and processed before they are available. As a result, available water level data commonly lag behind current conditions by several months or more, limiting their use to show current conditions (Alley, 2007). For example, as pointed out by Prinos et al. (2002), although water managers often make groundwater withdrawals decision based on weekly or monthly data, sometimes decisions need to be made based on changes in water levels that occur over just a few days. Real-time monitoring networks can be established by using telemetry systems, sensing technologies, and web-based data visualization to provide real time groundwater information. The telemetry system sends data to a web-based system and can be programmed to send alerts to operators if water levels drop below a certain threshold.

Real-time groundwater monitoring has many inherent advantages over data collected and distributed by traditional means. These advantages can be grouped into four categories: timeliness, data quality, data availability, and cost (Cunningham, 2001). Real-time monitoring provides groundwater data which can be acted on and reported in a timely manner. Real-time data collection is particularly beneficial at sites where access is difficult due to landowner restrictions or the remote nature of the site (Prinos et al., 2002). It eliminates trips to remote sites to download groundwater data (data can be accessed without removing instruments from the wells). This results in significant labour and travel costs. In contrast to traditional data loggers, which are retrieved on a monthly (or longer) schedule, real-time data are reviewed daily, and equipment malfunctions are identified quickly, missing or poor quality data can be reduced substantially and allow the collection of a large amount of data (Cunningham, 2001). According to Cunningham (2001), real-time information promotes interest in groundwater data. Data from the real-time network is presented in graphs and maps that have been designed for easy access and interpretation while retaining the content necessary to support water management decisions (Prinos et al., 2002).

Some of the potential drawbacks of high tech approaches include: high initial cost (equipment and the is visualization software are expensive), require skilled person for configuring and installing the instrument, sensors must be calibrated carefully otherwise they could be taking the wrong readings, high maintenance costs (if the system is malfunction data could be lost) do not work where there is no network coverage and some can take readings only during time intervals configured at the start and hence hydraulic responses to short-term stress occurring between measurements may be missed.

2.5 Groundwater monitoring network design approaches

There are two main approaches for the design of groundwater monitoring networks. These are: 1) hydrogeological approach, and 2) Geo-statistical approach. When the monitoring network design starts from scratch, without or with only scant historical groundwater monitoring data, the hydrogeological approach will be the only basis of the design procedure. On the other hand, when a network starts with the availability of sufficient historical monitoring data and the target parameters can be sufficiently quantified, the design can be considered as an optimisation problem and may be fully supported by statistical considerations (Uil et al., 1999). Combined hydrogeological and geo-statistical approach is preferred when data is available (Bhat et al., 2015).

2.5.1 Hydrogeological approach

A hydrogeological approach of groundwater monitoring network design involves the design of groundwater monitoring network based on conceptual understanding of hydrogeological systems. It uses both qualitative and quantitative hydrogeological information for monitoring network design. According to Loaiciga et al. (1992), the number and location of wells are strictly determined by the hydrogeological conditions based on expert judgement. Hydrogeological factors related to geologic formations and their water-bearing properties and factors controlling groundwater movement must be known in some detail to properly design groundwater monitoring networks (Aller, 1991). The approach relies heavily on descriptive information about the aquifer of interest, and often does not fully utilise the available quantitative hydrogeological information. The advantage of this approach is that the physical information of hydrogeological systems is fully taken into account and the important sampling sites will not be missed. The disadvantage is that there is no quantitative criterion to determine how many observation wells are required.

According to Loaiciga (1988), background information required for monitoring network design using the hydrogeological approach include: 1) hydrogeological data (lithology and stratigraphy), 2) groundwater flow patterns and volumes, 3) recharge areas and rates, 4) aquifer characteristics (e.g. hydraulic conductivity, dispersion coefficients), 5) existing monitoring wells and their locations. The design of groundwater monitoring network is a function of geology and hydrogeology of the aquifer system and the budgetary constraints prior to undertaking the network design one must have a predetermined set of number of locations at which new wells could be installed and the grid layout containing the sampling points and such layouts (i.e., shape and distance between sampling points) much be known (Loaiciga, 1988).

The design of groundwater monitoring network should target important aquifers. According to SOGW (2013), important aquifers are: 1) those which support withdrawal of regionally significant quantities of water, or support critical ecosystems, 2) those which cross national boundaries, and 3) the aquifers that contributes significant flow to, or receives flow from, surface-water bodies of regional or national importance. The required depth of a monitoring well is determined by the depth to one or more water-bearing formations that need to be monitored (Aller, 1991). A sufficient number of monitoring wells screened at the proper depths must be installed to ensure that the ground-water monitoring system provides useful information about groundwater conditions (water level or contaminant migration pathways). Table 3 presents factors influencing monitoring well spacing.

Table 3: Factors influencing the intervals between individual monitoring wells within potential migration pathways (US Environmental Protection Agency, 1986)

Monitoring well spacing can be closely if the site	**Monitoring well spacing can be wider if the site**
Is very small	
Has complicated geology	Has simple geology
- closer spaced fractures	-no fractures
- faults	-no faults
- tight folds	-no folds
- solution channels	-no solution channels
- discontinuous structures	-continuous structures
Has heterogeneous conditions	Has homogenous conditions
- variable hydraulic conductivity	-uniform hydraulic conductivity
- variable lithology	-uniform lithology
Is located in or near a recharge zone	
Has a steep or variable hydraulic gradient	Has a low (flat) and constant hydraulic gradient
Is characterized by low dispersivity potential	Is characterized by high dispersivity potential
Has a high seepage velocity	Has a low seepage velocity

2.5.2 Geo-statistical approach

The geo-statistical approach of design of monitoring network is based on geo-statistical analysis that investigates the amount of spatial variability in groundwater level. A central concept in geo-statistics is the variogram which describes the rate of change of groundwater level with respect to distance (Sophocleous, 1983). The geo-statistical approach involves the following three steps: 1) determination of semivariogram[4], 2) determining semvariogram model parameters, and 3) spatial interpolation. . The experimental semivariogram is calculated using Equation 1 (ASCE, 1990b). The goal of semivariogram modeling is to determine the best fit for a model that will pass through the points in the semivariogram (Figure 2).

$$\gamma^*(|h|) = \frac{1}{2N(|h|)} \sum_{i=1}^{N(|h|)} [z(x_i + h') - z(x_i)]^2 \qquad (1)$$

4 Semivariogram is a measure of spatial variability as a function of distance and calculated as half mean squared difference of values separated by a given distance vector.

Where $z(x_i)$= measurements value at point x_i; $z(x_i + h')$= measurement value at point $x_i + h'$; $|h|$ = average distance between pairs of data points belonging to a distance class; and $N(|h|)$= number of pairs of data point belonging to distance represented by h. Afterwards, one can fit a semivariogram model the measured value of $\gamma^*(|h|)$.

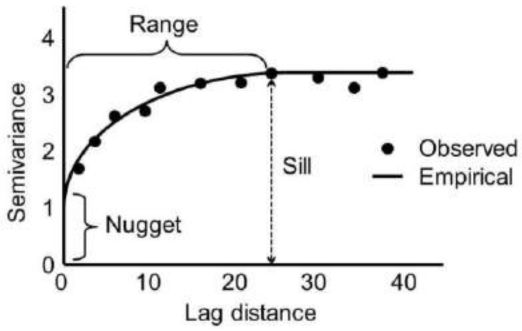

Figure 2: Sample Variogram fitted to observed data (Source: Biswas and Si (2013))

3. Description of the Study Area

The location of the Tuli Karoo Aquifer Area is shown in Figure 3. The Transboundary Aquifer Area covers about 12,293 km^2. The maximum length of the aquifer is 250 km from east to west and the maximum width is 92 km from north to south. About 57 % of the surface area is in Zimbabwe, 31% in Botswana and 12% in South Africa. Three sub-basins (Motloutse, Shashe, Mzingwani and Bubi) and two quaternary catchments (A63E and A71L) intersect the transboundary aquifer area. About 37 and 21% of the Transboundary Aquifer area is found in the Shashe and Mzingwani sub-basins, respectively.

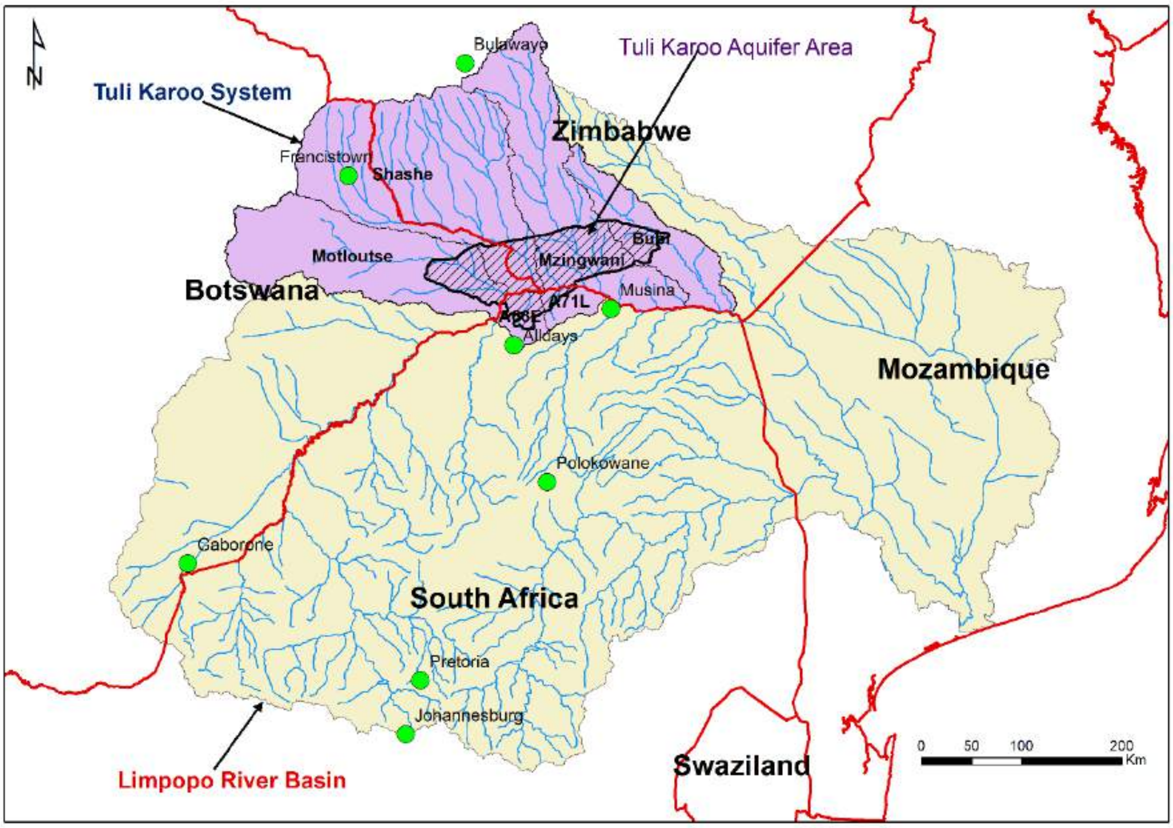

Figure 3: Tuli Karoo Transboundary Aquifer Area, sub-basins and quaternary catchments

3.1 Geology of the Tuli Karoo Aquifer Area

Geology of the Tuli Karoo Aquifer Area Tuli Karoo Aquifer is covered by five geology types (Figure 4). Most of the area is covered by Extrusive volcanics (basalt) followed by non –carbonate rocks. The Extrusive Volcanic rocks covers about 68% of the area, Non-Carbonate, 18%, Metasedimentary, 7%, Metaigneous 4%, and Alluvium – Fluvial 2%.

Dykes and faults in Tuli Karoo Aquifer Area the dyke and faults features were extracted from dykes and faults of the SADC region obtained from SADC-GMI. The aquifer is traversed by numerous dyke and faults (Figure 4). The length of dykes and faults in the Tuli Karoo aquifer area range from 18 to 115 km and 3 to 123 km respectively. The main feature is the Gobojango fault that acts as the northern boundary of the aquifer area. Dyke intrusion often cause secondary fractures to be formed along the contact plane and this area have been targeted for groundwater development all over South Africa (Du Toit, 2001). It is important to note that due to its regional nature, the SADC dyke and faults maps only represent large dyke and faults which may have regional significance. However, it is possible that the aquifer is traversed by small dykes and faults.

The pumping test carried out in the vicinity of known dolerite dykes in the cave sandstone aquifer, Morpulae, Botswana showed that the transmissivity of dolerite dykes is at least hundred times smaller than the transmissivity of the cave sandstone aquifer (Morel and Wikramaratna, 1982). In similar study in Botswana, it was reported that dolerite dykes less than 10 m thickness are tend to be permeable due to cooling joints and fractures that generate hydraulic continuity across the intrusion whereas, thicker dolerite dykes serve as groundwater barrier (Bromley et al., 1994).

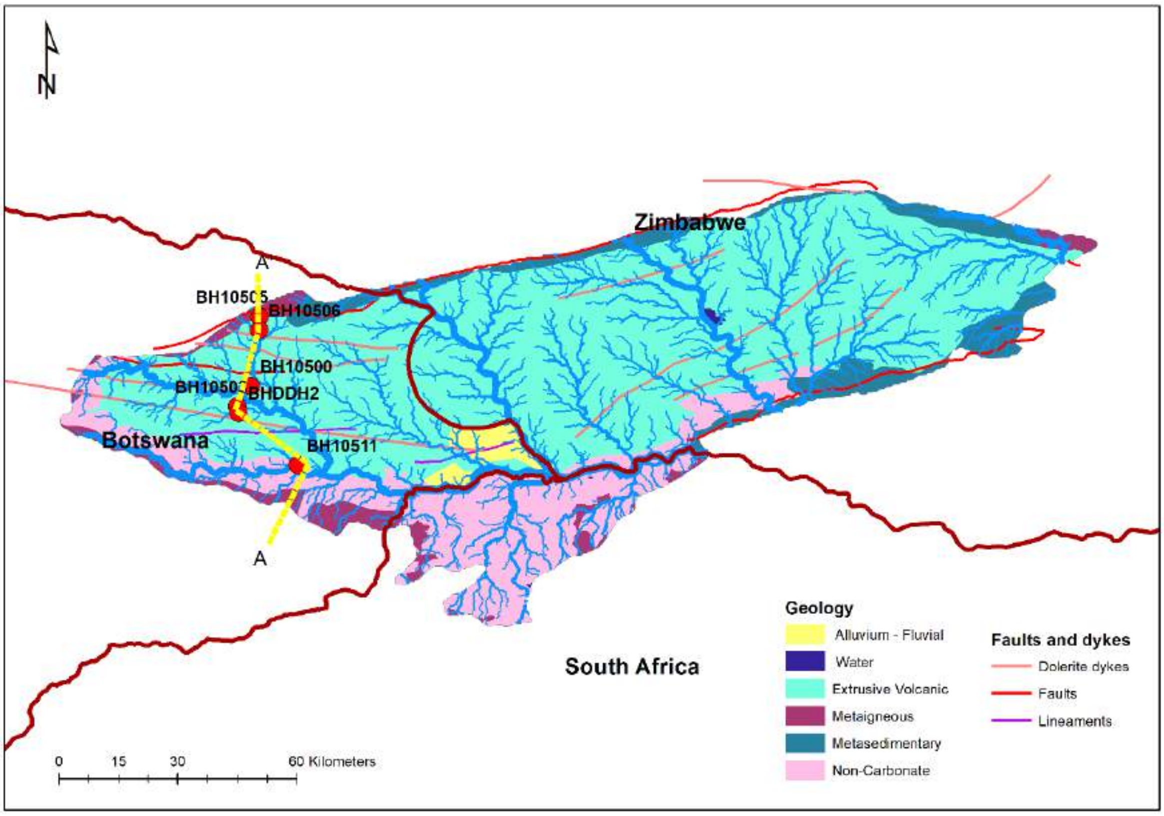

Figure 4: Geology of the Tuli Karoo Aquifer

Geological Cross Section of the Tuli Karoo Aquifer Area A cross section of the Tuli Karoo Aquifer Area is shown in Figure 5. As shown the extensive basalt layer is overlying the sand stone aquifer (tsheung formation), which is a more productive aquifer. The general shape of the x-section is V-shaped with basaltic layer thickness increasing from the edge to the centre. The basaltic layer is thick at the centre and extensive but it is less productive compared to the sand stone aquifer.

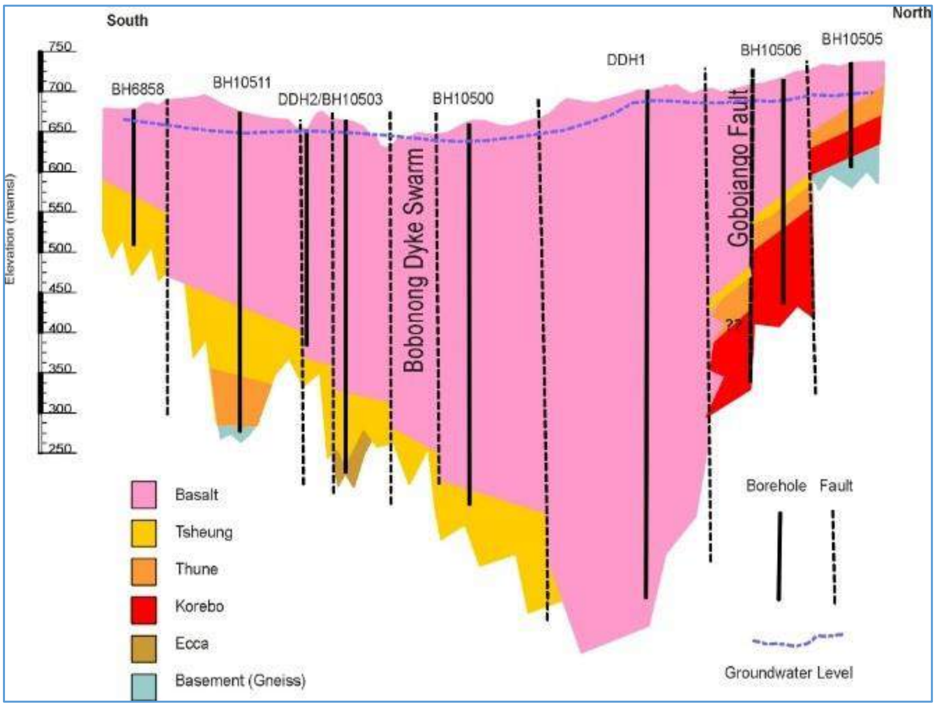

Figure 5: Geologic cross-section of Tuli Karoo Aquifer Area (A-A') shown in yellow broken line in Figure 4 (Source: Water Surveys Botswana (2007)). Below the Basalt is the Tsheung sand stone formation.

3.2 Hydrogeology of the Tuli Karoo Aquifer

Aquifer Type The three most important source of groundwater in the Tuli Karoo Aquifer are: 1) the sand stone aquifer, 2) the basaltic aquifer and 3) alluvial aquifer. The sandstone aquifer serves as an important source of ground water in a Tuli Karoo Aquifer[5]. The Sandstone is the consolidated sand and differs from it primarily by the presence of cementing material deposited between the grains (Heath, 1984). Sandstone is most important as a source of ground water where the cementing material have been deposited only around the points of contact of the sand particles, resulting in the retention of appreciable intergranular porosity (Heath, 1984). Sandstone may be fractured along bedding planes and more or less perpendicular to the planes. The productive sand stone aquifer is overlain by Karoo basalt and underlain by low permeability mudstone and fine-grained formation. The aquifer may be confined and semi-confined in some parts of the basin. The Karoo Igneous Aquifers/ Basaltic Aquifer is among the productive aquifer which is very extensive covering about 68% of the aquifer area with low to middle yields. Water-bearing openings in the basalt flows include lava tubes, shrinkage cracks, joints, and a fragmented and broken (brecciated) zone at the top of the flows (Heath, 1984).

