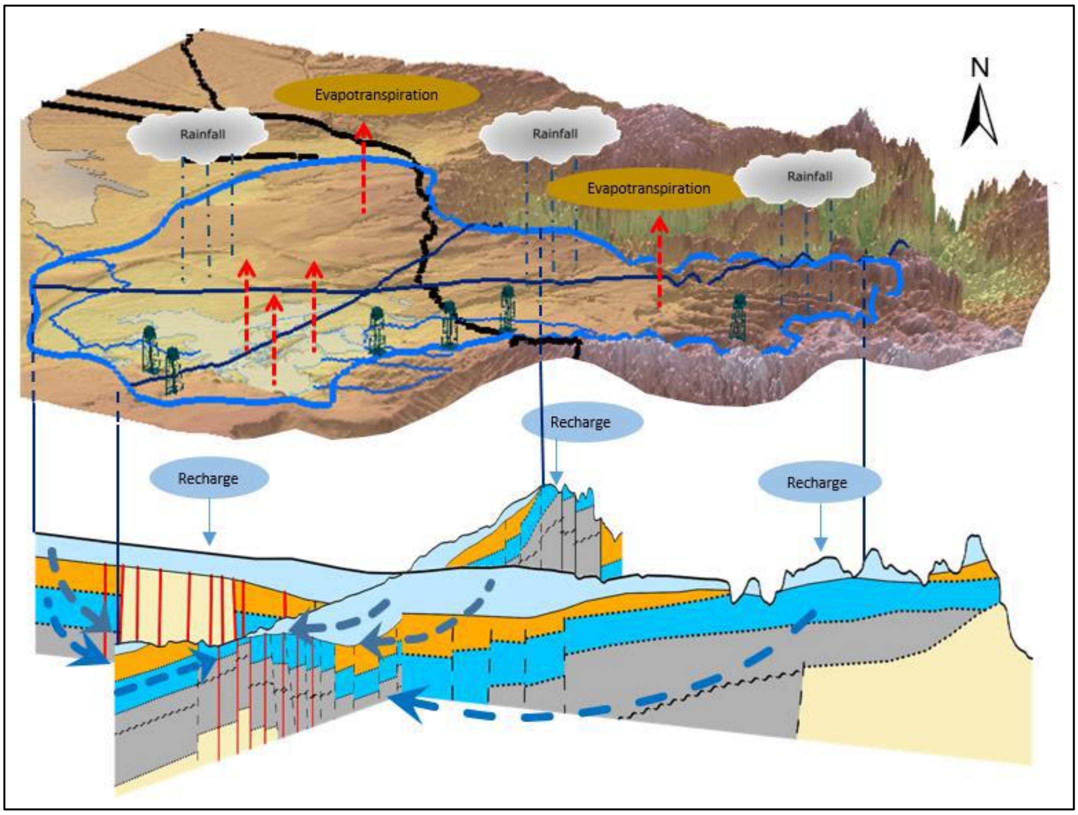
Hydrogeology of the Eastern Kalahari-Karoo Basin Transboundary Aquifer System (EKK-TBA)
Final Report



Water Resources Management Research in the Eastern Kalahari Karoo Basin Transboundary Aquifer (EKK-TBA)

ZA-SADC-GMI-114839-CS-QCBS

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EXECUTIVE SUMMARY

This report on the Eastern Kalahari-Karoo Transboundary Aquifer system (EKK-TBA), which is shared between Botswana and Zimbabwe, provides a status quo of hydrogeological information, data and analyses that can be used by an EKK-TBA management institution or groundwater management institutions in both countries, to sustainably manage the groundwater resources which constitute the main water source in the Basin for both humans and animals (domestic and wildlife).

The EKK-TBA extends from eastern Botswana into western Zimbabwe, is mainly located between latitudes 17° S and 22° S and longitudes 23° E and 29° E and covers approximately 127 000 km^2, of which 65% is in Botswana and 35% is in Zimbabwe. There are currently about 600 000 people living in the Basin (SADC-GMI, 2020) and the population is projected to grow to almost 1 million by 2050, which will exert additional pressure on land and water resources.

The topography of the EKK-TBA is generally flat and ranges between 880 and 1 400 m amsl. The climate is semi-arid with rainfall occurring between October and April, and July and August being the driest months. Low temperatures occur in July while high temperatures are experienced in October. Increasing temperature trends within the region have been established and these will impact the availability of water resources, particularly surface water and shallow groundwater. Surface water drainage is through the ephemeral Boteti and Nata Rivers (draining into the Makgadikgadi Pans) and the perennial Gwayi River and its tributaries (draining into the Zambezi River).

The Kalahari Group forms the topmost lithological unit and is ubiquitous within the EKK-TBA and outside the Basin. It is thickest in the centre of the Basin. A layer of Upper Karoo basalt underlies the Kalahari Group and is mostly eroded away in the southeastern and eastern fringes of the Basin exposing the underlying Upper Karoo Ntane/Forest Sandstone formations. The Ntane/Forest Sandstone is underlain by various formations comprised mainly of mudstones, viz, the Mosolotsane Formation (Upper Karoo) and Lower Karoo mudstones (Ecca Group). The Mea Arkose Sandstone Formation is deep seated and only outcrops in the Dukwi area in Botswana. The Basin is highly structurally controlled by numerous faults, fractures and lineaments resulting in grabens (depressions) and horsts of Basement Complex.

The Kalahari Group constitutes the shallow aquifer whereas the main aquifers are the deep Ntane/Forest Sandstone and the Mea Arkose Sandstone (Wankie Sandstone equivalent). The basalt forms an aquitard. Several public and private wellfields that include the Dukwi, Letlhakane, Maitengwe, Nyamandlovu and OLDM (Orapa, Letlhakane and Damtshaa Mines) and the Karowe Diamond Mine (KDM) have been developed along the fringes of the Basin where the sandstone aquifers outcrop and are recharged from rainfall. Indirect recharge occurs through the lineaments, faults and fractures. The groundwater is generally fresh within

the recharge zones but ages and salinizes with increasing depth and short distances away from the recharge areas towards the central portions of the basin. The groundwater generally flows slowly towards southwest and southwards and is discharged in the Makgadikgadi Pans in Botswana.

Groundwater monitoring within the Basin is carried out by public institutions and the mining companies and is largely confined to the wellfields. The monitoring is by and large, inconsistent and incoherent for public institutions in both countries as they are bedeviled with a plethora of challenges which include lack of resources (human resources, financial and material). Comprehensive monitoring data is not easily accessible from the mining companies.

As water availability is a major challenge in the Basin, potential areas for further groundwater development and other water conservation methods are proffered. Water demand is outstripping the supply for both human and wildlife, which for most areas is already at the verge of over-exploitation, hence the need for concerted efforts to monitor and sustainably manage the Basin's groundwater resources. Currently, there is no groundwater management institution for the EKK-TBA as a whole and the establishment of such a unit (has to be well resourced) is pivotal to the sustainable management of the groundwater resources of the Basin. The construction of an EKK-TBA groundwater model is proposed to inform and guide the design and establishment of a groundwater monitoring network which should involve stakeholders from both public and private sectors and civil society.

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ACRONYMS

^{13}C	Carbon-13
^{14}C/C-14	Carbon-14
^{2}H	Deuterium
^{3}H	Tritium
^{18}O/O-18	Oxygen-18
amsl	above mean sea level
BFI	Baseflow Index
BH	Borehole
BOS	Botswana Bureau of Standards
CMB	Chloride Mass Balance
CoB	City of Bulawayo
Covid-19	Coronavirus disease 2019
CRD	Cumulative Rainfall Departure
CRU	Climate Research Unit
DEM	Digital Elevation Model
DQC	Data quality control
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
EKK-TBA	Eastern Kalahari-Karoo Basin Aquifer
ET	Evapotranspiration
EVSF	Equal Volume Spring Flow
Fms	Formations
GIP	Groundwater Information Portal
GIS	Geographic Information System
GRACE	Gravity Recovery and Climate Experiment
HNP	Hwange National Park
IDW	Inverse Distance Weighting
K	Hydraulic conductivity
KDM	Karowe Diamond Mine
m bgl	metres below ground level
MAR	Managed Aquifer Recharge or Mean Annual Rainfall
Ml	Mega litre
NASA	National Aeronautics and Space Administration
Obs	Observed
OKACOM	Okavango River Basin Water Commission
OLDM	Orapa, Letlhakane and Damtshaa Mines
pmC	percent modern Carbon
QA	Quality Assurance

S	Storativity / Storage coefficient
SADC	Southern African Development Community
SADC-GMI	- Groundwater Management Institute
SADC-HGM	- Hydrogeological Map
SAP	Strategic Action Plan
SD	Standard Deviation
SRTM	Shuttle Radar Topography Mission
Sst.	Sandstone
SW-GW	Surface water – Groundwater
SWL	Static water level
T	Transmissivity
TDS	Total Dissolved Solids
WAB	Water Apportionment Board
WHO	World Health Organisation
WTF	Water Table Fluctuation
WUC	Water Utilities Corporation
ZAMCOM	Zambezi Watercourse Commission
ZINWA	Zimbabwe National Water Authority

DOCUMENT INFORMATION

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Cover: Conceptual hydrogeological model of the Eastern Kalahari-Karoo Basin Transboundary Aquifer System

1. BACKGROUND

1.1. Scope and purpose

This Hydrogeology Report of the EKK-TBA provides hydrogeological information and data and analysis for the new EKK-TBA as delineated during the EKK-TBA Transboundary Diagnostic Analysis (SADC-GMI, 2020).

The purpose of the report is to provide hydrogeological information that can be used by a EKK-TBA management institution to sustainably manage the groundwater resources which constitute the main water source of the Basin, particularly in light of the grave water insecurity within the Basin. The water availability situation will be worsened by a growing population (projected to double by 2050 – SADC-GMI, 2020) and this comes with increased demand for food, translating to increased irrigation, consequently imposing a higher demand for water resources whose amount and availability will be impacted by climate variability and change.

The specific objective of the Project is to enhance the capacity in SADC and its member states to collaboratively and effectively manage integrated transboundary groundwater and surface water resources.