[5] Most productive boreholes are located in the sandstone aquifer or at the interface of basaltic and sand stone aquifers. There are boreholes greater than 400 m deep.

Alluvial aquifers are among the most productive aquifers or high yielding aquifers. However, the alluvial aquifers are located along the main river challenges covers relatively the small proportion of the aquifer area (1.8%). Alluvial aquifers are the sources of most of the water pumped from wells in many region (Aller, 1991). Permeable sands and gravels are capable of yielding moderate to large water supplies to wells. The importance of sand and gravel as a source of ground water is a result of their capacity to yield water to wells at large rates.

Recharge Recharge occurs through the infiltration of precipitation and focused recharge. Recharge occurs around the edges of the aquifer through the sandstone or near the basement-basalt contact. Recharge also occurs within exposed and weathered/fracture basalt outcrops. However, it is isolated and does not interact with the main groundwater flow existing as perched aquifers. Once it enters the aquifer area it flows towards the center, and the groundwater flows in the south-eastward direction to discharge along the edge of the aquifer area. The discharge is in the form of artesian flows in the basalt and Tsheung, which is ultimately lost to evapotranspiration in sites such as Lentswelemoriti in Botswana (Water Surveys Botswana, 2007). Along the sandy river channels, focused recharge to the alluvial aquifer also occurs during flows. Generally, these alluvial aquifers extend to the flood plain and in some areas the deep boreholes (>100 m) drilled along the river banks connect the alluvial (top or shallow) and sandstone (bottom or deep) aquifers.

Groundwater flow direction A map was generated using static groundwater level data from differing time periods. The Inverse Distance Weighted (IDW) interpolation technique was used to interpolate groundwater level in the aquifer area. IDW uses the measured values surrounding the prediction location to predict a value for any unmeasured location. It gives greater weights to points closest to the prediction location, and the weights diminish as a function of distance. Inverse Squared Distance (power =2) is a widely used interpolator and the default IDW interpolator in ARCGIS. The output surface is sensitive to clustering and the presence of outliers. Static water level data from 82 boreholes were used for the interpolation (Figure 6). Except small local scale variation, the groundwater flow direction follows the topographic gradient.

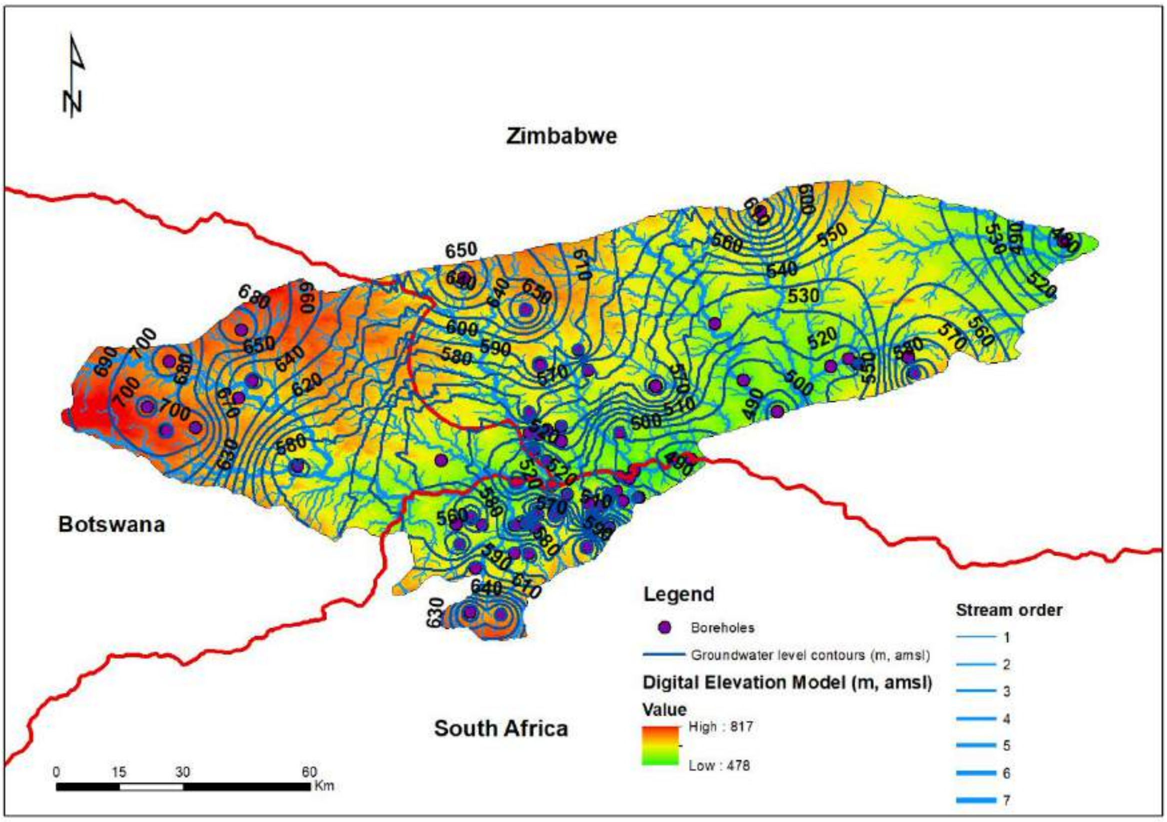

Figure 6: Groundwater contour map of the Tuli Karoo Aquifer overlaid with digital elevation and stream order maps

3.3 Soil types in Tuli Karoo Aquifer Area

The soil type based on the Soil Atlas Africa soil Map classification is shown in Figure 7. As shown the major portion (about 68%) of the study area is coved with leptosols, and about 19% of the area is covered with Luvisol. Lepotosls are shallow soils over hard rock while the Luvisols have a distinct increase in clay content with depths as a result of clay movement from the upper part of the soil to the lower part(Jones et al., 2013). Description of each soil type is provided in Annex 1.

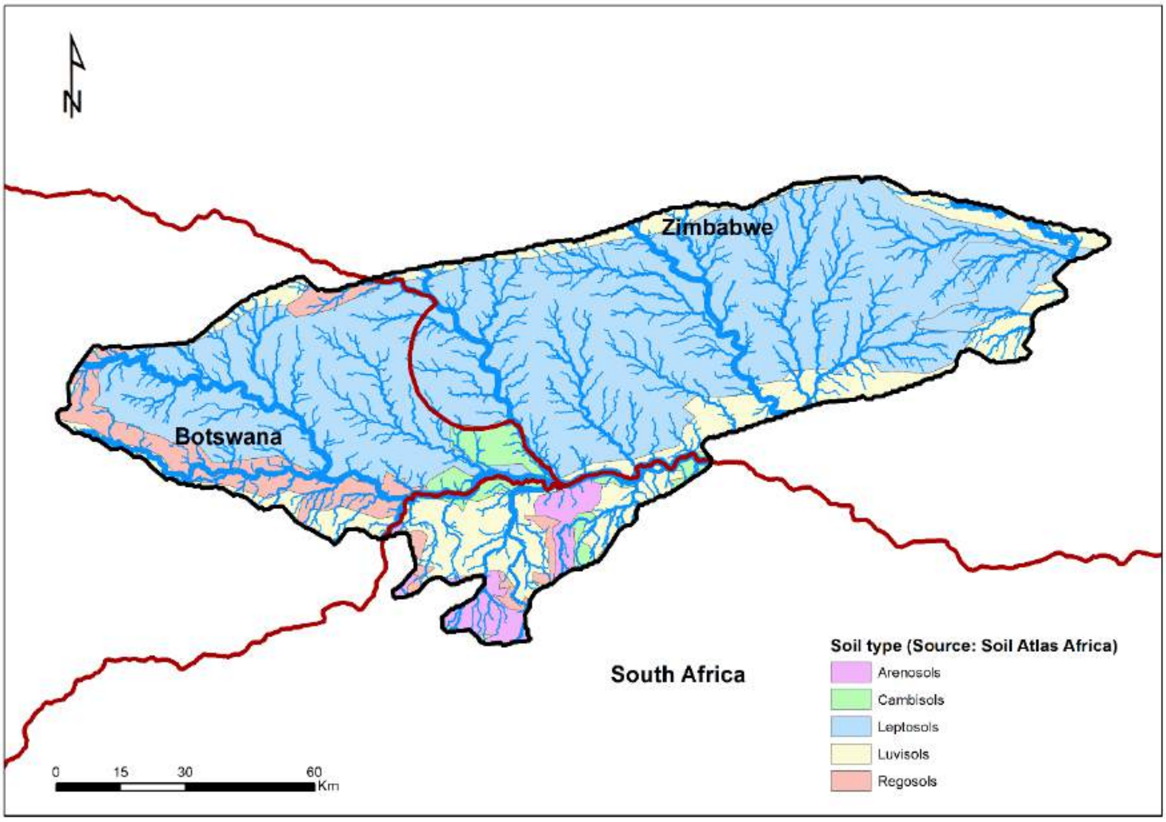

Figure 7: Soil types of Tuli Karoo Aquifer (Source: Soil Atlas Africa)

3.4 Existing monitoring network

Monitoring Borehole Distribution Borehole distribution in Tuli Karoo Aquifer Area is shown in Figure 8. The number of observation and production boreholes per country is presented in Table 4. The number of monitoring boreholes in Botswana and South Africa are 25 and 21, respectively. Monitoring borehole density in South Africa is greater compared to Botswana (one observation well per 66 km^2 in South Africa while in Botswana it is one observation borehole per 143 km^2). There is no single monitoring borehole in the Zimbabwean side. Observation borehole depth in Botswana ranges from 125 to 469 m (Figure 9) and in South Africa the observation borehole depth is ranging from 16 to 150 m (Figure 10).The existing monitoring boreholes in Botswana and South Africa are concentrated in some areas and are not well spatially distributed (Figure 8). It is also important to note that few of the observation boreholes in South Africa are active[6]. And only three observation boreholes in South Africa and six observation boreholes in Botswana are drilled to the deep productive sandstone aquifer (Table 5 and Figure 12).

Pumping Borehole Distribution Followed by South Africa, Zimbabwe has the highest number and density of pumping boreholes (Figure 8). Production boreholes in Botswana and South Africa are not shown in Figure 8, because the production borehole density in South Africa is very high and will be too dense to enable viable display on the map. The depth of production boreholes in Zimbabwe ranges from 11 to 133 m (Figure 11). Only one out of the 66 production boreholes are penetrating to the deep productive sand stone aquifer (Table 5). Figure 12 shows the location of eleven boreholes (10 observation and one production boreholes) penetrating all the way to the deeper sandstone aquifer.

[6] Some of the monitoring boreholes in South Africa which used to have data logger are not active due to financial constraint (Personal communication).

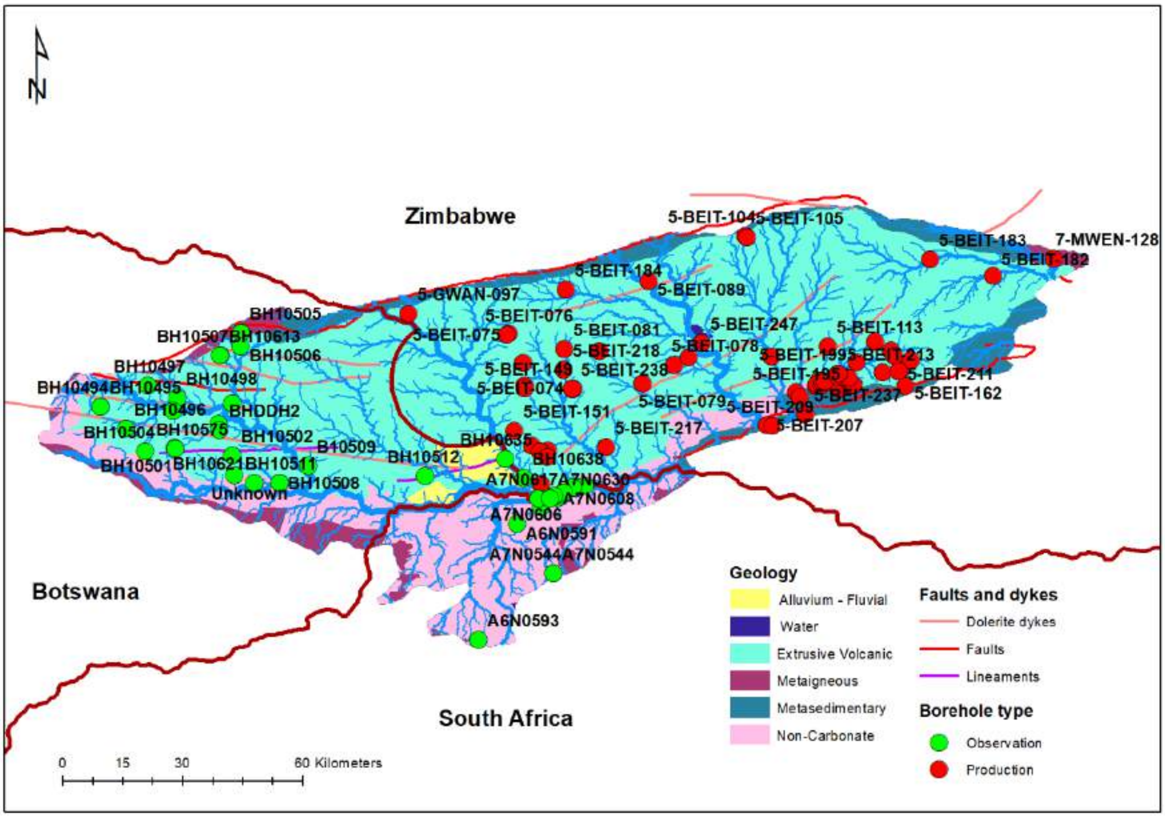

Figure 8: Existing monitoring network in Tuli Karoo Aquifer (Since there is no observation boreholes in Zimbabwean side, production boreholes are shown). Data source: Governments of Botswana, South Africa, Zimbabwe.

Table 4: Number of observation and production boreholes per country (Data source: countries). The number of production boreholes in the South Africa are from the National Groundwater Archive (NGA) and all NGA boreholes are assumed here as production.

Country	Area (km^2)	No of observation boreholes	Observation boreholes densities	No. of production boreholes	Production boreholes densities
Botswana	3828	25	0.007	21	0.005
South Africa	1433	21	0.015	1832	1.278
Zimbabwe	7032	0	0.000	118	0.017
Total	12293	46	0.004	1971	0.160

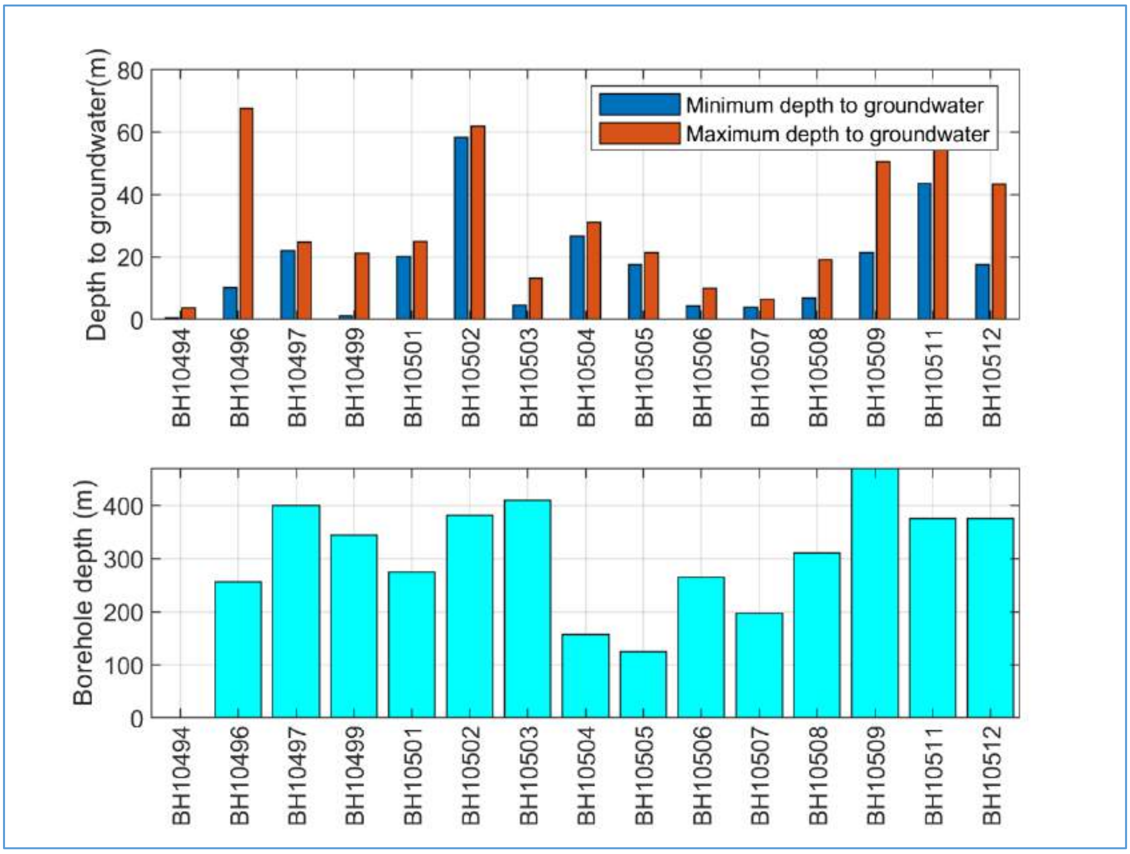

Figure 9: Borehole depth, minimum and maximum depth to groundwater in the Botswana portion of the Tuli Karoo Aquifer