1.2. Description of the study area

The EKK-TBA extends from eastern Botswana into western Zimbabwe, is mainly located between latitudes 17° S and 22° S and longitudes 23° E and 29° E and covers approximately 127 000 km^2, of which 65% is in Botswana and 35% is in Zimbabwe. The EKK-TBA system was redefined from an original size of 34 000 km^2 and now straddles two river basins: Okavango and Zambezi, which calls for joint governance and management efforts between Botswana and Zimbabwe. Figure 1.1 shows the location of the EKK-TBA within southern Africa and Figure 1.2 shows the position of the EKK-TBA within Botswana and Zimbabwe and that of Bulawayo City, towns, villages and Rural District Councils within and just outside the new EKK-TBA. The current population of the new EKK-TBA is estimated at 595 278 (SADC-GMI, 2020).

1.3. Methods and data collection

A composite of data acquisition approaches was employed in response to the spread of data sources, data availability and restrictions imposed by the Covid-19 pandemic. Data quality issues were attended to before it was utilized.

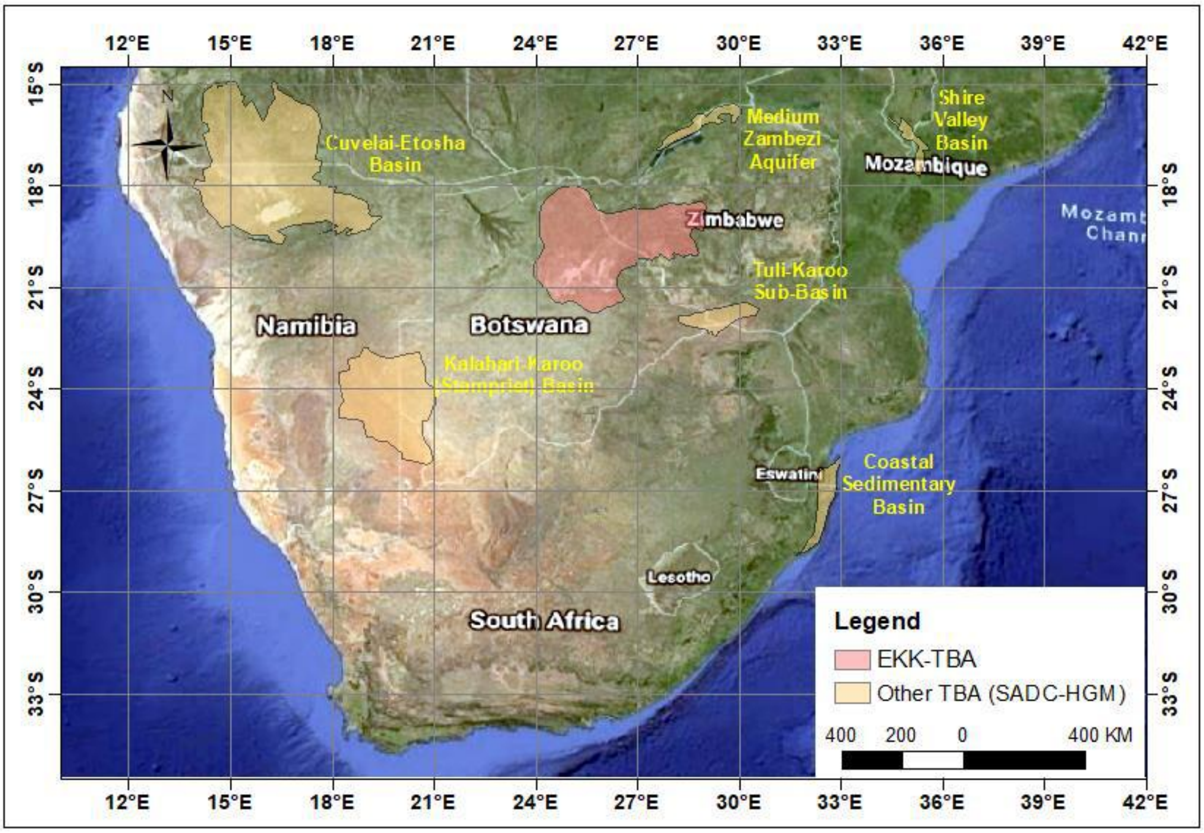


Figure 1.1: Location of the EKK-TBA in Southern Africa
Source: SADC-HGM (2010); SADC-GMI (2020)

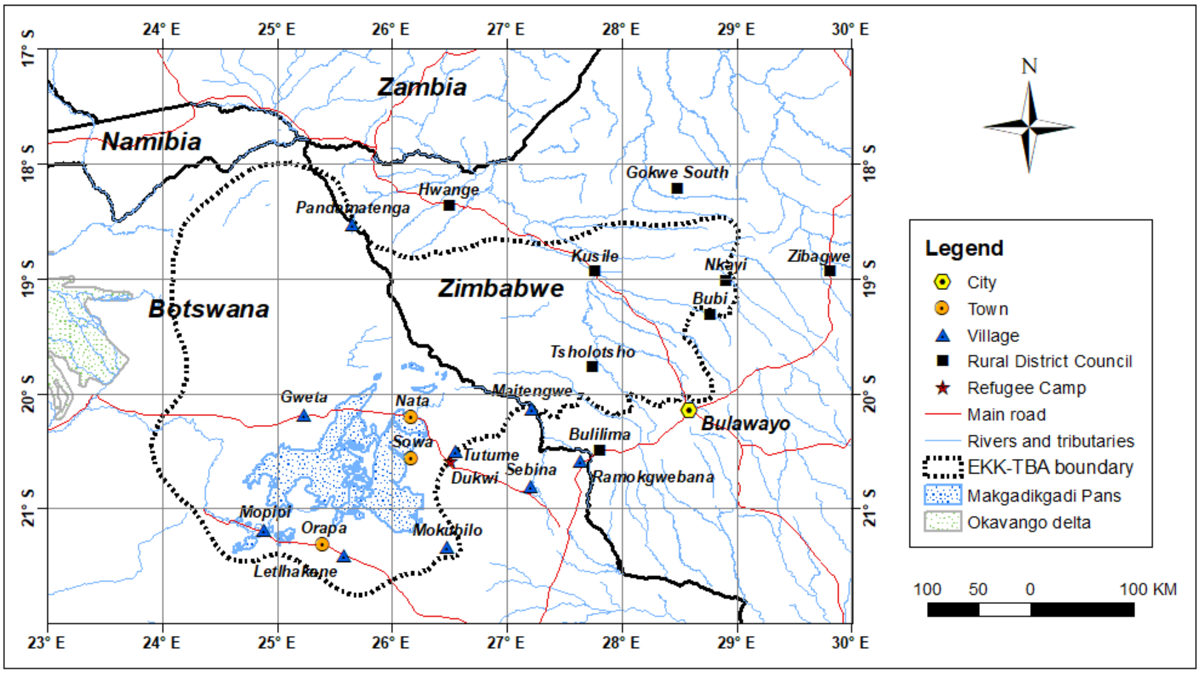


Figure 1.2: Location of the EKK-TBA within Botswana and Zimbabwe
Source: SADC-GMI (2020)

1.3.1. Data and information acquisition and limitations

Data and information acquisition: Data and information acquisition was through available literature (peer reviewed publications and internal organisational reports). The focal persons were the conduits through which monitored data such as climate and groundwater levels and hydro-chemical data and borehole abstractions was meant to be provided. Unfortunately, (field) visits could not be conducted, and neither could some of the required data be collected due to the constraints imposed by the Covid-19 pandemic and this mostly affected Zimbabwe. A substantial amount of crucial data and information was obtained although some key gaps remained, likely due to the reality that many of the desired data and information are simply not in existence and/or 'confidential' to be shared and if so, defeats the purpose of acquiring/collecting the data in the first place.

Data and information limitations: Attempts to understand the EKK-TBA is constrained by the reality that i) there are often major limitations on the availability of groundwater data and information, ii) poor quality of some of the available data and iii) the EKK-TBA is mainly located in fairly remote and sparsely populated regions of the two countries, and data tends to be scarce. Further, when data do exist, they come in varying forms. At times, they are not digitized but remain in handwritten form in a physical folder or technical report. Also, ensuring proper data quality requires a thorough and critical evaluation with checks and balances, and this seems to be lacking in both countries.

Advances and limitations of this report: The major advancements of this report are that it provides a consolidated overview of the EKK-TBA as a whole and show cases major gaps and proposes the setting up of a basin wide monitoring network among other recommendations. The hydrogeological relationship between the major wellfields in the EKK-TBA has been established. However, the report does not provide detailed hydrogeological information on each of the aquifer units on a basin wide perspective due to lack of data and information in certain parts of the basin. However, hydrogeological inferences have been done based on the available data and information and the consultant's experience in the region.

1.3.2. Data and information availability and quality control

In order to understand the regional perspective, borehole (BH) data and information for the area was obtained from Botswana, Namibia, Zambia and Zimbabwe in electronic format. Similar information was also obtained from the SADC-HGM project (2010) which is the same as that in the SADC-GMI Groundwater Information Portal (GIP). Table 1.1 provides the status of hydrogeological information in the SADC-HGM (2010) borehole database within the area bounded by longitudes 22 and 30 degrees East and latitudes 16 and 22 degrees South. Filtering of usable data was carried out as shown in Table 1.1.

Table 1.1: Status of hydrogeological information in the SADC-HGM borehole database

			Botswana	Namibia	Zambia	Zimbabwe
		Total No. BHs	**1 736**	**1 352**	**395**	**4 940**
Elevation difference: DEM - SADC-HGM (m amsl)		Range: From-To	-14 to 50	-2 to 7	No elevation data in HGM	-14 to 19
		No. BHs	199	43		138
		Mode (No. BHs)	-1 (56)	1 (22)		1 (79)
No difference		No. BHs	1 537	1 309		4 802
Filtering process	Depth to SWL	No. BHs	1 580	971	395	2 398
	SWL<0	No. BHs	0	0	1	0
	BH depth<=SWL	No. BHs	61	1	0	0
	BH depth-SWL (0-1)	No. BHs	15	1	1	0
	SWL>250m	No. BHs	4	0	0	0
	Depth to SWL	**Selected BHs**	**1 500**	**969**	**393**	**2 398**
	BHs with no depth info.	**Selected BHs**	**92**	**543**	**34**	**110**
	Lithology	**Selected BHs**	**304**	**0**	**62**	**1 989**
	EC	**Selected BHs**	**1 235**	**290**	**0**	**0**

Note that the depths to static water level (SWL) may represent different aquifer units since there is little information on the separate aquifers being tapped. Overall, the information on lithology is poor and scanty and is lacking for Namibia. Information on groundwater salinity (EC) is lacking for Zambia and Zimbabwe. Also note the lower density of BHs with information on SWLs or data scarcity in the central to northern part of the EKK-TBA, Figure 1.3.