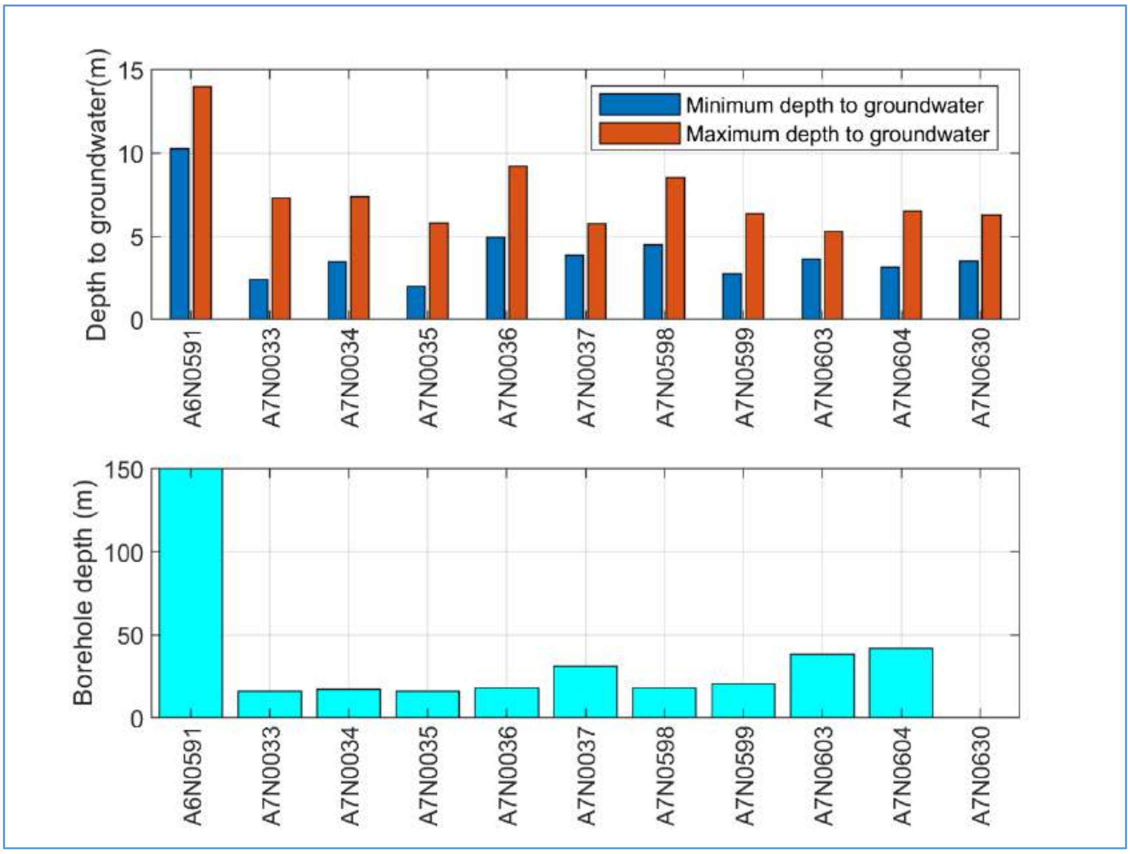

Figure 10: Borehole depth, minimum and maximum depth to groundwater in the South African portion of the Tuli Karoo Aquifer

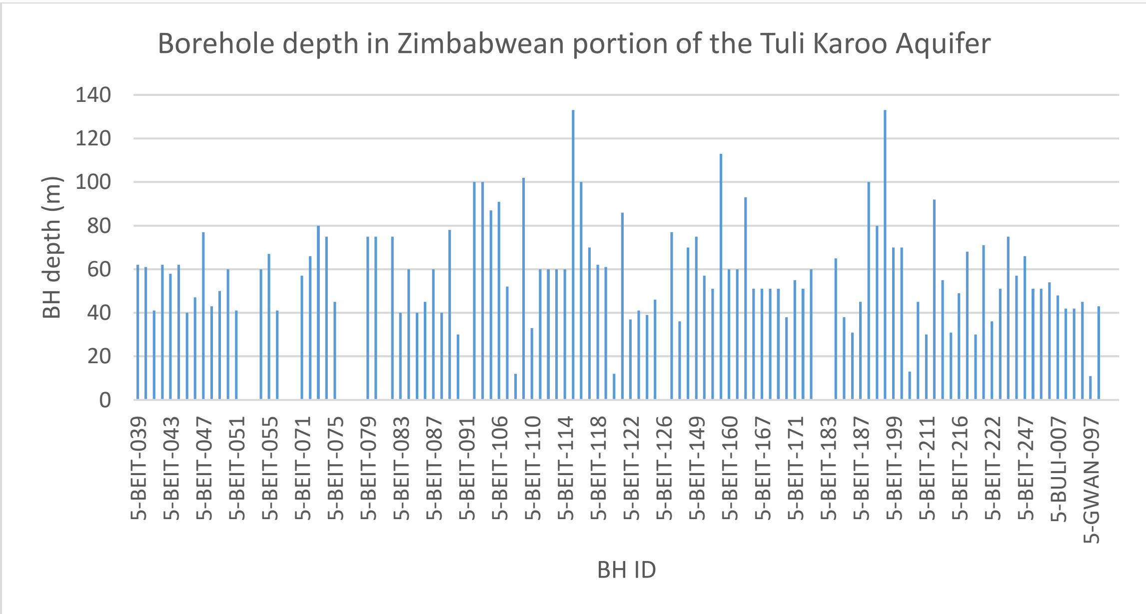

Figure 11: Borehole depth in Tuli Karoo Aquifer – Zimbabwean side

Table 5: observation boreholes in Botswana and South Africa and production boreholes in Zimbabwe tapping productive sandstone aquifer

BH Name	Country	Type	latitude	Longitude	Borehole depth
BH10495	Botswana	observation	-21.9921	28.3669	321
BH10496	Botswana	observation	-22.0412	28.42331	256
BH10501	Botswana	observation	-22.085	28.5336	274
BH10503	Botswana	observation	-22.030	28.631	409
10509	Botswana	observation	-22.1634	28.7683	469
10511	Botswana	observation	-22.085	28.5336	376
10512	Botswana	observation	-22.148	29.0952	375
A6N0591	South Africa	observation	-22.2558	29.30144	150
A7N0603	South Africa	observation	-22.1922	29.39028	38
A7N0604	South Africa	observation	-22.1836	29.40667	42
5-BEIT-109	Zimbabwe	Production	-21.9403	29.9748	102

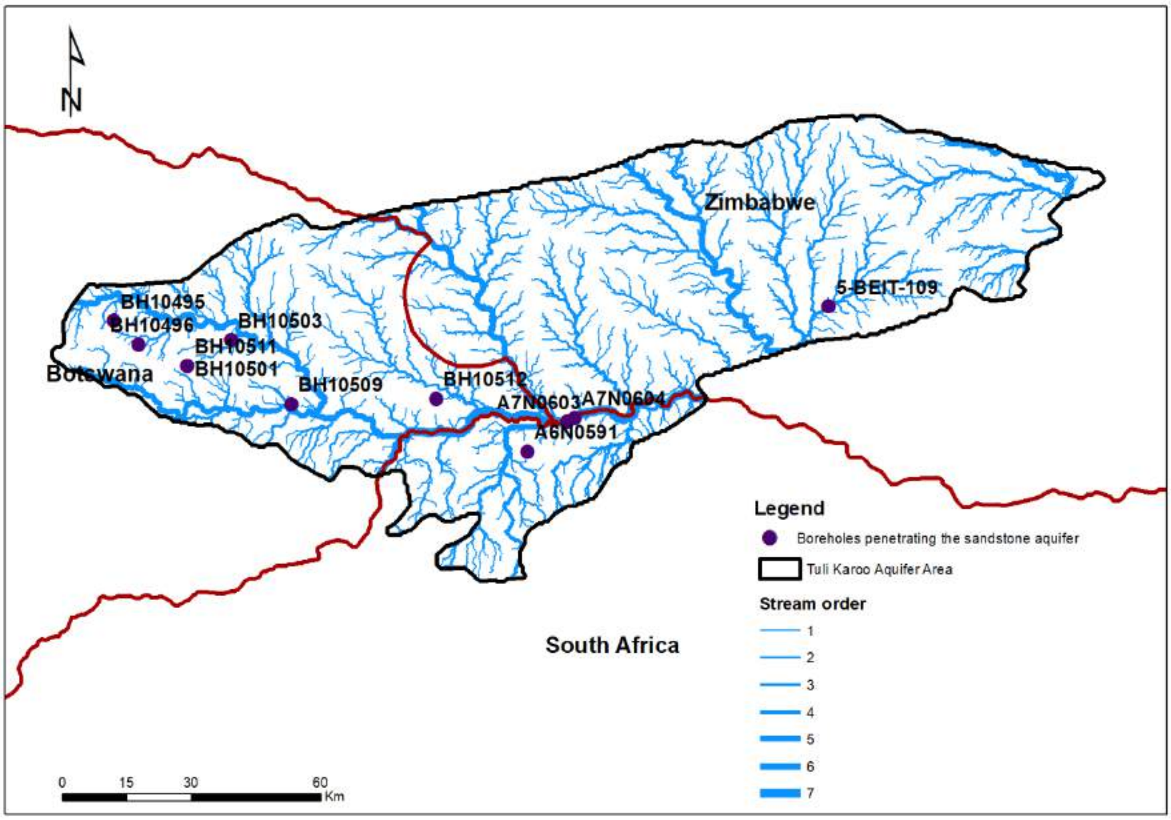

Figure 12: Boreholes penetrating the sandstone aquifer and stream order

4. Methods

This chapter describes the hydro-census conducted for this report, and optimal monitoring network design methods for the Tuli Karoo Transboundary Aquifer. The methods are described in six main parts. An overview of the hydro-census conducted in Botswana is first presented. The section next describes the Geographic Information System Multi-Criteria Decision Analysis (GIS-MCDA) used to map potential priority monitoring zones (i.e. hydrogeological approach). Geo-statistical approach used to develop semivariogram model to determine spatial variability in groundwater level are then described, followed by the combined hydrogeological and geo-statistical approach for design optimal monitoring network. Finally, the section describes the approaches for prioritizing real time monitoring well selection and present the description of the real-time monitoring system.

4.1 Hydro-census (field assessment of existing monitoring networks)

A hydro-census was carried out in the Botswana portion of the Tuli Karoo Aquifer 21-24 February, 2020. The purpose of the hydro-census is to assess the borehole condition of existing boreholes. It could be that some boreholes are damaged or have been blocked by stones. Hydro-census include registering geo-graphic coordinate, water level measurement, borehole elevation casing height above ground, borehole owner, land use in the vicinity of the borehole, sources of contamination or significant pumping in the vicinity (if any), and accessibility. During the four day hydro-census in Botswana 23 observation boreholes were visited. Details about the 23 observation boreholes and additional six unconnected production boreholes surveyed are presented in Annex 2. The results of the hydro-census guide the selection of observation boreholes for installation of near real-time monitoring system and monitoring boreholes to be excluded from monitoring network design due to damage.

It is important to note that borehole depth and water strike information were obtained from the drilling sheet through desktop study. Coordinates were recorded using handheld GPS and compared with coordinates provided in drilling sheet, depth to groundwater was measured using dip meter and casing height was measured using tape. Network strength was estimated using mobile phone signal (approximate).

4.2 GIS-MCDA for mapping priority monitoring for the Tuli Karoo Aquifer

GIS-MCDA is selected because of its ability to consider and integrate geological, hydrogeological, topographic and climatic information into a single analysis to guide the hydrogeological approach of monitoring network design by prioritizing potential groundwater monitoring zones. This approach has been used by many researchers for the design of groundwater monitoring network (Singh and Katpatal, 2017; Uddameri and Andruss, 2014; Zhou et al., 2013) and mapping of potential groundwater zones (Magesh et al., 2012). In the context of groundwater level monitoring network design GIS-MCDA can be used to identify priority monitoring index. GIS-MCDA has also been used for many other purposes such as to identify the most preferred option, to rank different options, or to distinguish feasible from non-feasible alternatives. One of the advantage of this approach is that it often allows the consideration of numerous design criteria (Woldt and Bogardi, 1992). The standard GIS-MCDA approach consists of four steps. These include: 1) selection of criteria, 2) standardization of criteria, 3) assigning relative weights for each criteria and 4) combination of criteria to produce the overall map.

4.2.1 Criteria selection and data sources

The selection of criteria were based on literature review. The selected criteria include surface, subsurface and catchment characteristics. Every selected criteria has to be measurable and non-redundant. Based on literature review and data availability we selected seven criteria for mapping priority zones using GIS-MCDA. These criteria include: slope, land use/land cover, soil, geology, rainfall, lineament density and drainage density. The data source and resolution of these criteria is presented in Table 6.

Uddameri and Andruss (2014) used six criteria for identifying priority areas for groundwater monitoring network in Texas, USA. These include: estimate of pumping, recharge potential at the monitoring location, proximity of the monitoring location to district boundaries, and proximity of the monitoring location to Perennial River, creeks or spring. The authors identified priority monitoring zones using GIS- MCDA but they did not optimized the location and number of monitoring wells. They determined predication standard deviation using kriging and entropy.

Zhou et al. (2013) used eight criteria for mapping potential priority zones for groundwater monitoring network design for Beijing plain, Chania. These include: 1) geomorphology, 2) geology, 3) depth to groundwater, 4) soil properties, 5) land use, 6) precipitation, 7) proximity to river, lakes and springs, and 8) proximity to reservoirs and well fields. The authors used geomorphology and geology to create hydrogeological zones map. Depth to groundwater and soil properties to construct unsaturated zones map. Land use and precipitation to create recharge zones map. And proximity to rivers, lakes and springs and proximity to reservoirs and well fields to create influencing zones maps. Using these four maps (i.e. hydrogeological zones, unsaturated zones, recharge zones and influencing zones maps) the authors developed groundwater regime zones. The groundwater regime zone map was used to design groundwater level monitoring network (by adding new wells where there is no monitoring but important to capture certain process like mountain recharge, groundwater surface water interaction and to monitor groundwater levels in regime zones of no observation wells). The authors did not apply GIS-MCDA. They coded each regime zones with the names of hydrogeological zone, unsaturated zones, recharge zone and influencing zone and created the groundwater regime zone map using a unique combinations of hydrogeological zones, unsaturated zones, recharge zones, and influencing zones.

Singh and Katpatal (2017) used 10 criteria to delineate priority monitoring zones in Wainganga Basin, India using GIS-MCDA. These include: command area and non-command area, geology, geomorphologic unit, land use/land cover, lineament density, groundwater level fluctuation, recharge, slope and soil media. Command area represent irrigated area from surface water and non-command area, represent area irrigated from groundwater. Magesh et al. (2012) used seven criteria for Delineation of groundwater potential zones in Theni district, India using GIS-MCDA. The seven criteria used by the authors include were lineament density, land use, lithology, drainage density, slope, rainfall and soil.

Table 6: Selected criteria and their data sources

Thematic layers	Source	Resolution
Slope	Derived from SRTM 3 ARC-Second Global	90 m
Soil	Soilgrid 250m ISRC-World Soil Information	250 m
Land use/Land cover	European Space Agency (ESA)	20 m
Geology	African Geological map from British Geological Survey	3 km
Rainfall	Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)	5.6 km
Lineament density	Southern African Development Community (SADC)	
Drainage density	Determined from SRTM 90 m	90 m

4.2.2 Description of selected criteria

Slope There is an inverse relationship between topographic slope and soil infiltrations. Steep slopes results more runoff, which will affect the amount of infiltration. Less infiltration will occur on slope and hills than on flat areas and depression where runoff is slow, accumulates in depressions, and has more time for infiltration to occur. That means in highly sloping areas, the run-off is more offering less retention time for runoff to infiltrate, reducing groundwater recharge potential significantly. In contrast, gentle slope will have high potential for groundwater recharge. The Tuli Karoo Aquifer Area is a relatively low lying area (Figure 13). About 83% of the area has slope in the range of 0-2%. About 11% of the area has slope in the range of 2-4% and only 6% of the area has slope greater than 4%.

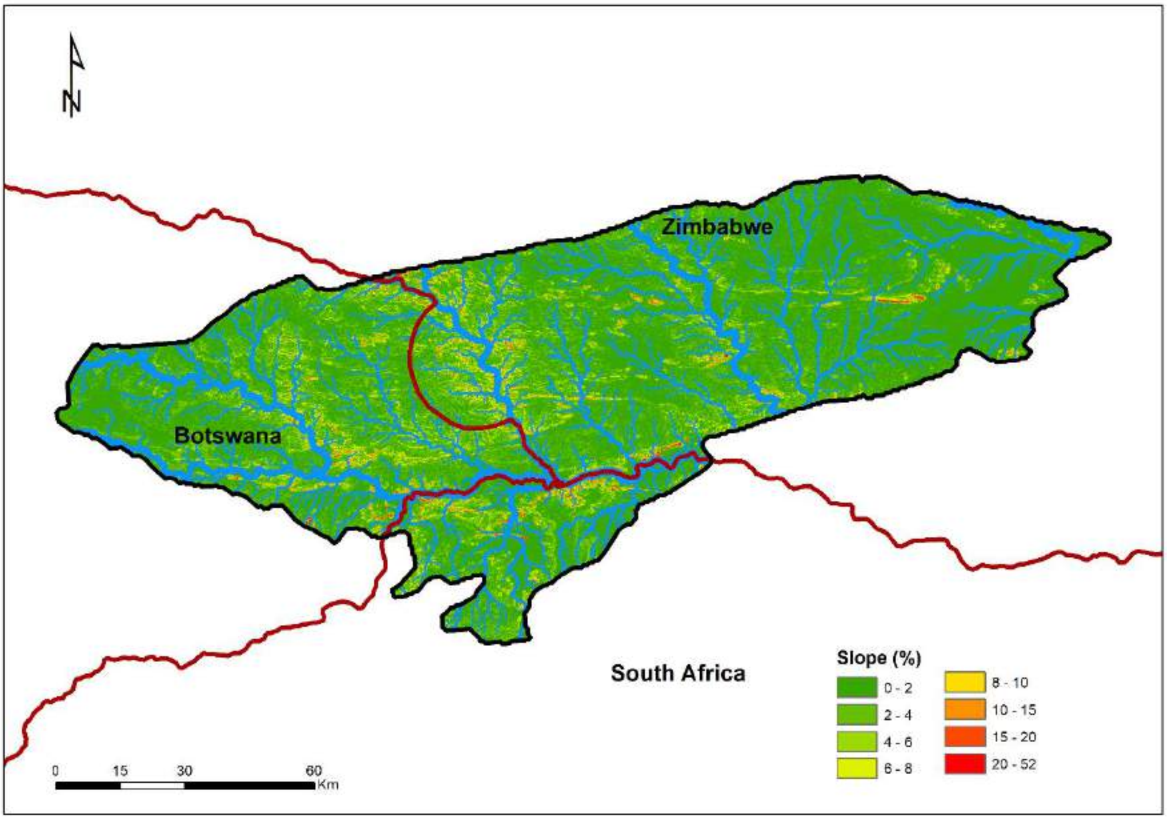

Figure 13: Slope

Land use/Land cover Vegetation has the potential to increase infiltration in three ways: by retarding runoff, by reducing rain drop compaction, and by increasing organic matter content, bulk density and surface horizon depth (Adams et al., 2004). Root systems of vegetation increase soil porosity and permeability while increase in organic matter increase pore size and pore size distribution. Built-up areas generally decrease infiltration rate and increase surface runoff as a result of increasing presence of various impervious surface. In groundwater potential zone mapping, Magesh et al. (2012) assigned low value for forest areas because even though these areas may have good groundwater recharge, the groundwater is not being extracted from this land. As shown, approximately 60% of the study area is covered by shrubs (Figure 14). About 26% of the study area is covered with grassland, 4% with crop land, 3% with trees and the rest 1% is covered with spares vegetation, bare areas, open water, built-up areas and regularly flooded areas.

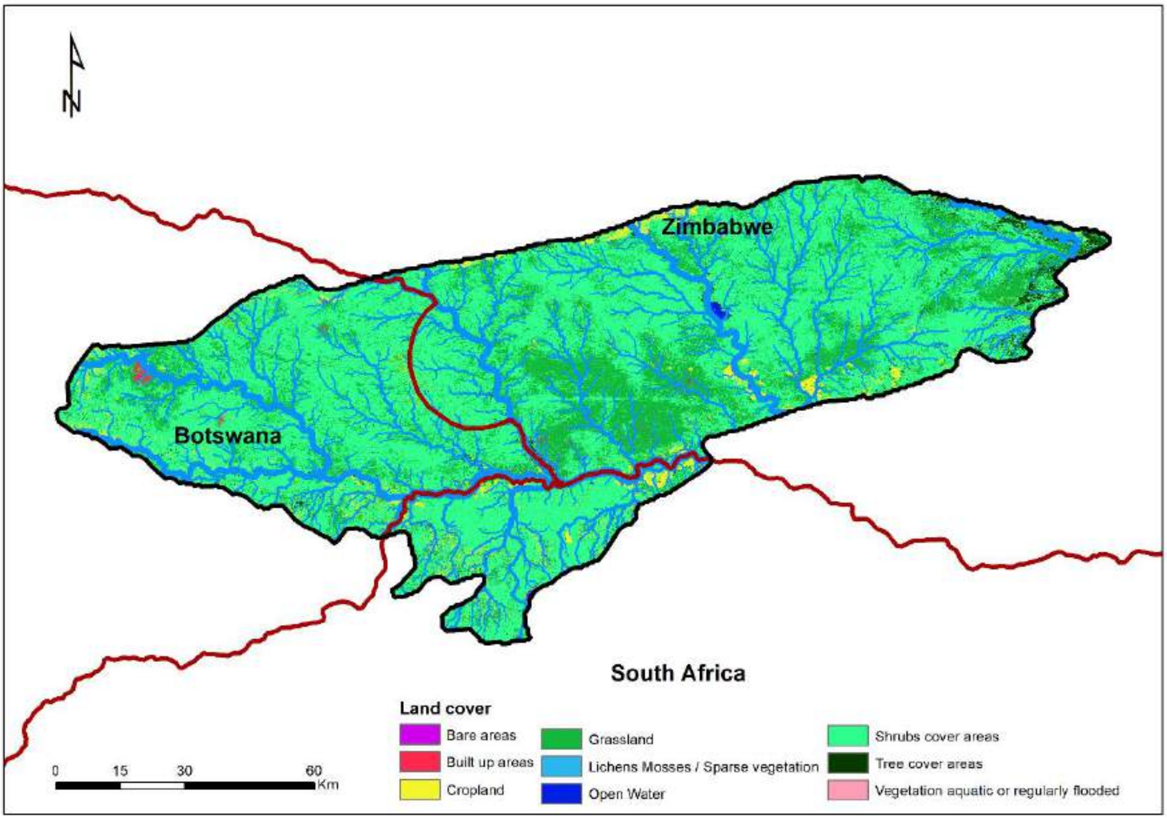

Figure 14: Land Cover

Geology Groundwater occurrence, storage, and movement is primarily controlled by geology. Hence, geological mapping serves as a basis for groundwater potential assessment. This is because different geologies have different potential for groundwater. For instance, the unconsolidated (loosely arranged) sand and gravel, alluvium have a large volume of interconnected pore space for water storage and good groundwater potential. Similarly, fractured bedrocks surface greatly increase infiltration rates, whereas layers of un-fractured bedrock has low infiltration and storage. About 68% of the study area is covered with igneous rock (basalt) and about 26 % is covered with consolidated sedimentary-inter- granular fracture (Figure 15). Below the basalt is the sandstone aquifer which is primary aquifer which can store and transmit significant volume of water. The alluvial deposits along the river are not visible in Figure 15 mainly because of the scale of the map. Furthermore, the basement and consolidated sedimentary flow are not visible due to small area (less than 0.01% combined area coverage).

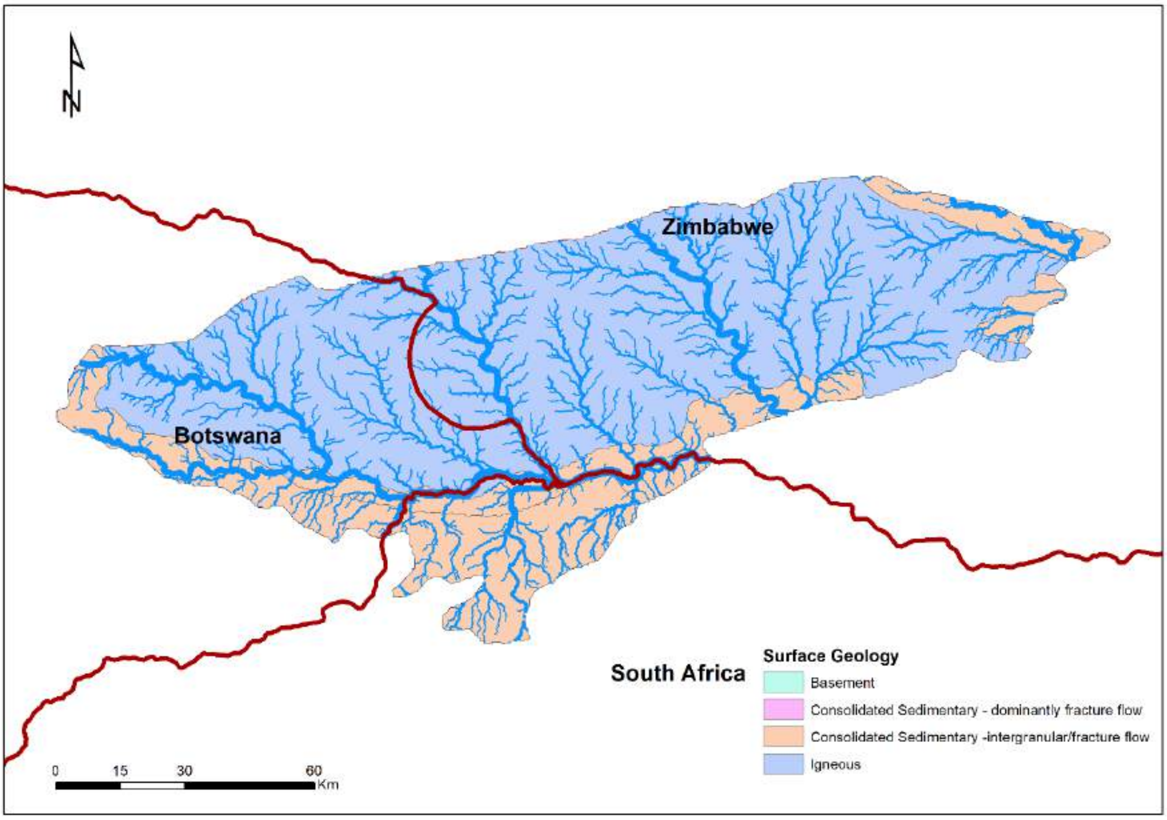

Figure 15: Surface Geology

Drainage Density This is calculated as the total length of all streams in a basin divided by the total drainage area. The higher the drainage density, the higher the run-off, and less infiltration, hence, not preferred as a potential groundwater zones. As demonstrated by Rajaveni et al. (2017), drainage density in this study is calculated using the Kernel density method in ARC GIS using stream feature. The drainage density map (Figure 16) is reclassified with areas having less density (0.05–0.25 km/km^2) designated with higher rank. It is also important to note that even if less drainage density is preferred as it has high potential in terms of decreasing surface runoff and promoting infiltration from rainfall, but it is possible that higher drainage density areas (e.g. alluvial streambed) may promote focused recharge from the riverbed.

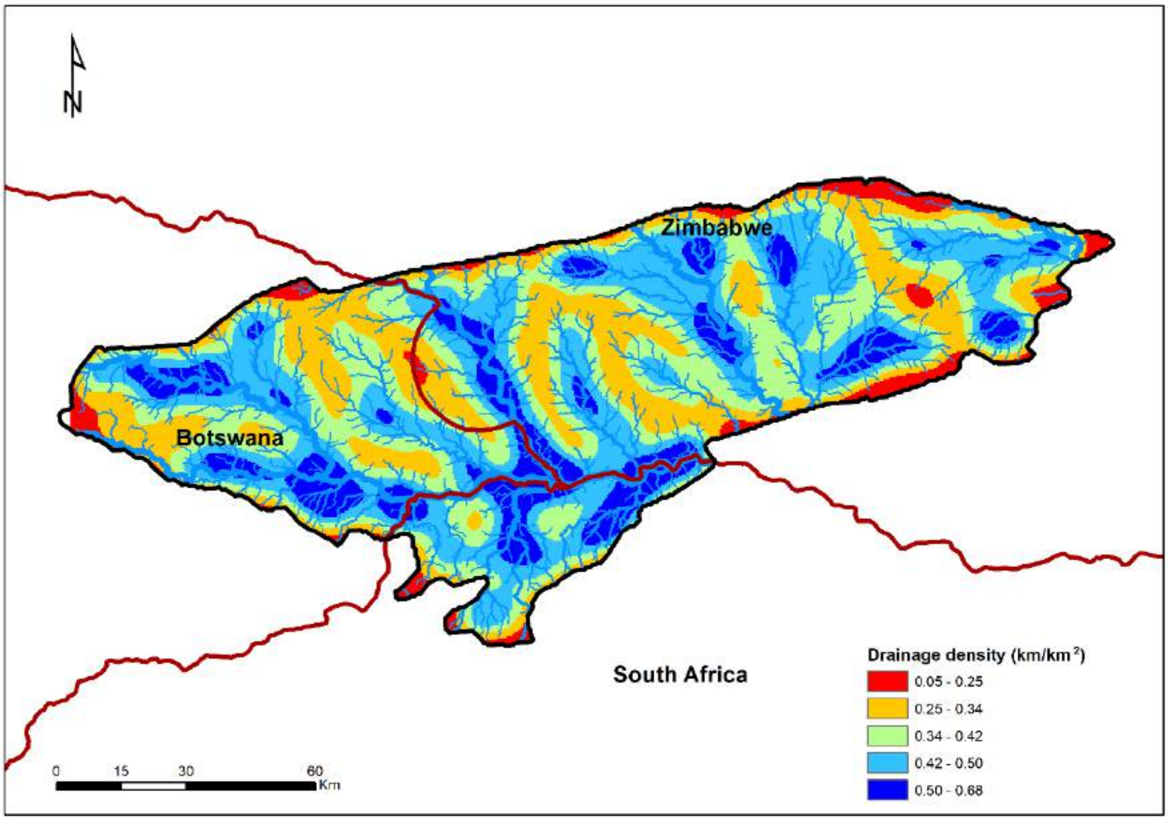

Figure 16: Drainage density distribution in Tuli Karoo Aquifer

Lineament density Lineament in the form of dykes and faults serve as the main conduits for movement or act as impermeable for groundwater flow. Dykes act as a water conduits or as barriers depending on their structure, location and orientation with respect to the groundwater flow (Gupta et al., 2012). Dyke intrusions, even a single big dyke normal to the groundwater flow direction, would significantly attenuate the flow of water. If attenuation is sufficient, the principal groundwater flow direction could change to a direction parallel to the alinement of dykes (Takasaki and Mink, 1985). If the dyke intrusions become sufficiently numerous and intersect, the dyke-intruded rock section could become a barrier to groundwater flow. Dykes act as potential aquifer when they are jointed/fractured. On the other hand, when they lack primary porosity and permeability and are not jointed/fracture, they act as groundwater barriers. In such a case, the upslope of the terrain function as a good repository while the downslope remains unproductive (Singh and Jamal, 2002). Dykes act as a good repository for groundwater potential where the strike of the dykes are consistent with the direction of the regional groundwater flow and where permeable aquifer is intruded by widely scattered dykes. The least favourable conditions occur as the number of dyke intrusions and intersections increases and their orientations are mixed (Takasaki and Mink, 1985).

Following Magesh et al.'s (2012) approach, lineament density map was prepared using line density method in ARC GIS (Figure 17). It has been reported in many studies that the variation of groundwater is influenced by higher lineament density and hence priority has to be given to higher lineament density and vice-versa.

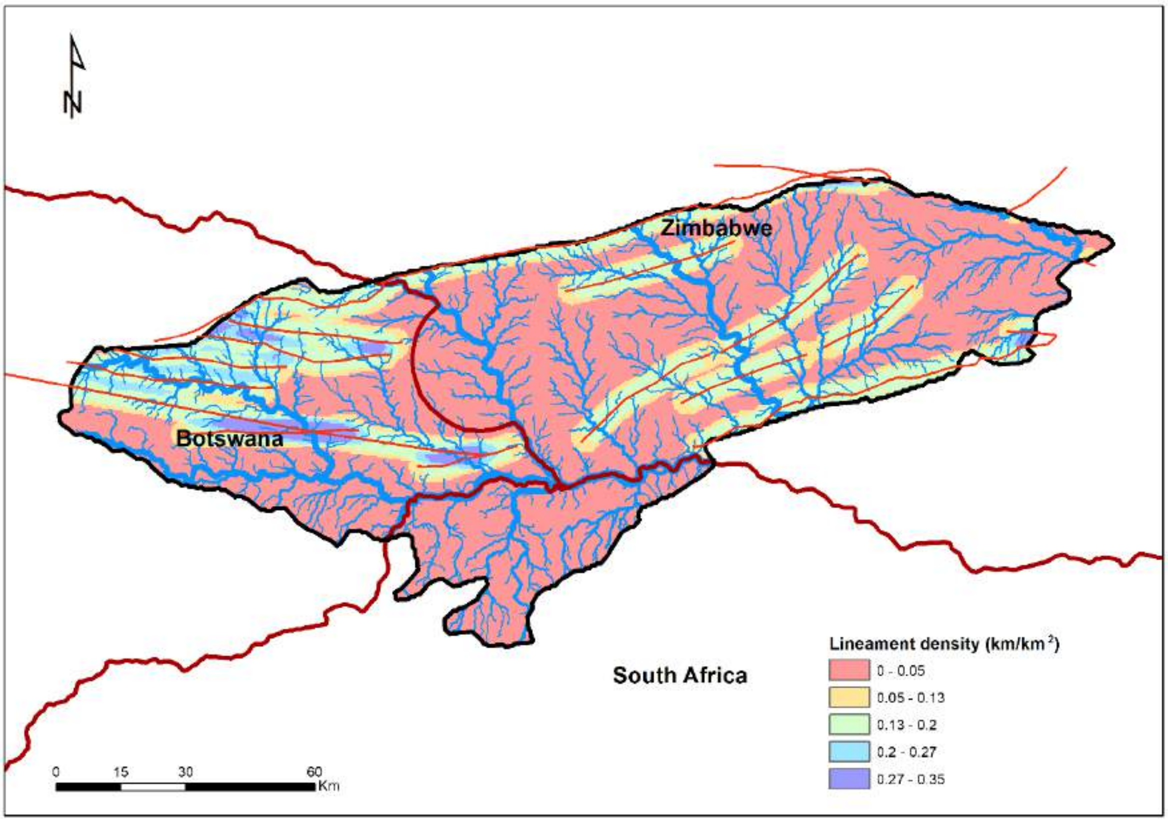

Figure 17: Lineament density map for the Tuli Karoo Aquifer (the red line represent lineaments)

Rainfall Spatial variability of rainfall exert significant control of recharge variability and groundwater potential in space and time. Rainfall distribution along with the slope gradient directly affect the infiltration rate and runoff and groundwater potential. The mean annual rainfall distribution of the Tuli Karoo Aquifer area is shown in Figure 18. Higher rainfall areas are preferred.

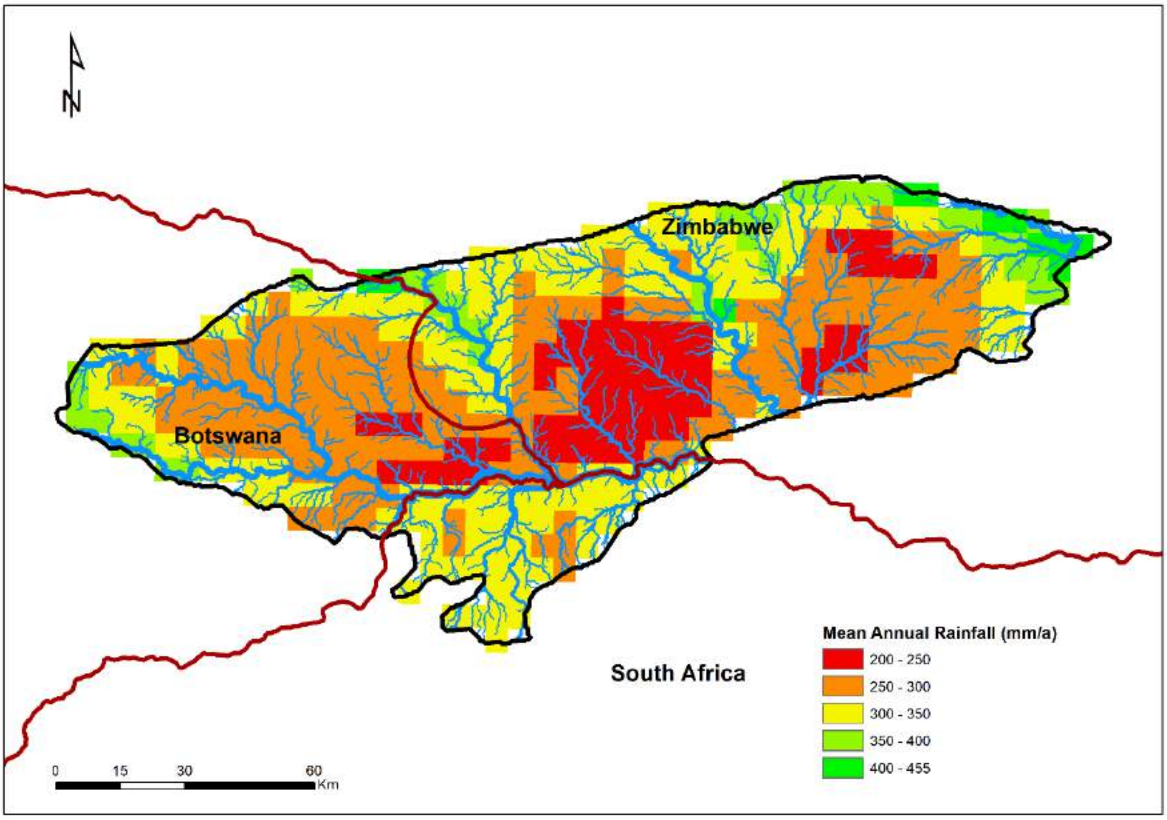

Figure 18: Rainfall distribution in Tuli Karoo Aquifer

Soil Soil properties are among the most significant factors affecting infiltration rate. In general, soil infiltration rate decreases with increasing clay content in the soil. Runoff conditions on low-permeable soils develop much sooner and more often than sands and gravels, which have infiltration rates higher than most rainfall intensities. The Soil type map (Figure 19) is extracted from global soil texture class map obtained from ISRIC-World Soil Information (https://www.soilgrids.org) is preferred for the present study for potential monitoring zone mapping over the soil map derived from Soil Atlas Africa. The ISRIC-World Soil Information soil classification utilizes United State Department of Agriculture (USDA) soil texture triangle and divided soils based on their relative amounts of clay, silt and sand into 12 soil types (Hengl et al., 2017). In general, sandy soils have the highest infiltration capacity, while clay soil have the lowest.