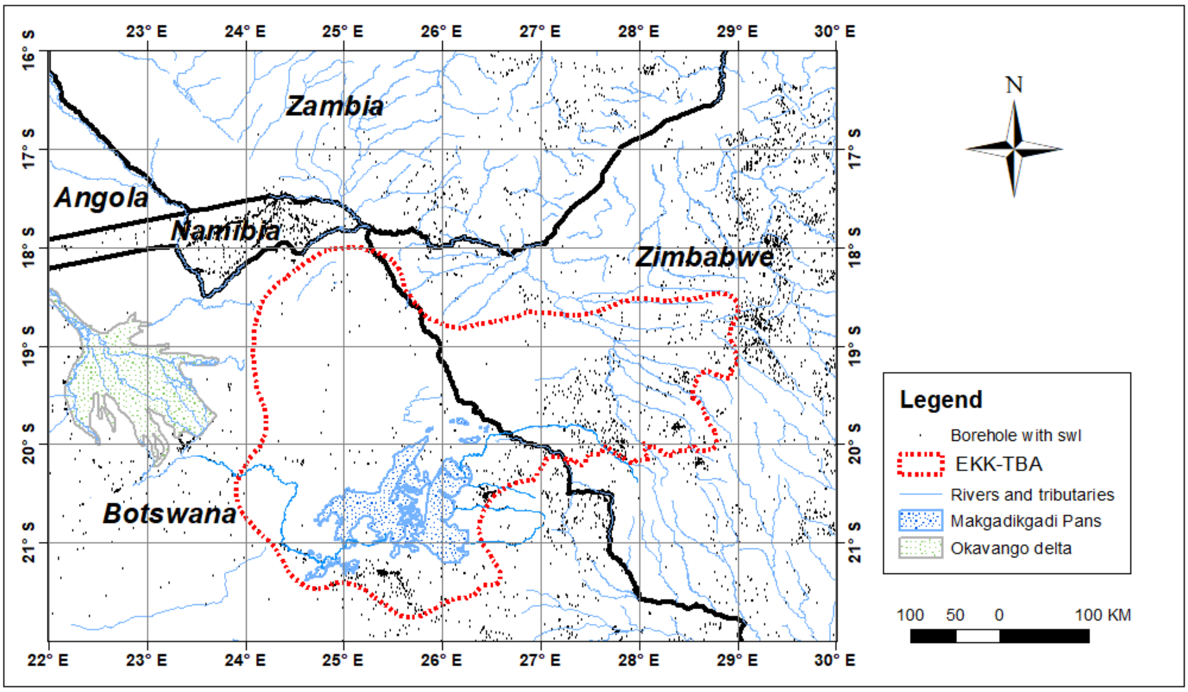


Figure 1.3: Distribution of boreholes with swl data
Source: SADC-GMI (2020)

2. CLIMATE

This chapter presents data sources and the quality of key climatic variables, mainly rainfall and temperature and their trends, and evapotranspiration for the EKK-TBA (SADC, 2020).

2.1. Data sources and quality of data

A combination of locally/field measured and remotely collected data provided the key data sources. Data gaps posed challenges during analysis.

2.1.1. Data sources

Data from six (6) climate stations in the EKK-TBA were available for analysis (4 from Botswana and 2 from Zimbabwe) as shown in Table 2.1 and Table 2.2. In addition, data from the Climate Research Unit (CRU) Version 4.04 dataset (http://www.cru.uea.ac.uk/data; Harris et al., 2020) were used to complement the limited data that was available. The climate dataset used are rainfall, and minimum and maximum temperatures. Virtual climate stations were assumed at the centre of each grid as shown in Figure 2.1, and in total, seventy nine (79) virtual stations were established in such a way that they covered the whole EKK-TBA and the surrounding area. The virtual stations were meant to assist with the determination of spatial climate trends over the EKK-TBA. While the CRU data starts from 1901, the data period selected for the EKK-TBA was 1970-2019, which represents a period where historical climatic observations was available in both countries.

Table 2.1: Characteristics of climate data from five stations in the EKK-TBA

Station name	**Kasane**	**Pandamatenga**	**Letlhakane**	**Sua Pan**	**Nyamandlovu**
Country	Botswana	Botswana	Botswana	Botswana	Zimbabwe
Longitude (deg. E)	25.15	28.63	25.58	26.06	28.27
Latitude (deg. S)	17.82	17.82	21.42	20.53	19.87
Rainfall					
Data period	1980-2018	1997-2016	1993-2018	1991-2018	1932-1999
% Missing data	2.1	0	0.6	3	0
T-max					
Data period	1989-2019	1998-2019	1994-2019	1992-2019	-
% Missing data	1.8	1.7	1.7	1.7	-
T-min					
Data period	1989-2019	1998-2019	1994-2019	1992-2019	-
% Missing data	3.5	1.9	3.2	2.6	-

Source: data obtained from national governments

2.1.2. Quality of climate data

As shown in Table 2.1, almost all the datasets have missing values. Although the percentages of the missing values are low, they present a challenge if analyses were to be done on a shorter time step such as daily as there would be many missing values that would represent major data gaps. Further, analysis of the data revealed other challenges, for example, the presence of questionable or doubtful data. In some cases, low temperatures of less than 2 °C were recorded for the whole month of March, which is impossible given the known climatic conditions of the area and such data was ignored in the analysis. This further brings to the fore the credibility of the data considered 'acceptable'.