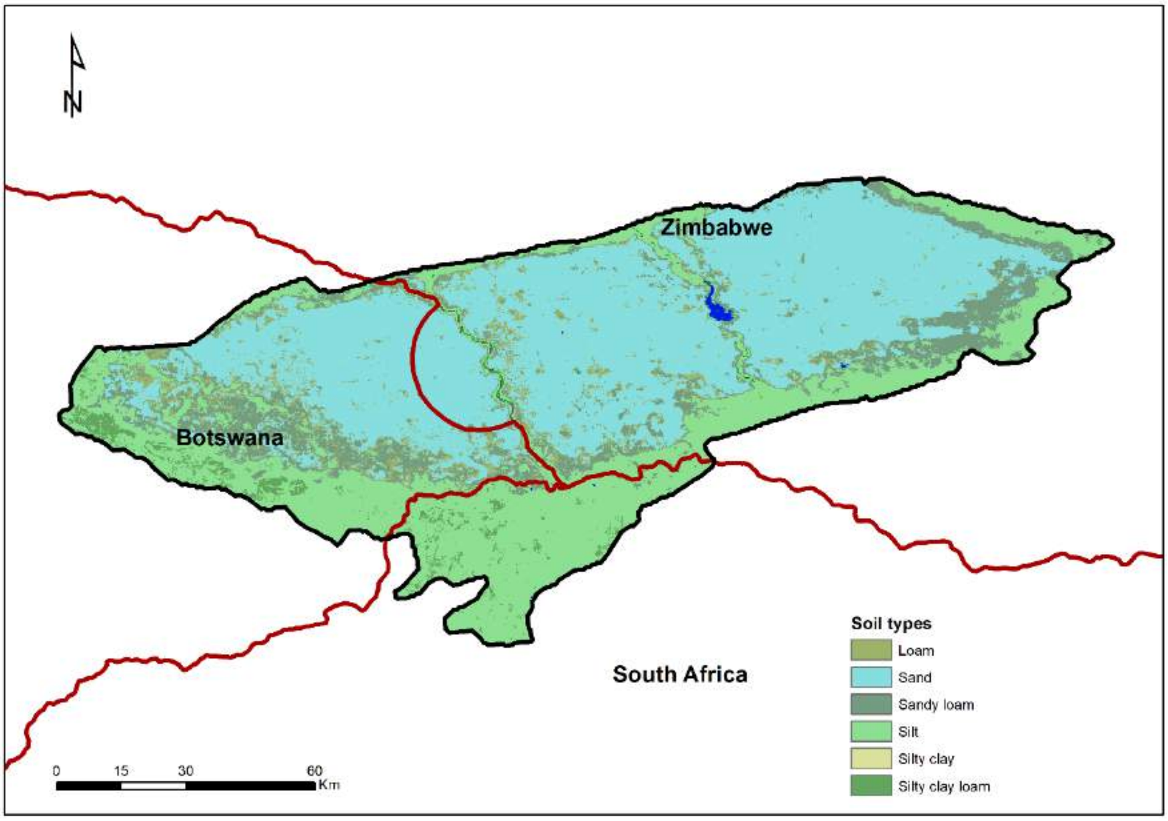

Figure 19: Soil type map (Source: ISRC global soil map). The blue area in the Zimbabwean side of the aquifer is represent open water

4.2.3 Criteria standardization

Standardization involves describing each criteria in a common scale. Usually each layer of the map is classified into a common scale value between 0 and 1 (the higher the value the most preferred). The step-wise and linear functions are the most common standardization methods. Table 7 presents classification and standardized values for the seven criteria described in the previous section.

Table 7: Criteria classification and standard values

Criteria	Classification	Standardize value	Reference
Lineament density (km/km^2)	0 – 0.05	0.2	(Magesh et al., 2012)
	0.05 – 0.13	0.4	
	0.13 – 0.2	0.6	
	0.2 – 0.27	0.8	
	0.27 – 0.35	1.0	
Land use	Tree cover areas	0.25	
	Shrubs cover areas	0.5	
	Grassland	0.75	
	Cropland	1.0	
	Vegetation aquatic or regularly flooded	0	
	Lichens Mosses / Sparse vegetation	0.5	
	Bare areas	0.5	

	Built up areas	1.0	
	Open Water	0	
Geology	Unconsolidated	1.0	(MacDonald and Davies, 2000; MacDonald et al., 2010)
	Consolidated sedimentary-I	0.8	
	Consolidated sedimentary-IF	0.6	
	Igneous (volcanic rocks)	0.5	
	Consolidated sedimentary-F	0.4	
	Basement	0.2	
Drainage density (km/km^2)	0.05 – 0.25	1.0	(Rajaveni et al., 2017)
	0.25 – 0.34	0.8	
	0.34 – 0.42	0.6	
	0.42 -0.50	0.4	
	0.50 – 0.68	0.2	
Slope (%)	0-3	1	(Preeja et al., 2011)
	3-5	0.9	
	5-10	0.7	
	10-15	0.4	
	15-35	0.2	
	>35	0	
Rainfall (mm/a)	200-250	0.2	
	250-300	0.4	
	300-350	0.6	
	350-400	0.8	
	400-456	1.0	
Soil	Sand	1.0	(FAO, 1979)
	Sandy loam	0.75	
	Loam	0.5	
	Silt	0.25	
	Silty clay loam	0.25	
	Silty clay	0.25	

4.2.4 Assigning weights for the selected criteria

Assigning relative weight is one of the most important steps in the GIS-MCDA approach. The weight assigned to a particular criteria reflects the relative preference of that element compared to other criteria. There are many methods for assigning relative weight. These include: rating methods, ranking method, pairwise comparison, and Multi-Influencing Factor (MIF) Method. Rating methods involves assigning weight based on expert knowledge. The ranking method on the other hand, involves ranking of criteria according to their rank order from the most important to the least. Then the weights are calculated by $((N-r+1)/\sum(N-r+1))$, where N is total number of criteria, and r is rank order. The pairwise comparison involves comparing each criteria one another and the most common approach is The Analytic Hierarchy Process (AHP) method (Saaty, 2008). The MIF method (Magesh et al., 2012; Shaban et al., 2006; Yeh et al., 2009) is another method that involves graphical representation of cause and effect relationship among the selected criteria. Criteria with major effect on another criteria assign as core of 1 and if criteria has minor effect would have score of 0.5 and finally all major and minor effects for each individual criteria are summed and divided by the total score to determine the relative criteria weights for each criteria. In the present study we used the ranking methods because of its simplicity and less subjectivity. The weights calculated based on the ranking method is compared with weights calculated in previous study with MIF for the same rank order used in this study (Magesh et al., 2012).

The calculated criteria weights and their comparison with weight calculated based on MIF is presented in Table 8.

Table 8: Criteria weight based on the ranking method (Rank order of Magesh et al. (2012))

Criteria	Rank (r)	N-r+1	Weight [in this study] ((N-r+1)/∑(N-r+1))	Weights used in Magesh et al. (2012)
Lithology	1	7	0.25	0.25
Land use/cover	2	6	0.21	0.22
Slope	3	5	0.18	0.16
Lineament density	4	4	0.14	0.13
Rainfall	5	3	0.11	0.09
Drainage density	6	2	0.07	0.09
Soil	7	1	0.04	0.06
Sum		**28**	**1.00**	**1.00**

4.2.5 Aggregating criteria to obtain monitoring priority index

The final step of the GIS-MCDA is to aggregate the criteria to obtain a priority monitoring index map. The monitoring priority index map is generated using linear combination of the seven criteria thematic maps based on their relieve importance. Each criteria maps are multiplied by their weight and summed to get the monitoring priority index map (Equation 2). The priority monitoring index values theoretically ranges between 0 and 1.

$$S = \sum wi\ xi \qquad (2)$$

Where S= suitability, wi= weight for factor i and xi= criterion score of factor i

4.3 Geo-statistical analysis of groundwater level data of Tuli Karoo Aquifer Area

Geo-statistical analysis was performed using the Geo-statistical Analyst, which is an ARCGIS extension tool. First, exploratory spatial data analysis was carried out to assess the statistical properties of groundwater level data such as examining data distribution, identification of trends, and assessing directional influences etc. Second, a semivariogram model was developed to examine spatial relationships between measured water level points. Third, cross validation was performed to assess how well the developed semivariogram model predicts groundwater level at unmeasured locations. The kriging technique was selected to determine groundwater level at unmeasured location and to determine prediction error at measured location.

4.3.1 Exploratory spatial data analysis

As noted by Gringarten and Deutsch (2001), the first step in geo-statistical modelling is to determine the correct property of the model and to make sure that this property is stationary over the domain of the study. The presence of a significant trend makes the variable nonstationary (Gringarten and Deutsch, 2001). If the data show a systematic trend, this trend must be modelled and removed before variogram modelling and geo-statistical simulations. Variogram analysis and subsequent simulations are performed on the residuals. The trend is added back to estimated or simulated values at the end of the analysis. Trend in the data can be identified from the experimental variogram, which keeps increasing, above the theoretical sill (Gringarten and Deutsch, 2001). This means that as distances between data pairs increase, the difference between data values also systematically increase.

4.3.2 Determining Semivariogram model

The semivariogram model for the present report was determined using observed groundwater level data measured during the hydro-census in Botswana (20-24 Feb, 2020). In total, groundwater level data measured in 15 observation boreholes were used to construct the semivariogram model. Groundwater level data measured in two deep observation boreholes (BH10509 and BH10512) and two shallow observation boreholes (BH10635 and BH10638) were excluded as they have groundwater response different from the others. The fitted semivariogram model is shown in Figure 20.

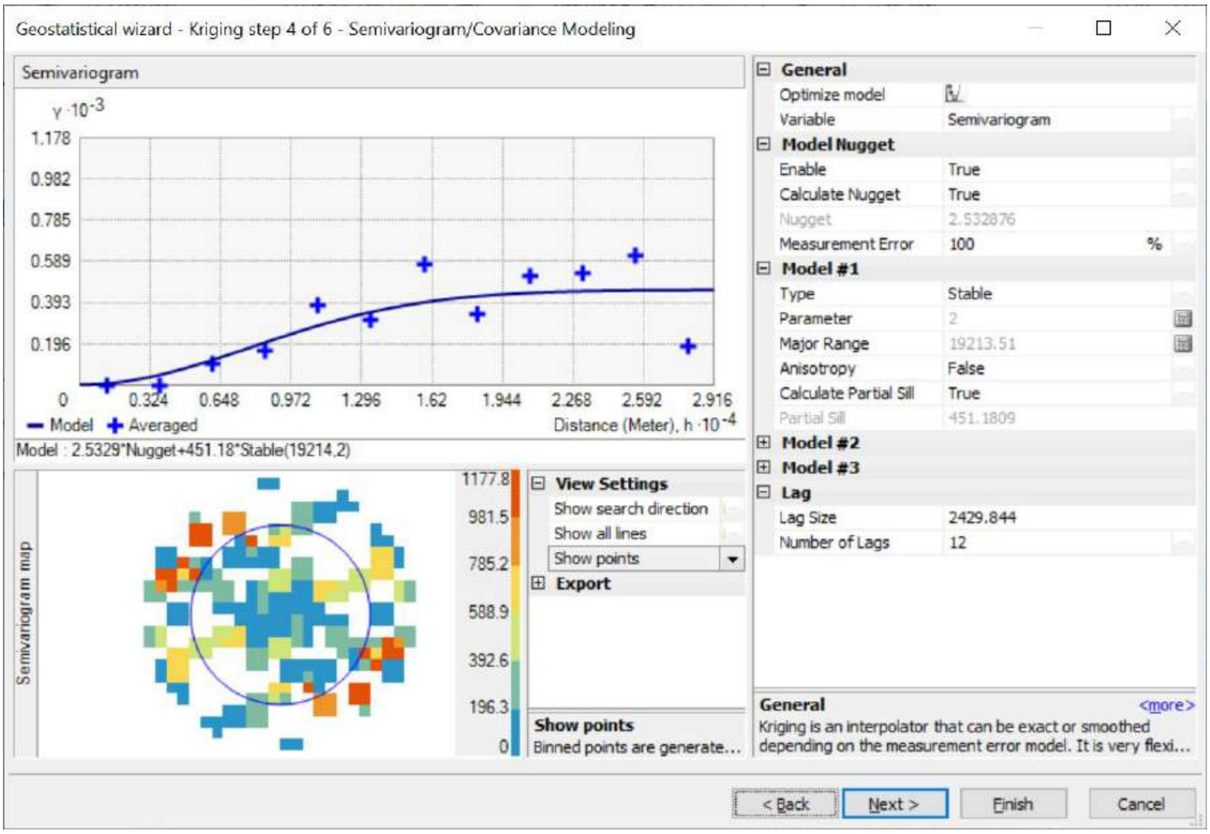

Figure 20: Semivariogram model developed universal kriging with first order polynomial trend

4.3.3 Cross-validation

Cross-validation provides an idea how well the selected semivariogram model predicts the unknown values. Cross-validation sequentially omits a point in the dataset, predicts a value for that point's location value using the rest of the data, then compares the measured and predicted values (the difference between the measured and predicted value is known as a prediction error. The statistics calculated on the prediction errors serve as diagnostics that indicate whether the model is reasonable for predicting values unmeasured locations. For a model that provides accurate predictions, the mean error should be close to 0, the root-mean-square error and average standard error should be as small as possible and the root-mean-square standardized error should be close to 1. The cross validation statics for the present study is shown in Table 9. Given the limited data the mean error of the prediction error is acceptable however the RMSE is rather very high. Although it is commonly accepted that a lower RMSE is better, Willmott and Matsuura (2005) recommended to use Mean Absolute Error (MAE) for evaluations and inter-comparisons of average model performance error as it is the most natural measure of average error magnitude compared to RMSE which is an unambiguous measure of average error magnitude.

Table 9: Cross Validation results for the semivariogram model

Performance measures	Error statics
Mean	3.11
Root-Mean-Square error	12.55
Mean Standardized error	0.11
Root-Mean-Square Standardized error	1.06
Average Standard Error	12.57

4.4 Combined hydrogeological- geo-statistical approach

The number and location of groundwater monitoring wells are determined following Bhat et al.'s (2015) approach. Bhat et al. (2015) determined the correlation length using geo-statistical method and constructed stratified hexagonal grid based on correlation length. Monitoring wells are located in the center of the regular hexagonal cells. Hexagonal sampling strategy is optimal compared to regular grid in monitoring network design (Olea, 1984).

In the present report. the correlation length determined based on observed groundwater level data is used to construct hexagonal polygon using Generate Tessellation function in ARCGIS (specifying hexagonal area of 315 km^2). This results in 58 hexagonal polygon. About 14 of these polygon are located at the edge of the aquifer with area less than 100 km^2. The premise is that new observation wells should be located at the center of the hexagonal polygon for the network to be optimal. The priority monitoring index determined using GIS-MCDA is overlaid with hexagonal sampling polygons and to see the location of the newly introduced observation wells in relation to priority monitoring index. Existing observation wells close to the center of the hexagonal polygon were identified and included as part of the network design.

4.5 Selection criteria for real-time monitoring wells

Given that finances and logistics are unlikely to enable purchase of all data loggers to enable intensive monitoring of the aquifer, particularly in the first year of roll-out, it was necessary to prioritize boreholes. Following consultation among the project team, it was concluded that a borehole should be prioritized if it:

- taps the productive sand stone aquifer (i.e., the major aquifer)[7]
- is strategically located close to river that provide information on groundwater-surface water interaction
- is located close to river gauging stations
- possesses casing that are suitable for installation of data logger
- is located in a location with strong network signal required for data transmission
- is located close enough to pumping that enable controlling drawdown
- is close to recharge areas, to enable natural recharge assessment

[7] A single well tapping multiple aquifer may not be desirable as it is difficult to properly interpret the results

- is accessible
- possesses proper documentation (well log details, such as borehole depth, water level fluctuation, lithology), verified during the hydro-census

4.6 Description of the real-time monitoring system (Telemetry system)

The real-time monitoring system developed by UIT GmbH (Dresden, Germany) was used for this report. The framework consists of data logger installation, telemetry system, and data processing and visualization platform. The CTD-GPRS system is used for measuring and storing conductivity, water level and temperature data. The CTD-GPRS is the vented system hence automatically compensate barometric pressure. The specification of the CTD-GPRS system is presented in Table 10. Typical system installed in Tuli Karoo Aquifer is shown in Figure 21. To conserve the battery life, the real-time system was programmed to collect data every six hours but to be transmitted to the online system once in a day. This frequency of measurement will be adjusted for dynamic system (e.g. monitoring groundwater-surface water interactions). The online data is transmitted to the server administered by UIT, GmbH Dresden, Germany for the project period and arrangement will be made to migrate the system to the LIMCOM or SADC-GMI platform.

The most important factors to consider during the telemetry system installation are water level fluctuation, water level during the data logger installation, network signal and lock system for protection of vandalism. Water level fluctuation during the dry and wet season determine the cable length and the location of the sensor (Figure 22). This is because the sensor should be fully submerged under water. It should not go dry or the pressure above the sensor location should not be higher than the allowable measuring range of the sensor, otherwise the data logger would burst or results in faulty measurement. Therefore, it is important that the minimum and maximum water level fluctuation be determined carefully from historic water level measurement data. Water level at the event of installation of the system has to be measured using dip meter to calibrate and verify the proper functioning of the system. It is also important manual measurement be continued at least once in a month to serve as verification of system functionality. Good network signal is one important issue to be considered for telemetry system installation. The other important point to be considered during data logger installation is the issue of vandalism. In some cases, it is necessary to upgrade the security of the logger by installing metal covers that can be secured with a padlock.

Table 10: data logger with Telemetry system specifications installed in Tuli Karoo Aquifer

CTD-GPRS, relative pressure system (vented system), measuring prop CTD (conductivity, temperature, water level)	
CTD-sensor	
Relative pressure sensor	0 -100 m water level
Absolute pressure sensor	
Accuracy	Resolution:0.002% FS Accuracy: 0.05% FS at 10-40 ^{O}C
Temperature sensor	Range -0-50 ^{O}C, Resolution: 0.04% FS, Accuracy +/- 0.05 ^{O}C
Conductivity sensor	0-20 mS/cm
Dimensions	Diameter 22 mm Length 340 mm
Data Logger LogTrans 6-compact (Recording and transmission system)	
Dimensions	Diameter 48 mm, length 395 mm
Protection degree	
Temperature range	
Power supply	4 lithium batteries, type Energizer L91/1.5 V-3Ah

External antenna	External PUK antenna to improve reception for weak signals including cable connection with data logger
Interface	
GPRS-data transmission-receiver station	
Receiver station	WEB-server with SENSO web
Parametrization and readout Software SENSOlog	SENSOlog is a PC software that represents a graphic control interface for the operation and allows configuration of data logger Read out data ans storage data Visualisation of read out data by tables and graphs
Cable	Vented cable including air compensation capillary
Main material	Stainless steel/graphite
Storage	Storage 512 MB for data

Figure 21: Real Time monitoring system

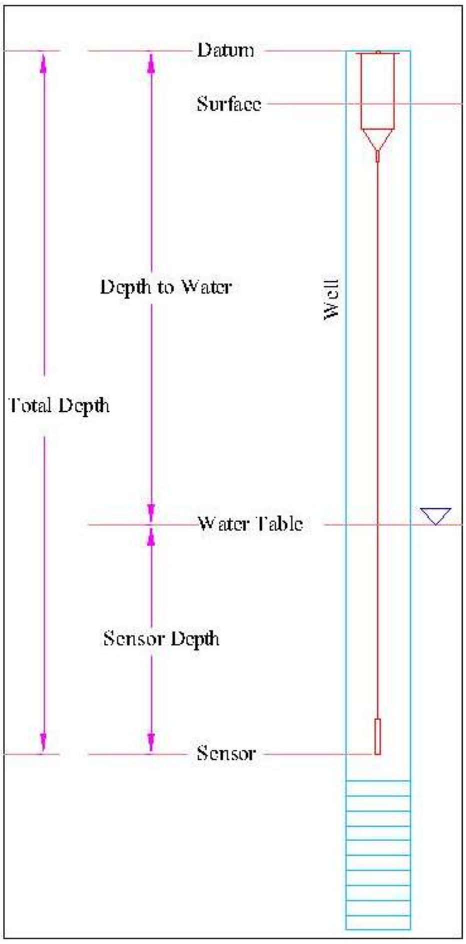

Figure 22: Typical data logger installation depths

5. Results

Results are divided in six parts. First, results of the hydro-census are presented. Second, the priority monitoring index map is discussed. Third, determination of semivariogram model parameters are discussed. Fourth, the optimal number and location of monitoring wells for Tuli Karoo Aquifer Area are outlined. Fifth, network density graph for the Tuli Karoo Aquifer area is presented. Sixth, selected wells for real-time monitoring are discussed.

5.1 Results of hydro-census (field assessment of existing monitoring networks)

Around 53 observation boreholes are found in the Tuli Karoo Aquifer. Thirty are found in Botswana and 23 in South Africa. During the hydro-census in Botswana 23 out of the 30 were visited (Table 11). Depth to groundwater and casing height for the 21 out of the 23 observation boreholes where information is available is presented in Figure 23, and for the same observation wells borehole depth and signal strength is presented in Figure 24.

As shown in Figure 23, the depth to groundwater ranges from 0.48-30.62 m below the top of the casing and the casing height ranges from 0.15 -2.3 m above the ground. The depth to groundwater from the ground surface ranges from -1.1 -30.5 m. Due to artesian nature the depth to groundwater is above the groundwater surface for some observation boreholes. The borehole depth ranges from 28 to 469 m. The shallowest and deepest observation boreholes respectively are BH10635 and

BH10509. Network strength ranges from none – good. Among the seven boreholes with appropriate wellhead and lock system (suitable for data logger installation) two have no network signal [BH10635 and BH10638], one with weak signal [BH10507], and another one with fair signal [BH10504] and three with good network signal [BH10505, BH10509 and BH10512]. The observation borehole with no network signal [BH10638 and BH10635] are strategically located far in the South in the Game reserve close to the Shashe River, to capture the response of groundwater to surface water flows.

Among the 23 visited boreholes during the hydro-census, five observation boreholes are artesian and six observation boreholes are damaged or shown sign of vandalism. Only six observation borehole have suitable masonry box with proper locking system that is suitable for data logger or telemetry system installation. All the rest have steel casing and are not suitable for data logger or telemetry system installation unless some modification is made. Annex 3 presents damaged observation boreholes or with some kind of issues (e.g., illegal connection).

Table 11: Hydro-censed observation Borehole (BH) information summary table (Botswana)

Borehole information	Description	Comments
Number of observation boreholes visited	23	Six additional unconnected production boreholes were visited (in total 29 boreholes)
Borehole depth (m)	259 ±139	From BH drilling sheet
Casing height (m)	1.0 ± 0.6	Two with very high casing height were not measured [BH10498 and BHDDH2]
Depth to groundwater (m)	15 ±11	Depth to groundwater is not measured in six of the observation boreholes due to unable to open the lock [BH10503, BH10495, and BH10502] and due to high steel casing or damaged borehole BH10498, BH10499, BHDDH2, BH10500]
Artesian	5	BH10498, BH10498, BH10499, BH10500, BHDDH2
Network strength	No signal=3 Very poor=1 Weak=4 Fair= 4 Good=11	Network strength is classified by looking at mobile phone signal, hence very approximate. With no signal are BH10635, BH10638 and BH10502 From the borehole with masonry and appropriate lock for data logger installation Two with no signal [BH10635 and BH10638], one with weak signal [BH10507], another one with fair signal [BH10504] and three with good network signal [BH10505, BH10509 and BH10512]
BH casing type	Masonry suitable for data logger installation (n=7)	BH10504, BH10505, BH10507, BH10509, BH10512, BH10635 and BH10638
	Steel case type (n=16)	All the rest
Boreholes damaged or vandalised	6	BH10496, BH10498, BH10499, BH10500, BH10502, BH10512

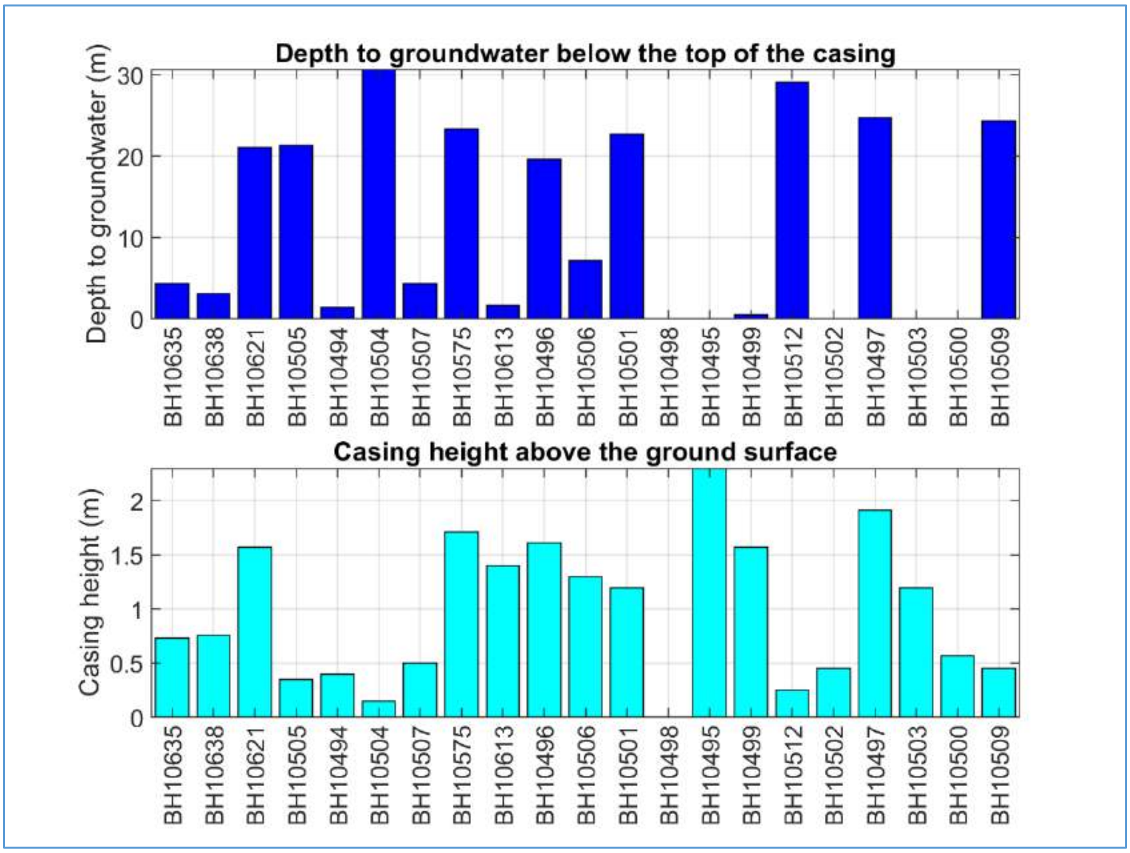

Figure 23: Depth to groundwater and casing height for the hydro-censuses observation boreholes. Boreholes with depth to groundwater close to zero are artesian wells.

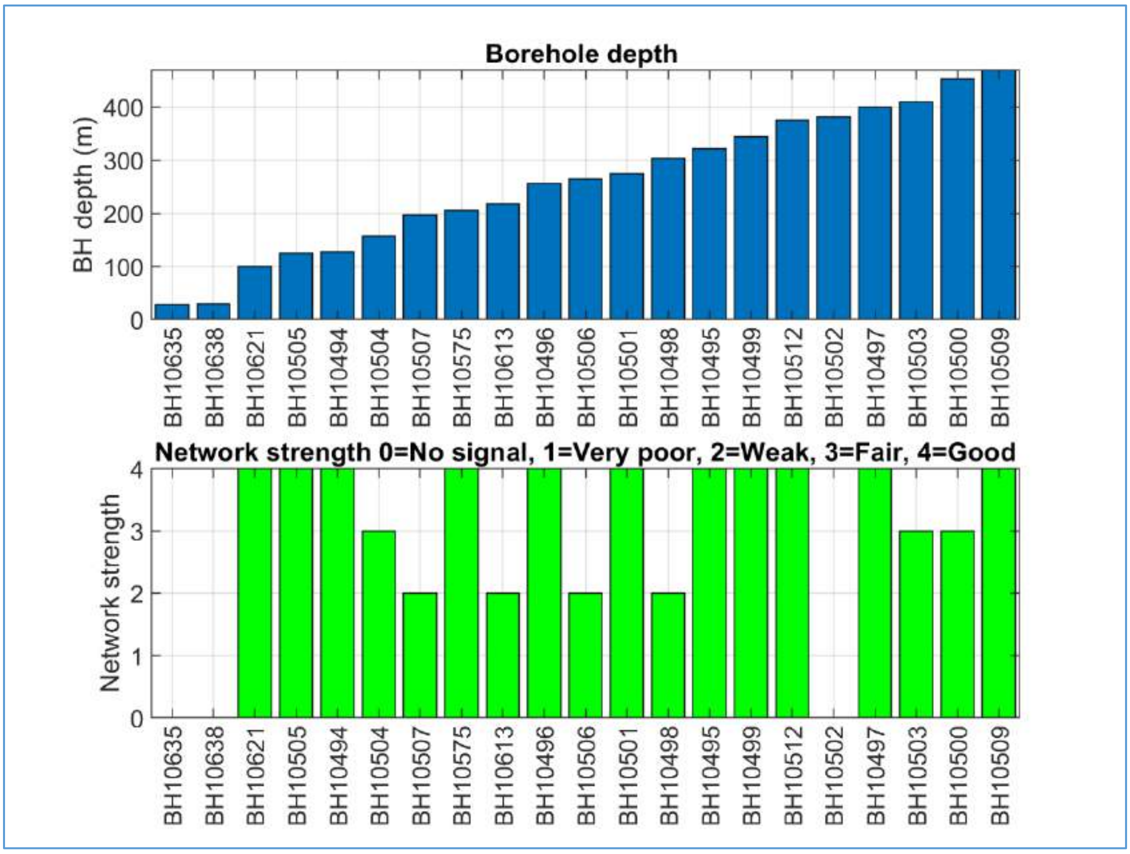

Figure 24: Borehole depths and signal strength for the hydro-censuses observation boreholes

5.2 Results of priority monitoring index mapping

The objective of the priority monitoring index mapping is to enable identification of priority monitoring areas. The computed monitoring priority index ranges between 0.3 and 0.9 (Figure 25). As seen very high priority zones are concentrated in the northwestern side of the aquifer (Botswana) and mostly in the edge of the aquifer area in Zimbabwe. Evident from this map is that high and very high priority monitoring indexes are concentrated along the lineaments amplifying lineaments as important priority potential groundwater monitoring zones. About 63% of the study area has priority index in the range of 0.57-0.7 and 1.9% of the study area has priority index greater than 0.7. High priority index are areas where priority monitoring is necessary. In addition to high priory monitoring index additional monitoring is necessary in areas of municipal groundwater use (the number of public water supply wells in the area), agricultural pumping, local recharge and groundwater-surface water interaction areas. According to Kim et al. (1995), some of the criteria to consider for location of monitoring wells include: 1) spatial distribution, 2) aquifer characteristics of the hydrogeological units, 3) local groundwater flow regime, 4) linkage and proximity with surface hydrology observations, 5) site accessibility, and 6) cost. The other factor which is equally important is the susceptibility of the aquifer for contamination. It may also possible that there could be locally significant aquifer which is relatively less extensive or productive; these aquifers can be identified through refined delineation and estimates of potential yield. This may reveal an area of potentially significant groundwater supplies which are not currently determined. Areas such as these should be added to the monitoring system.

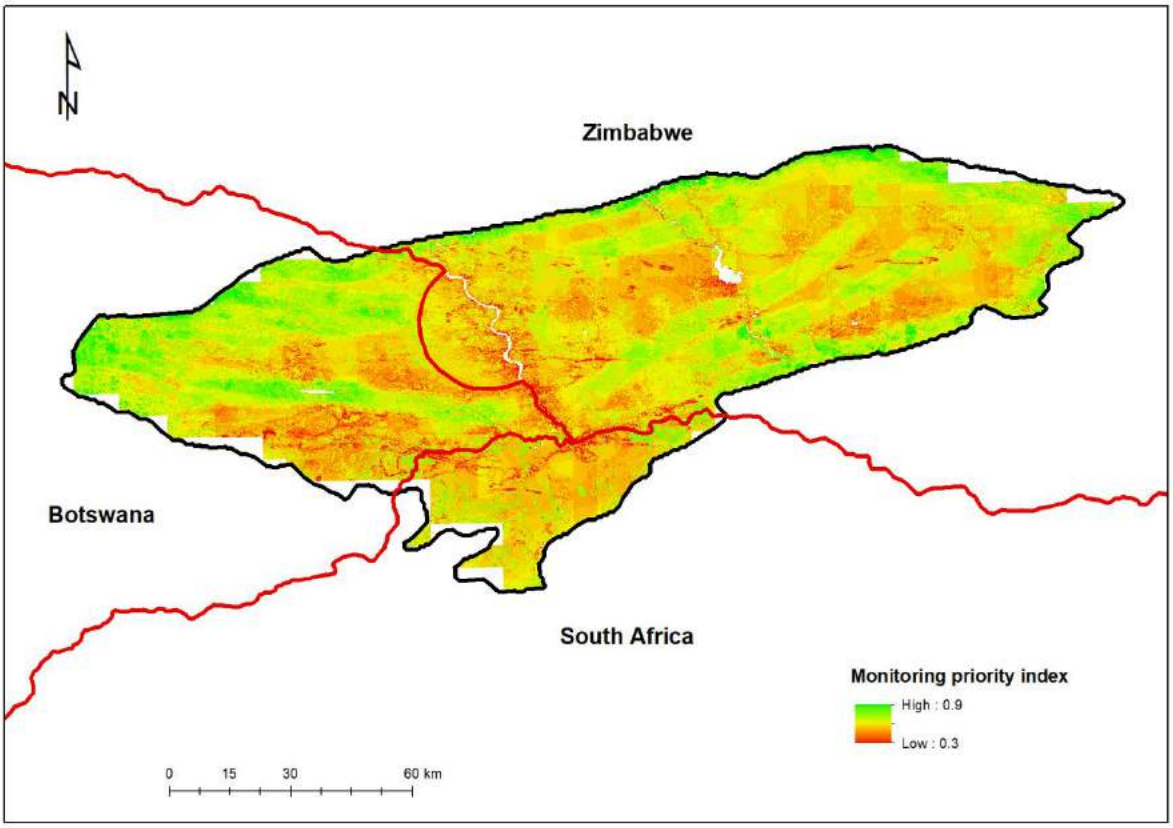

Figure 25: Monitoring Priority Index Map

5.3 Estimation of semivariogram parameters

The stable semivariogram was selected to fit the semivariogram determined using groundwater level data based on Universal Kriging with first order polynomial trend. The developed semivariogram model has nugget, range and partial sill of 2.5 m^2, 19 km and 451 m^2 respectively. It is important to note that for geo-statistical modelling, data points greater than 50 points are required for developing robust semivariogram modelling (Hengl, 2009). The structural parameters of the Semivariogram model are also depend on the season when the target parameter is measured (Western et al., 2004). That is why consistent time period was used in this study for constructing the semivariogram model. Due to limited data for fitting the semivariogram model and skewed location of observation of wells used to construct the semivariogram model, the semivariogram parameters calculated in this study are subject to high uncertainty.

The most critical parameter for the design of monitoring network based on the geo-statistical approach is the range or correlation length. To validate our approach we selected a common common time period for all existing monitoring network of March 2018 in 17 observation wells (15 from Botswana and two from South Africa) and re-constructed the semivariogram model and determined the range. In this case the empirical semivariogram model type of stable and Ordinary Kriging spatial interpolation was selected. The computed rage or correlation length is 17.5 km which is close to the 19 km calculated based on water level data measured during the hydro-census. Hence the correlation length of 19 km is reasonable estimate and used for determining the optimal number and location of monitoring wells.

5.4 Determining optimal number and location of monitoring wells

Based on correlation length of 19 km and hexagonal grid sampling strategy the number and location of optimal monitoring wells were determined. In total, about 58 monitoring wells roughly spaced 19 km apart are required for the Tuli Karoo Aquifer Area (total area of 12,293 km^2). This translates to one observation well per 211 km^2. The potential priority monitoring index is overlaid with hexagonal sampling grid and existing monitoring boreholes in Botswana and South Africa and production boreholes in Zimbabwe (Figure 26). There are a reasonable number of existing wells in the high priority monitoring index areas particularly in the north and northwestern section of the aquifer in Botswana. Most of the existing monitoring wells in South Africa are concentrated along the alluvial Limpopo River (medium priority monitoring index). The observation boreholes in South Africa are secondary monitoring network type located next to pumping wells for the purpose of controlling drawdown due to excessive pumping. Areas with cones of depressions can be determined by subtracting groundwater level contours map of pre-development after development (Zhou et al., 2013). However, this was not possible due to lack of spatially distributed water level data to make a water level contour map for the two periods.

The location of the existing and new optimal monitoring network is shown in Figure 27. In total, 58 observation wells are proposed consisting of four existing monitoring boreholes, eight existing production boreholes that can be used for monitoring if in case they are abandoned, and 44 new proposed observation boreholes. 32 observation boreholes are required in Zimbabwe, 16 in Botswana and 10 in South Africa. It is important that the existing monitoring wells currently not included in the monitoring network should be retained for continued monitoring. These wells may provide detailed local groundwater flow patterns than by the regional scale primary monitoring network designed in this study. It is always important to assess the information loss before deciding to remove observation well from the monitoring network. If observation well provides the same spatial information as a neighboring observation well or if the well is completed in the same water bearing zone as nearby observation well the information loss of removing one of the observation well may not be significant.

As noted by Swain and Sonenshein (1994), the density of wells in a monitoring network depends on a number of factors, which include: the cost of drilling, aquifer geology and groundwater flow, regulatory requirements, and the type of monitoring network. The European Union recommend monitoring network density of 1 in 25 km^2 in a more or less regular geometric pattern as thumb rule, however, in a large uniform hydrogeological setting with low impact the spatial density can be lowered (EEA, 2008). Jousma (2008) recommended a monitoring network density of one well per 10 to 25 km^2 for more intensive observation of groundwater such as defining flow directions while monitoring network density of one observation well per 25 to 100 km^2 is recommended for groundwater storage assessment. The monitoring network density depends on the nature of the groundwater system and the number and magnitude of the points of stress (Heath, 1976). For example, a relatively dense network is required for local unconfined flow while for deeper confined or semi-confined aquifer a much less dense network is sufficient.