One of the stations in Botswana had questionable daily rainfall values for one of the months, where the monthly total rainfall was more than 1200 mm which is impossible for a semi-arid region in which no extreme rainfall events were recorded or experienced during the same period. Other issues relate to duplicate values, for example, a single day had dual records which had different values. It is therefore advisable that data handling institutions dedicate time and resources to data quality control (DQC) in terms of its completeness, consistency, accuracy, validity, and timeliness. Good quality data yield reliable predictive outcomes. Similarly, the users should be aware of the quality of the data before carrying out any detailed analysis, interpretation and reporting on the results since flawed data would yield inaccurate results from which wrong decisions would be formulated or based on.

2.2. Temperature

Five climate stations with mean monthly minimum and maximum temperature data were available from the the EKK-TBA (Table 2.2 and Table 2.3).

2.2.1. Minimum temperatures

The least mean monthly mimimum temperature was obtained at Letlhakane station (6.84 °C, in July) and the highest was obtained at Sua Pan station (20.08 °C, in February), Table 2.2. In general, and on average, low temperatures occur in July (7.86 °C) while December appears to be warmer than other months (19.51 °C). The Gwayi Catchment data show that in Zimbabwe, high mean minimum temperatures are experienced in November (19.2 °C), while July has the lowest mean minimum temperature (8.3 °C). In general, minimum temperatures are low in Zimbabwe compared to Botswana, except for the winter months (April to September) in which the minimum temperatures are by and large, slightly higher than some stations in Botswana.

2.2.2. Maximum temperatures

Table 2.3 presents mean monthly maximum temperatures from the four stations in Botswana, and from Gwayi Catchment in Zimbabwe. For the stations in Botswana, the maximum temperature ranges between 24.51 °C at Letlhakane (in July) and 35.42 °C at Sua Pan (in October). In general, low maximum temperatures occur in July while high temperatures are experienced in October across all the stations. The mean monthly maximum temperature ranges between 29.83 °C at Pandamatenga and 30.72 °C at Sua Pan. Sua Pan is displaying warmer temperatures compared to other stations. Data from the Gwayi Catchment show that maximum temperatures are generally low in Zimbabwe (28.91 °C), compared with Botswana with a mean annual temperature of 30.31 °C. Highest maximum temperatures in the EKK-TBA are experienced in October and November whereas the lowest maximum temperatures occur in June and July.

Table 2.2: Mean monthly minimum temperature (°C) for climate stations

Month	Kasane	Pandamatenga	Letlhakane	Sua Pan	Gwayi Catchment	Mean
Jan	19.39	19.43	19.72	19.69	19.10	19.47
Feb	19.32	18.98	19.32	20.08	18.90	19.32
Mar	18.31	18.26	17.86	18.63	17.90	18.19
Apr	15.37	15.2	14.56	14.36	15.40	14.98
May	11.55	11.41	10.15	10.77	11.80	11.14
Jun	8.89	8.97	7.35	7.54	8.60	8.27
Jul	8.40	8.65	6.84	7.13	8.30	7.86
Aug	11.07	11.2	9.92	9.42	10.80	10.48
Sep	15.26	15.29	14.24	14.06	14.80	14.73
Oct	18.98	19.27	17.93	18.36	18.20	18.55
Nov	20.05	19.77	19.36	19.09	19.20	19.49
Dec	19.68	19.54	19.82	19.42	19.10	19.51
Min	**8.40**	**8.65**	**6.84**	**7.13**	**8.30**	**7.75**
Max	**20.05**	**19.77**	**19.82**	**20.08**	**19.20**	**19.93**
Mean	**15.52**	**15.5**	**14.76**	**14.88**	**15.18**	**15.16**

Table 2.3: Mean monthly maximum temperatures (°C) of climate stations

Months	Kasane	Pandamatenga	Letlhakane	Sua Pan	Gwayi Catchment	Mean
Jan	30.50	30.16	32.09	32.53	29.90	31.04
Feb	30.82	30.33	32.13	32.95	29.70	31.19
Mar	30.72	30.39	31.24	32.33	29.70	30.88
Apr	30.25	29.70	29.55	29.34	28.80	29.53
May	28.49	28.06	27.50	28.23	26.90	27.83
Jun	26.27	25.60	24.96	24.99	24.60	25.28
Jul	26.03	25.23	24.51	25.59	24.40	25.15
Aug	29.53	28.41	28.09	28.09	27.20	28.26
Sep	33.38	32.38	31.84	32.77	30.70	32.22
Oct	35.17	34.44	34.09	35.42	32.50	34.32
Nov	33.46	32.62	33.59	34.29	32.10	33.21
Dec	31.14	30.61	32.68	32.14	30.40	31.39
Min	**26.03**	**25.23**	**24.51**	**24.99**	**24.40**	**25.19**
Max	**35.17**	**34.44**	**34.09**	**35.42**	**32.50**	**34.78**
Mean	**30.48**	**29.83**	**30.19**	**30.72**	**28.91**	**30.30**

2.2.2.1. Spatial maximum temperatures

The limited information from the climate stations however, makes any reasonable spatial inference for the EKK-TBA difficult. The observed data were compared with CRU temperatures from virtual stations as shown in Figure 2.1. The seasonal variation is reasonably captured by the CRU data (matching of observed data and CRU data), with October generally displaying high temperatures while low temperatures are experienced in June and July.