The network density calculated in this report is on the lower side compared to Jousma (2008) recommendation at least 1 monitoring well per 100 km^2. Two factors should be mentioned for low network density in this report: 1) the calculated correlation length could be large due to sparse and limited groundwater level data used to construct the semivariogram model. Large correlation length means less heterogeneity and less number of monitoring wells, 2) the aquifer is confined and semi-confined in some parts of the aquifer area. Hence, results low ground water response or variability in groundwater level, which lead to low density in monitoring wells. However, it is important to note that the present monitoring network is a primary monitoring network type. Hence, it is important to supplement or densify the current network with secondary monitoring network (e.g. in areas of known strategic monitoring locations).

The optimal number and location of monitoring boreholes are purely determined by the geo-statistical approach. The natural question to ask is: what is the added value of priority monitoring index mapping? The value added by monitoring priority index map based on GIS –MCDA is twofold: 1) it helps to prioritize the installation of the optimal monitoring wells designed using the Geo-statistical approach, 2) provide an idea about the placement additional of strategic monitoring well locations.

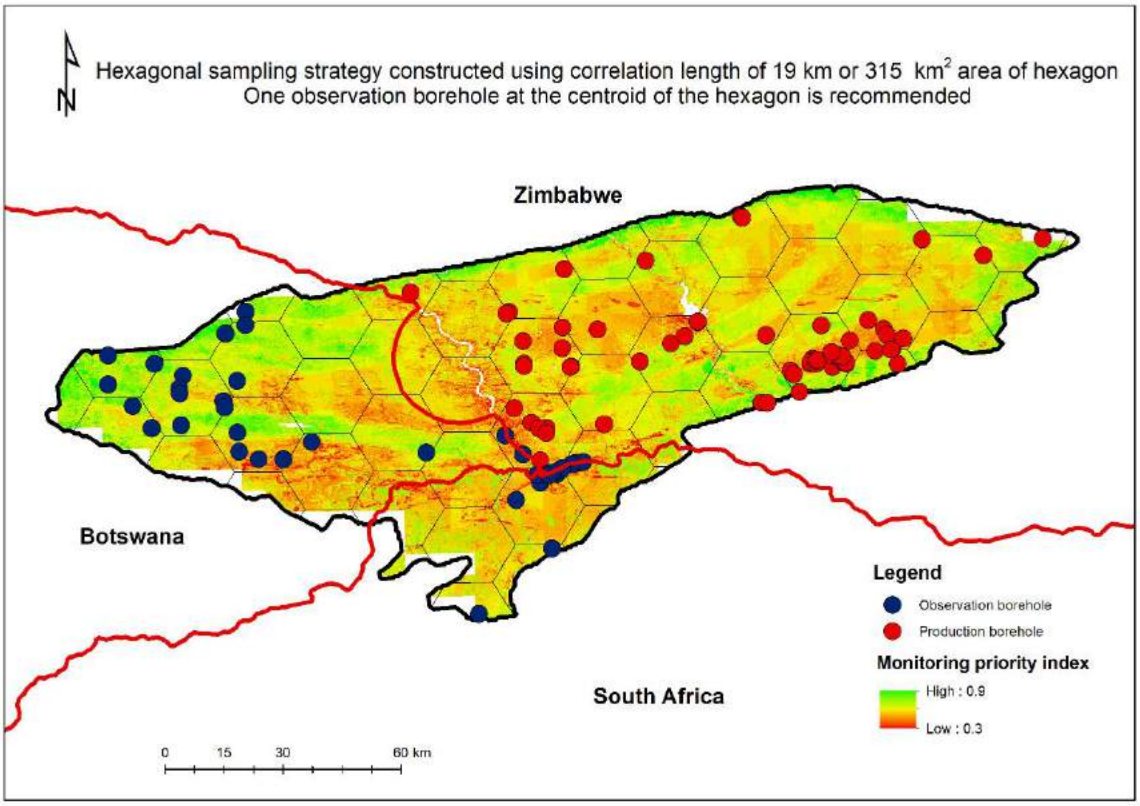

Figure 26: Hexagonal sampling grid over laid with monitoring priority index map and existing monitoring and production boreholes

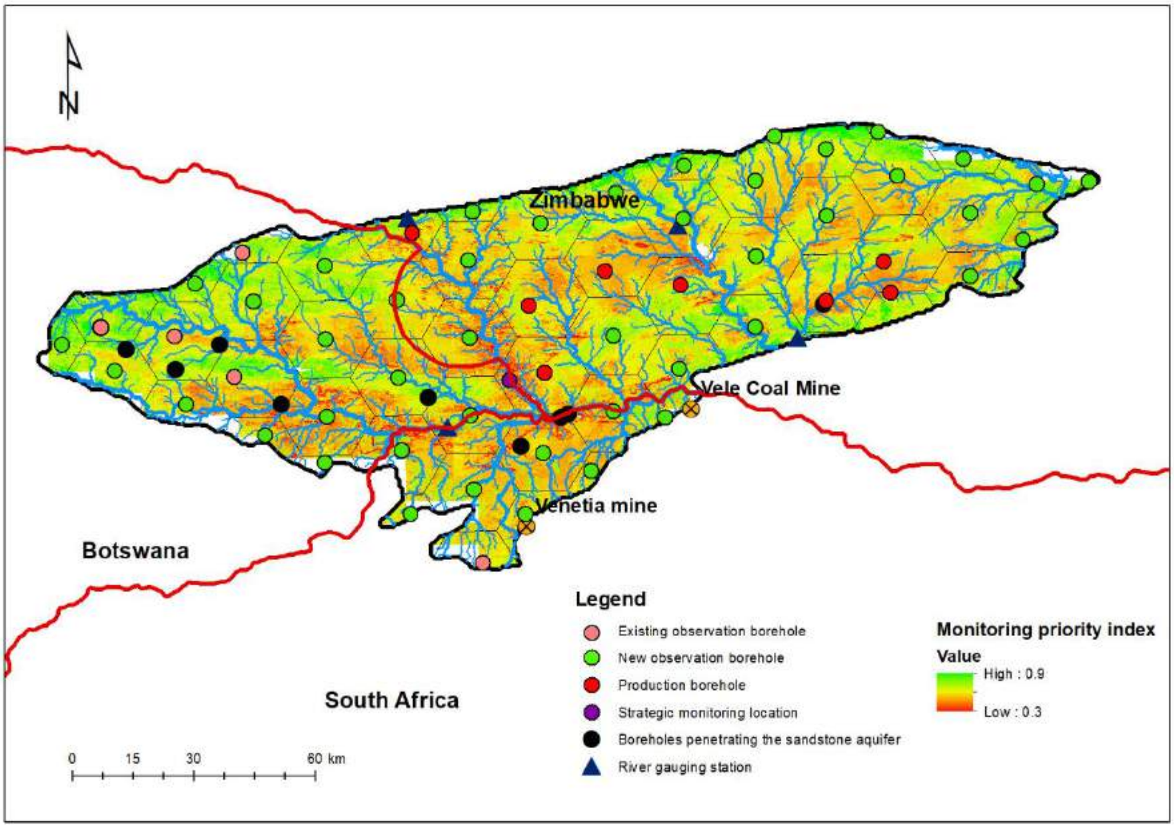

Figure 27: Optimal monitoring boreholes for the Tuli Karoo Aquifer overlaid with existing monitoring boreholes tapping the sandstone aquifer and monitoring priority index.

5.5 Developing the network density graph

The effectiveness of a network is often related to the accuracy of the spatial estimation error. A network density graph is a plot of standard deviation of the estimation error against the number of observation wells. The determination of network density represents determination of the number and location of observation wells for groundwater monitoring with the required accuracy and their spatial location (Yang et al., 2008). In many cases, groundwater managers are interested in the global performance of a monitoring network than the point estimation accuracy (Zhou, 2001). Determination of network density is based on Kriging approach. The average kinging standard deviation is usually used as a criteria for the determination of network density. Once the precision for spatial estimation (i.e. maximum tolerable average Kriging standard deviation) is specified, the required number of observation wells can be read from the network density graph. Hence, network density graph offers a simple but efficient way to determine the network density (Yang et al., 2008).

For the present report, a network density graph was developed using NETGRAPH program developed by Zhou (2001). In the NETGRAPH program, network density graph can be generated based on ordinary kriging for three systematic sampling: hexagonal, rectangular and triangular. The NETGRAPH program output two files. One file for creating network density graph containing total number of observation wells and average standard deviation of estimation error and debugging file containing location of observation wells and estimation points. These files can be used to create the location map of observation wells.

In NETGRAPH program, the semivariogram has to be fitted with available measurements using ordinary kriging. However, since the observed groundwater level data exhibits trend we used universal kriging to develop the semivariogram model. Here we used the same structural semivariogram parameters (i.e., the nugget, sill, and range) obtained by the Universal kriging and used it in the NETGRAPH program. The implicit assumption we made here is that the semivariogram parameters calculated by ordinary kriging will not be significantly different from that calculated by universal kriging except that during the Universal kriging the semivariogram model is fitted to the data after removing the trend. This assumption should be investigated further. Since the Stable and Gaussian experimental variograms provided comparable results during semivariogram model fitting using the universal kriging, we chose the Gaussian variogram model as Stable variogram is not available in the NETGRAPH program. We chose hexagonal sampling pattern as it has the lowest average standard deviation compared to triangular and rectangular sampling configurations (Zhou, 2001). Figure 28 shows the Network density graph for the Tuli Karoo Aquifer Area.

The average standard deviation decreases as the number of observation wells increase. The required number of observation wells can be read from the network density graph for user defined acceptable standard error. it can be seen from network density graphs that the reduction of the average standard deviation will be marginal with further increasing the number of observation wells beyond a certain density. The average standard deviation for 76 and 58 observation wells are 2.5 and 4.5 m, respectively. For the same number of observation wells, the average standard deviation decreases with the increase in correlation length. Therefore, to reach a given maximum tolerable average standard deviation, more observation wells are need for aquifers with small spatial correlation lengths. In other words, correlation length and number of observation wells required are inversely related. More observation wells are needed for the system with high sill to achieve a given tolerable average standard deviation (Yang et al., 2008). With high nugget effect, the average standard deviation does not significantly decrease beyond a relatively small number of observation wells (Zhou, 2001).

As demonstrated here and previous sections, the optimal number and location of observation wells can be determined using two different approaches. Bhat et al.'s (2015) approach is determined based on hexagonal grid constructed using correlation length determined based on geo-statistical approach (see previous section). The number of observation wells is decided by the number of hexagonal polygon. The disadvantage of this approach is that there is no performance measure associated to it. The second approach is to determine the number and location of observation wells based on network density graph as demonstrated by Yang et al. (2008). In this approach, network density graph is developed for selected sampling pattern (e.g. hexagonal) and average kriging standard deviation is calculated as a function of number of observation wells. Once the network density is plotted the desired number of observation wells are determined for user specified maximum allowable standard deviation. This approach is preferred as it relates the network density to a quantitative criteria. The average Kriging standard deviation of estimation error can be used as a measure of network effectiveness. In this report, however, we relied on optimal number and location of observation wells based on the Bhat et al. (2015) approach due to the uncertainties in the latter approach due to application of Universal Kriging based semivariogram model parameters instead of Ordinary kriging estimated.

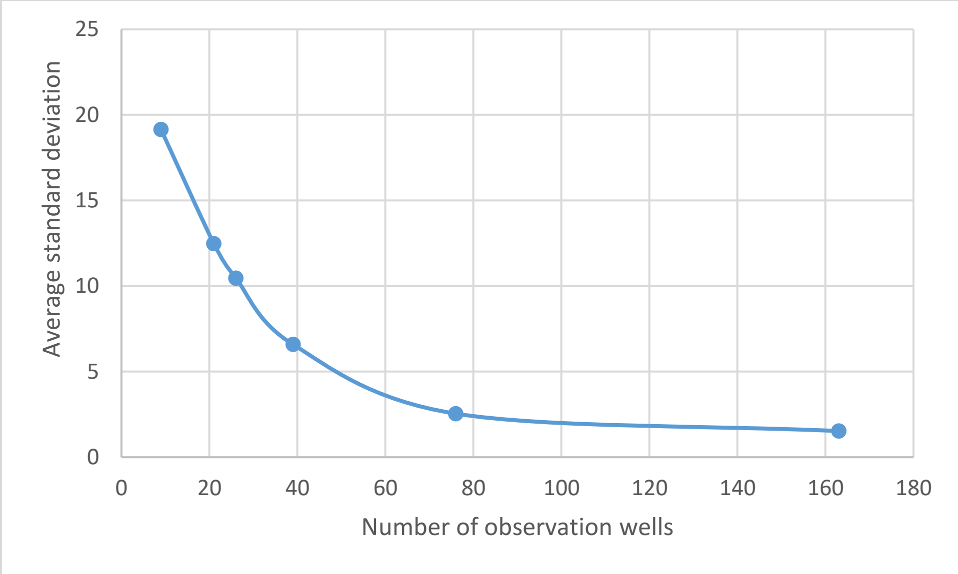

Figure 28: Network Density Graph

5.6 Selection of real time monitoring wells

Four real-time monitoring wells were selected to be installed with real-time monitoring system. The initial plan was to install one real-time monitoring well per each country and one at strategic location to monitor response of groundwater to surface water flow. In the context of COVID 19, however, the plan was revised to install three in Botswana (BH10504, BH10509 and BH10635), and one in South Africa (A6N0591). This is because since we conducted hydro census in Botswana we have better knowledge of the existing monitoring systems and similarly in South Africa there are observation wells that can be easily adapted unlike in Zimbabwe where there is no single observation well. See Figure 29 for the location of the wells.

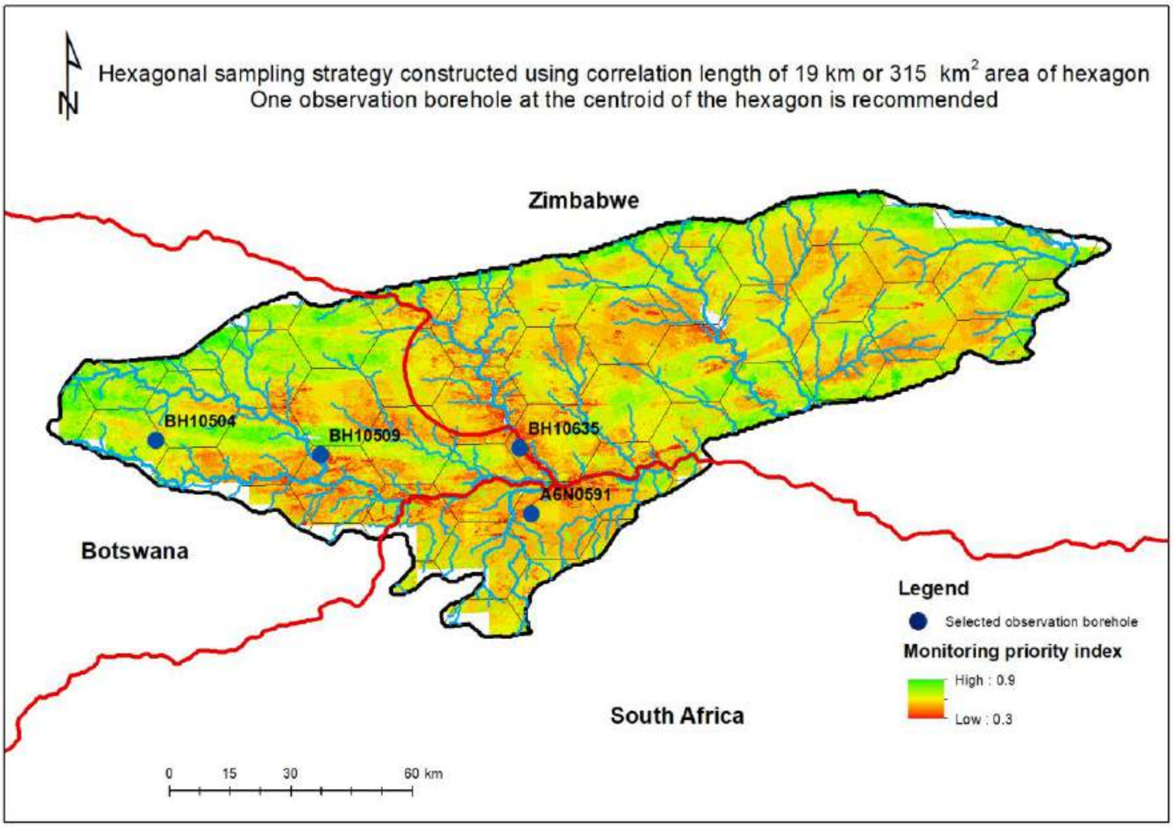

Figure 29: Four wells selected for real-time data logger system installation.

6. Discussion

Design of the Pilot Monitoring System for the Tuli Karoo Aquifer has driven numerous insights. A first issue relates to designing an effective system in the context of multi-layered geology that encompasses Basalt and Sand stone aquifers. In the multi-layered system, it is important to design systems separately. This means semivariogram model need to be determined for each separate system and correlation length need to be determined for spacing of the monitoring networks. However, due to lack of data it was not possible to develop two separate semivariogram model. Therefore, since the two system are hydraulically connected (Water Surveys Botswana, 2007), one seivariogram using groundwater level data from the two systems were developed and correlation length is determined. Based on the correlation length the spacing and optimal number of observation wells were determined. In addition, it is important to mention that, the semivariogram model is developed based on water level data from the Botswana side of the aquifer which is covering only 31% of the aquifer and skewed to the west, hence many not be representative for the whole aquifer area and is also is subject to high uncertainties n due to data limitations.

A second issue relates to designing a system for a transboundary aquifer, in which one aquifer-sharing state is 'starting from zero', i.e., currently undertakes no monitoring in their portion of the aquifer. During the workshop in October 2-4, 2019 in Francistown, a member of the Zimbabwe delegation pointed out that in the Zimbabwean side of the aquifer there are many abandoned pumping wells due to closure of mining activities that can be used for monitoring with little maintenance. However, it should be cautioned that there are always a reasons for abandoning production borehole, such as: borehole damage, low yield, water quality issue and others. Furthermore, existing production boreholes may fall short on key technical requirements, lack proper documentation including a well log and/or other construction data that adequately describes the physical setting and construction of the well, borehole depth, screen levels, water level fluctuation are unknown, the borehole completion including casing may not be suitable for the telemetry system installation. As most of the aquifer area is located far from cellular towers, network signals also affect the selection of real-time monitoring wells.

Box 1: Practical Installation of the pilot real-time monitoring system

Installation of real-time monitoring telemetry system were completed in the four selected boreholes (Figure 29). Based on historic water level fluctuation data cable length of 120 m for BH10504, cable length of 60 m for BH10509, cable length of 25 m for BH10635 and cable length of 30 m for BH A6N0591 were used.

Joint installation of the first real-time system by representative from DWS South Africa, DWS Botswana, ZINWA, SADC-GMI, IWMI, UIT was carried out on Feb 20, 2020 in Botswana (Figure 30), and the plan was to proceed to install additional systems soon thereafter. Unfortunately, plans could not be realized as a lockdown was implemented and international travel restrictions. To move things forward in the context of the new normal, a plan B had to be devised and implemented. Instead of IWMI staff directly installing data loggers, country partners were capacitated to install. Online training consisting of data logger configuration, sensor calibration and instrumentation, and online assistance during instrumentation was provided to the focal persons by UIT (Unmelt-und Ingenieurtechnik) GmbH Dresden, Germany and IWMI staffs. One to one training for the focal persons with the instrument were provided September 22-23, 2020 and additional training for larger group consisting of 15 peoples from the three countries was provided on 6th of October 2020. Support was then provided to enable them to travel and install data loggers. Two additional systems were installed in Botswana in October 26 and 28, and one in South Africa, in November 5, 2020.

Figure 30: Pilot test-instrumentation. Botswana

Institutions from the three countries such as DWS, South Africa, DWS Botswana, Zimbabwe National Water Authority (ZINWA) and SAD-GMI are relevant authorities that are actively engaged in the monitoring network design and installation, and are responsible for managing the monitoring system. LIMCOM is the other main institution that is actively engaged in overseeing the monitoring network design and installation of the monitoring system and is the relevant organization that derive this process and continued implementation in the Tuli Karoo Aquifer.

A third issue related to practical challenges of implementation. Notably, while key progress has been made in roll-out of the network design (Box 1), emerging challenges associated with use of existing observation or production wells include:

- Existing wells seldom fulfil all technical or logistical conditions set by the monitoring network design (example, casing, network signal, borehole depth, etc.)

- Accessibility for conducting hydro-census and selecting existing boreholes suitable for instrumentation
- Production boreholes have the potential for interaction with groundwater monitoring boreholes if the boreholes enters important aquifer units and are information on the geological strata encountered by the borehole and borehole completion details are available. These include the depth of the boreholes, its diameter, and construction details (casing, screen and pack). These details may be obtained from driller's log, but driller's logs are often not available. Some existing boreholes may lack proper documentation including a well log and/or other construction data that adequately describes the physical setting and construction of the well.
- Few monitoring boreholes tap the productive sand stone aquifer and there may be a need to drill fully penetrating additional well to characterize the aquifer system. In other words, the limited boreholes do not achieve a sufficient spectrum of aquifer layers.
- There is a paucity of streamflow gauging stations in area were we selected as strategic location to assess groundwater-surface water interactions
- Vandalism and theft are among critical problem emphasized by member state. Since the real time monitoring sites are located in remote areas, the risk of vandalism and /or theft can be a serious issue.

7. Conclusions

The existing groundwater level-monitoring network in the Tuli Karoo Aquifer Area is somewhat sparse and, more importantly, independently implemented by two of the three countries. Needless to say, it is not sufficient to enable proper groundwater resource characterization, and regional trend of groundwater level variations. Hence, there is little knowledge about the status of groundwater quantity availability and trend in the transboundary aquifer area. The main objective of this report to design an improved groundwater-monitoring network for the transboundary aquifer area and deploy a real-time monitoring system in selected observation wells to provide fast and reliable groundwater level data in timely fashion.

For the design of groundwater level monitoring network, a combined hydro-geological and geo-statistical approach was implemented. GIS-MCDA was used for identification of priority monitoring index. These were based on seven criteria (rainfall, soil, geology, lineament density, land use/land cover, slope and drainage density). The aim of priority monitoring index mapping is to support the identification of location of monitoring wells using the hydro-geological approach. To identify the optimal number and location of monitoring wells a geo-statistical approach was implemented. A semivariogram model was developed using water level data from 15 observation wells monitored during the hydro-census in Botswana (FEB 20-24,2020). Based on estimated correlation length hexagonal sampling pattern was constructed and existing observation boreholes close to the centroid of the hexagon were identified as optimal. In areas where there is no existing monitoring borehole new boreholes are proposed at the centroid of the hexagonal sampling grid.

It was found that about 58 monitoring boreholes needed to optimal monitoring the groundwater level in the transboundary aquifer. Fit-for-purpose approaches could nonetheless be followed that accept a relaxation of this ideal number, placing focus on monitoring hot spots of local concerns such as excessive groundwater drawdown, and trends relevant for understanding groundwater-surface water interactions. This should be supported by the monitoring priority index map.

The monitoring network design in this report should be viewed as a dynamic system which is responsive to changing information needs. It is important to review the monitoring network design periodically and provide recommendations for improving the efficiency and accuracy of the network. It is also important that hotspot regions be identified and secondary monitoring networks be established where necessary. Furthermore, it is important to note that groundwater resources cannot be managed in isolation. Climate and surface water monitoring networks should be improved and sustained. It is important to note that the geo-statistical analysis in the present study is significantly hampered by lack of spatially distributed observed groundwater level data and hence the developed semivariogram model is uncertain. However, the propriety monitoring index map provide a basis for identification of potential monitoring sites and helps to site monitoring wells case by case basis. Nonetheless, the GIS-MCDA mapping needs to be updated as new data become available.

As noted above (Box 1), four observation wells were installed with real-time monitoring system as a first step. One system was installed in before COVID-19 “old normal“ (before March 2020) and three systems were installed during COVID -19 pandemic in the “new normal” using Plan B. While IWMI staff directly installed the first data logger with countries, country partners were capacitated to install the remaining three (as IWMI staff were prohibited from travel to field). Online training consisting of data logger configuration, sensor calibration and instrumentation, and online assistance during instrumentation was provided to the focal persons by UIT GmbH Dresden, Germany and IWMI staff. Support was then provided to enable them to travel and install data loggers. The real-time monitoring wells monitor water level, temperature and electrical conductivity. The real time monitoring system is programmed to monitor every six hours and transmit data once in a day. Users can access the data via a web browser on a computer or smartphones.

The next steps include three activities: 1) IWMI will support expansion and provide technical support for monitoring of additional sites in Botswana and South Africa, 2) SADC-GMI to support field instrumentation in the Zimbabwe side of the aquifer, and 3) Spatial and temporal analysis of measured data (groundwater level, temperature and Electrical conductivity)

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Annex 1: Description of soils in Tuli Karoo Aquifer (Jones et al., 2013))

Soil reference group name	Description	Detailed descriptions
Arenosols	Easily erodable sandy soil with low water- and nutrient holding capacity (from Latin, arena, meaning sand).	Arensols develop as a result of the in situ weathering of quartz-rich parent material or in recently deposited sands (e.g. dunes in deserts and beaches). They are among the most extensive soil types in the world and are the dominant soil in Africa Soil formation is often limited by a low weathering rate. If vegetation has not developed, they can be prone to wind erosion. Once vegetated, the accumulation of organic matter, clay bands or the formation of humus-aluminium complexes can occur. They cover around **3%** of Tuli karoo Aquifer.
Cambisols	Soil that is only moderately developed on account of limited age (from Latin cambiare, to change)	These are young soils. Generally lacking distinct horizons, Cambisols exhibit only slight evidence of soil-forming processes usually through variations in colour, the formation of structure or presence of clay minerals. They are extensive throughout Africa and can have varied characteristics depending on the nature of the parent material, climate and terrain. They cover around **3%** of Tuli karoo Aquifer.
Leptosols	Shallow soil over hard rock or gravelly material (from Greek leptos, thin).	Leptosols are shallow soils over hard rock, very gravelly material or highly calcareous deposits. Because of limited pedogenic development, Leptosols have a weak soil structure. Leptosols occur all over Africa, especially in mountainous and desert regions where hard rock is exposed or comes close to the surface and the physical disintegration of rocks due to freeze/thaw or heating/cooling cycles are the main soil-forming processes.They cover around **68%** of Tuli karoo Aquifer.
Luvisols	Slightly acid soils with a clay-enriched subsoil and high nutrient-holding capacity (from Latin luere, to wash).	Luvisols have a distinct increase in clay content with depth as a result of clay movement from the upper part of the soil to the lower part. The clay is usually a mixture of kaolinite, illite and montmorillonite, giving the soil a high nutrient-holding capacity. In general, Luvisols have a well-developed soil structure, which contributes to a good water-holding capacity. Luvisols in Africa are mainly found in the Mediterranean region and in the southern and eastern parts of Africa on relatively young surfaces. They cover around **19%** of Tuli karoo Aquifer.
Regosols	Weakly developed soils in unconsolidated material (from Greek rhegos, blanket)	Regosols are weakly developed mineral soils in unconsolidated medium and fine-textured material – more coarse-textured soils are Arenosols (in the case of sand) or Leptosols (in the case of gravel). Regosols show only slight signs of soil development - some accumulation of organic matter producing a somewhat darker topsoil is often the only evidence of soil formation. Limiting factors for soil development range from low temperatures, prolonged dryness, characteristics of the parent material or erosion. Regosols are extensive in eroding lands such as mountains or deserts where soil formation is generally absent. They cover around **7%** of Tuli karoo Aquifer.

Annex 2: Hydro-Census summary Table in the Botswana side of the Tuli Karoo Aquifer

BH ID	Picture	Borehole information	
BH10494		Latitude	-21.992139
		Longitude	28.366917
		Ground elevation	732
		BH depth (m)	127
		casing height above ground (m)	0.4
		water strike	
		depth to groundwater from top of the casing (m)	1.44
		date of groundwater measurement	20-02-2020 (16:20)
		BH type	observation
		Aquifer type	
		Network	Good
		Remarks	This BH is about 4.2 from the BH10495
BH10495		Latitude	-21.992139
		Longitude	28.3669
		Ground elevation	Not measured
		BH depth (m)	321
		casing height above ground (m)	2.3
		water strike	17,148,182
		depth to groundwater from top of the casing (m)	Not measured
		date of groundwater measurement	20-02-2020 (16:20)
		BH type	observation
		Aquifer type	Artesian
		Network	Good
		Remarks	This BH is about 4.2 from the BH10494 and Water level was not measured as the BH was difficult to open and the height of the casing is high.
BH10494-BH10495		Distance measurement between BH 10494 and BH10495, the distance is about 4.2 m	

BH10494-BH10495& production BH		This is to show the arrangement of BH10494, BH10495 and unconnected production BH	
BH10496		Latitude	-22.041194
		Longitude	28.42325
		Ground elevation	709
		BH depth (m)	256
		casing height above ground (m)	1.61
		water strike (m)	17,55,125
		depth to groundwater from top of the casing (m)	19.6
		date of groundwater measurement	23-02-2020 (15:50)
		BH type	observation
		Aquifer type	
		Network	Good
		Remarks	The observation BH is located along drainage line next to WUC production BH10569, damaged foundation
BH10497		Latitude	-21.944417
		Longitude	28.473111
		Ground elevation	697
		BH depth (m)	400
		casing height above ground (m)	1.91
		water strike (m)	131,345
		depth to groundwater from top of the casing (m)	24.79
		date of groundwater measurement	23-02-2020 (9:30)
		BH type	observation
		Aquifer type	
		Network	Good
		Remarks	This BH is located about 8.3 Km from Bobonong Village.
BH10498		Latitude	-21.971389
		Longitude	28.538528
		Ground elevation	678
		BH depth (m)	303
		casing height above ground (m)	Not measured
		water strike (m)	249
		depth to groundwater from top of the casing (m)	Not measured
		date of groundwater measurement	23-02-2020 (12:30)
		BH type	observation
		Aquifer type	Artesian
		Network	Weak
		Remarks	Broken and water is freely flowing

BH10499		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.00124 28.530528 694 344 1.57 17,147,188,200,284 0.48 23-02-2020 (14:00) observation Artesian Good Near to unconnected production BH (BH10572), about 20. Broken steel casing at the welding joints
BH10500		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-21.983833 28.662278 694 453 0.57 213,450 Not measured 22-02-2020 (14:30) observation Artesian fair The BH is hammered and the casing is damaged, sign of Vandalism.
BH10501		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.084944 28.53375 717 274 1.2 107 22.72 24-02-2020 (11:27) observation Good About 20.2 m from the production BH10575
BH10502		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.101861 28.662861 678 381 0.45 Not measured (difficult to open) 24-02-2020 (15:43) observation No signal The observation BH is close to drainage line and the masonry foundation of the

			steel casing is eroded on one side.
BH10503		Latitude	-22.029778
		Longitude	28.631111
		Ground elevation	711
		BH depth (m)	409
		casing height above ground (m)	1.2
		water strike (m)	332
		depth to groundwater from top of the casing (m)	Not measured (difficult to open)
		date and time	22-02-2020 (16:05)
		BH type	observation
		Aquifer type	
		Network	Fair
		Remarks	Distance to the next BH (BH10622) is 24.50 m
		This is to show the arrangement of BH10503 and BH10572, which is about 24.5 m apart.	
BH10504		Latitude	-22.092167
		Longitude	28.467056
		Ground elevation	718
		BH depth (m)	157
		casing height above ground (m)	0.15
		water strike (m)	54
		depth to groundwater from top of the casing (m)	30.62
		date and time	23-02-2020 (17:40)
		BH type	observation
		Aquifer type	
		Network	fair
		Remarks	Observation BH 18.4 m from production BH10573. The Telemetry system was installed in this BH in the last day
BH10505		Latitude	-21.825639
		Longitude	28.681972
		Ground elevation	723
		BH depth (m)	125
		casing height above ground (m)	0.35
		water strike (m)	Dry
		depth to groundwater from top of the casing (m)	21.38
		date and time	21-02-2020 (8:40)
		BH type	observation
		Aquifer type	
		Network	Good
		Remarks	The BH is located close to the farming area inside a fence, about 100 m from the main road.

BH10506		Latitude	-21.856694
		Longitude	28.680861
		Ground elevation	706
		BH depth (m)	265
		casing height above ground (m)	1.3
		water strike (m)	169,227
		depth to groundwater from top of the casing (m)	7.21
		date and time	22-02-2020 (10:15)
		BH type	observation
		Aquifer type	
		Network	weak
		Remarks	
BH10507		Latitude	-21.875889
		Longitude	28.635694
		Ground elevation	705
		BH depth (m)	197
		casing height above ground (m)	0.5
		water strike (m)	16,165
		depth to groundwater from top of the casing (m)	4.39
		date and time	22-02-2020 (10:30)
		BH type	observation
		Aquifer type	
		Network	weak
		Remarks	Observation BH is located to drainage line and next to another observation well (BH10613) with an approximate distance of 21.6 m.
BH10509		Latitude	-22.123611
		Longitude	28.832833
		Ground elevation	
		BH depth (m)	469
		casing height above ground (m)	0.45
		water strike (m)	228,255,282
		depth to groundwater from top of the casing (m)	24.36
		date and time	20-02-2020 (10:30)
		BH type	
		Aquifer type	observation
		Network	Good
		Remarks	There is a production borehole around 20 m from this BH which is not connected. First Telemetry system installation
BH10512		Latitude	-22.148
		Longitude	29.095139
		Ground elevation	
		BH depth (m)	375
		casing height above ground (m)	0.25
		water strike (m)	35,295
		depth to groundwater from top of the casing (m)	29.07
		date and time	21-02-2020 (10:40)
		BH type	observation
		Aquifer type	
		Network	Good
		Remarks	This BH was illegally connected to Production BH

			in 2016 and disconnected when the case was known. Located in the Game reserve close to the lodges. There is a water harvesting pond for feeding wild animals around 50 m upstream of the observation well. There is also nearby grid line.
BH10635		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.109083 29.275139 524 28 0.73 21 4.33 21-02-2020 (14:20) observation No signal This BH used to have a data logger but due to malfunction of the data logger it was removed. The BH is about 19.7 m from the Sashe River. The river bed elevation just downstream of BH10635 is 520 m above mean sea level.
BH10638		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.151417 29.316611 531 29 0.76 12 3.13 21-02-2020 (15:30) observation No signal The distance of this BH from the bank of Sahse River is 25 m. The BH is located inside a flood plain. There is a huge flood plain area behind this BH.
BHDDH2		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.044306 28.634 700 Not measured (casing is too high) 22-02-2020 (16:45) observation Artesian Fair D/s of this artesian well there is an artesian production BH approximately 120 m. Water is freely flowing out in the

			production BH pump. This BH is one of the BH drilled in the Bobonong project.
BH10613		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-21.875778 28.635556 708 218 1.4 177 1.68 22-02-2020 (11:35) observation Weak This borehole is about 21.6 m from production BH10507.
BH10621		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.163222 28.712 633 100 1.57 No significant water strike 21.08 24-02-2020 (14:45) observation Good
BH10622		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.03 28.631056 709 382 1.4 50 8.45 22-02-2020 (16:00) observation Fair Distance from observation BH10503 is 24.50 m
Unknown		Latitude Longitude Ground elevation BH depth (m) casing height above ground (m) water strike (m) depth to groundwater from top of the casing (m) date and time BH type Aquifer type Network Remarks	-22.145611 28.666556 657 2.11 17.14 24-02-2020 (14:10) observation very poor The BH has no name, hence, should be identified based on location. The place where the BH located is called Simrobe

BH10568		Latitude	-21.9256639
		Longitude	28.367028
		Ground elevation	733
		BH depth (m)	235
		casing height above ground (m)	1.6
		water strike (m)	154,160
		depth to groundwater from top of the casing (m)	2.39
		date and time	20-02-2020 (16:20)
		BH type	Unconnected production BH
		Aquifer type	
		Network	Good
		Remarks	
BH10572		Latitude	-22.012583
		Longitude	28.530667
		Ground elevation	695
		BH depth (m)	265
		casing height above ground (m)	1.6
		water strike (m)	188,220
		depth to groundwater from top of the casing (m)	1.56
		date and time	23-02-2020 (14:10)
		BH type	Unconnected production BH
		Aquifer type	
		Network	Good
		Remarks	This production BH is about 20 m from observation BH10499.
BH10573		Latitude	-22.092028
		Longitude	28.466972
		Ground elevation	719
		BH depth (m)	210
		casing height above ground (m)	1.6
		water strike (m)	107,125
		depth to groundwater from top of the casing (m)	32.26
		date and time	23-02-2020 (17:35)
		BH type	Unconnected production BH
		Aquifer type	
		Network	Fair
		Remarks	Production BH not connected. Distance from observation BH10504 is 18.4 m.
BH10575		Latitude	-22.085056
		Longitude	28.533917
		Ground elevation	717
		BH depth (m)	205
		casing height above ground (m)	1.71
		water strike (m)	106,190
		depth to groundwater from top of the casing (m)	23.3
		date and time	24-02-2020 (11:30)
		BH type	Unconnected production BH
		Aquifer type	
		Network	Good
		Remarks	Distance from BH10575 to Observation BH10501 is about 20.2 m

Annex 3 six observation boreholes damaged or has some problems

BH	Picture	comments
BH10496		The observation BH is located along drainage line next to WUC production BH10569. The foundation of the observation BH is damaged by flooding.
BH10498		The BH is broken just above the ground so that water is freely flown. This BH took us about 3 hrs to locate
BH10499		The measured water level is not representative as someone broke the steel case at weak welding points and water is simply flowing out like orifice flow (Vandalism, punching the borehole at weak welding points so that water to flow out). Near to unconnected production BH (BH10572), about 20 m.
BH10500		The BH is hammered and the casing is damaged, sign of Vandalism. The water is slightly salty.

BH10502		The observation BH is close to drainage line and the masonry foundation of the steel casing is eroded on one side.
BH10512		This BH was illegally connected to Production BH in 2016 and disconnected when the case was known. Located in the Game reserve close to the lodges. There is a water harvesting pond for feeding wild animals around 50 m upstream of the observation well. There is also nearby grid line.