Maximum temperatures from the CRU stations (Figure 2.1) show that the temperatures are higher in Botswana compared with Zimbabwe, with the western part of the EKK-TBA displaying high temperatures of more than 30 °C. Note that this spatial trend was also observed for mimimum temperatures.

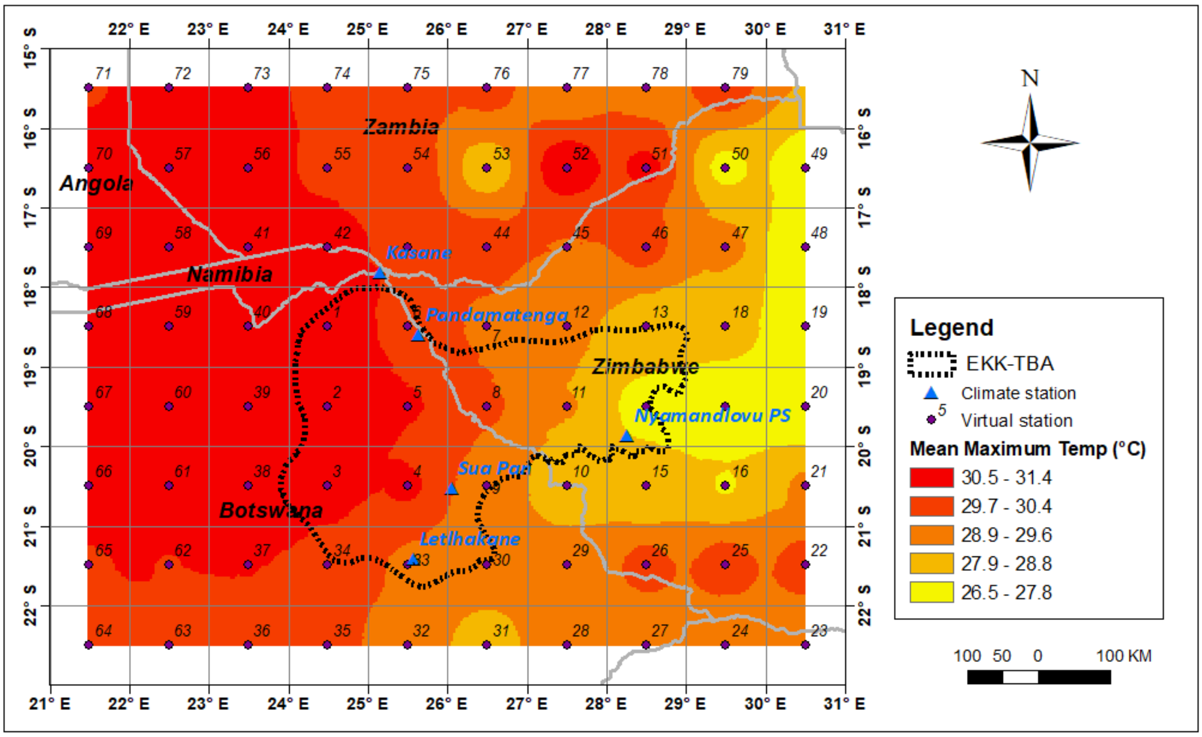


Figure 2.1: Mean monthly maximum temperatures from virtual stations

2.3. Rainfall

2.3.1. Monthly rainfall

Monthly rainfall values from the six climate stations are presented in Table 2.4 as well as the mean annual rainfall (MAR). It is clear from the table that rainfall occurs between October and April, with January having the highest rainfall (basin mean of about 128 mm) and July and August being the driest months.

Table 2.4: Mean monthly rainfall (mm) in the EKK-TBA

Month	Kasane	Pandamatenga	Letlhakane	Sua Pan	Nyamandlovu	Gwayi Catchment	Mean
Jan	136	133	96	122	127	156	128
Feb	126	100	84	84	101	136	105
Mar	67	62	48	56	65	88	64
Apr	20	19	19	18	24	26	21
May	3	4	4	4	5	5	4
Jun	3	2	9	13	2	1	5
Jul	0	0	0	1	0	0	0
Aug	0	0	0	0	1	0	0
Sep	1	1	3	4	4	3	3
Oct	19	15	13	13	25	20	18
Nov	74	49	51	53	90	72	65
Dec	118	112	69	81	119	140	106
MAR	**568**	**496**	**395**	**447**	**564**	**647**	**520**

The Botswana stations show that the mean annual rainfall ranges between 395 mm (at Letlhakane) and 568 mm (at Kasane), with stations in the north-eastern part of the EKK-TBA recording higher rainfall. Despite the limited number of climate stations that we had access to, the annual rainfall for the Nyamandlovu station (564 mm), and from the Gwayi Catchment[1] (647 mm), both in Zimbabwe, show that the Zimbabwean part of the EKK-TBA receives higher rainfall compared to the Botswana part of the EKK-TBA, which has a mean annual rainfall of 477 mm.

A high interannual variability was observed which is common in arid and semi-arid areas. The variability is also linked to rainfall uncertainty, which is expected to increase mainly due to climate variability and change.

2.3.2. Virtual stations rainfall data

In order to test the usefulness of the CRU dataset, rainfall values from the CRU were extracted at the same locations as the climate stations (Figure 2.2), with an assumption that the CRU would match or fit the observed rainfall well.

Since the climate stations are limited (limited spatial basin coverage), CRU data from the 79 virtual stations were used to better understand the regional rainfall distribution over the EKK-TBA and surrounding area (Figure 2.2). The point/grid rainfall with a resolution of 0.5^o x 0.5^o (same resolution as that of the CRU data) were then interpolated over the entire area using the inverse distance weighting (IDW) method in ArcGIS.

[1] The Gwayi catchment falls within Hydrological Zone A in Zimbabwe and consists of 25 sub-zones of the 151 subzones in the country (Zimbabwe National Water Authority, 2020).

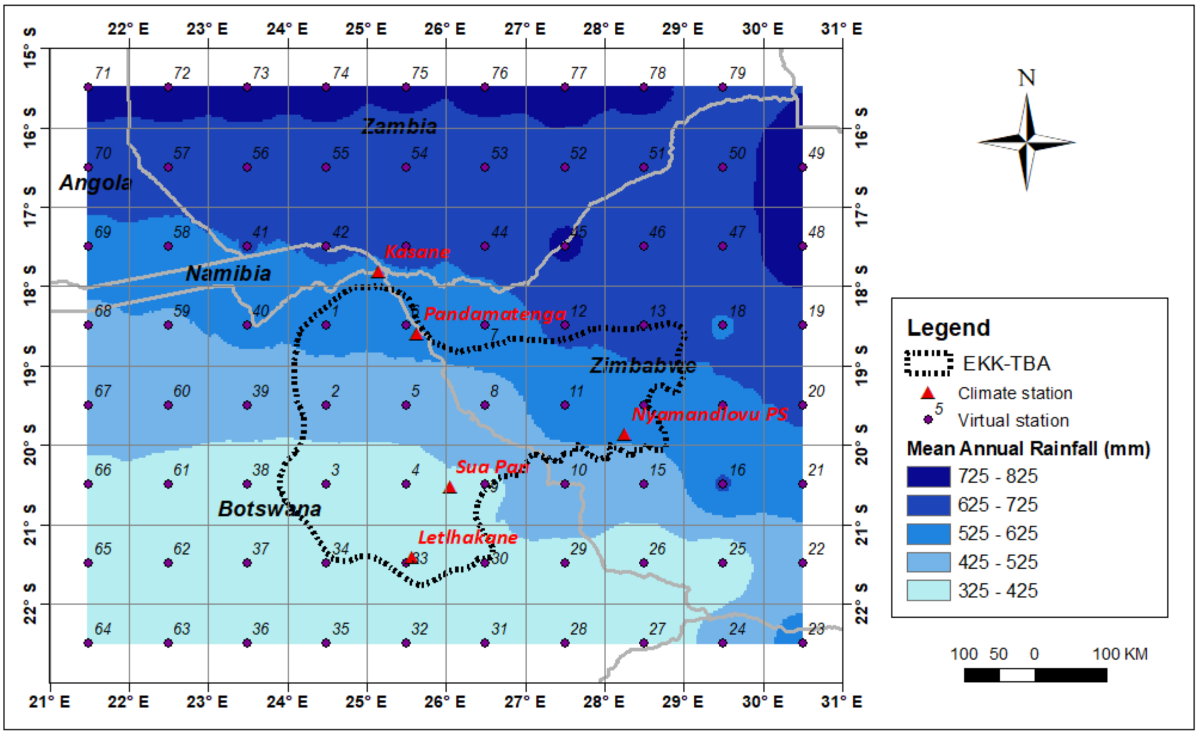


Figure 2.2: Mean annual rainfall from virtual stations

The monthly results (from January to December: 1-12) are plotted in Figure 2.3. The results show that the CRU data captures the seasonality of the observed rainfall and thus matches the observed rainfall fairly well. However, the magnitude of rainfall is overestimated by the CRU data for some of the stations such as Kasane (for January) and Pandamatenga (for almost all the months). The last plot (EKK-TBA) shows average values from the five climate and virtual stations.

To assess the CRU datasets further, annual time series from the CRU data were compared with station data, and the results are plotted in Figure 2.4. The CRU data mimics the observed data well, particularly for the Kasane, Letlhakane and Nyamandlovu stations despite minor discrepancies for certain years (particularly for very wet or dry years). The CRU data overestimates the rainfall for the Pandamatenga station. The last plot in this figure makes use of all the available datasets in the EKK-TBA and it shows that the long term inter-annual variability is well represented by the CRU data. There are no discernible rainfall trends within the basin except for the Pandamatenga station, which shows a decreasing trend for both observations and CRU data (although the CRU overestimates rainfall) (Figure 2.4).

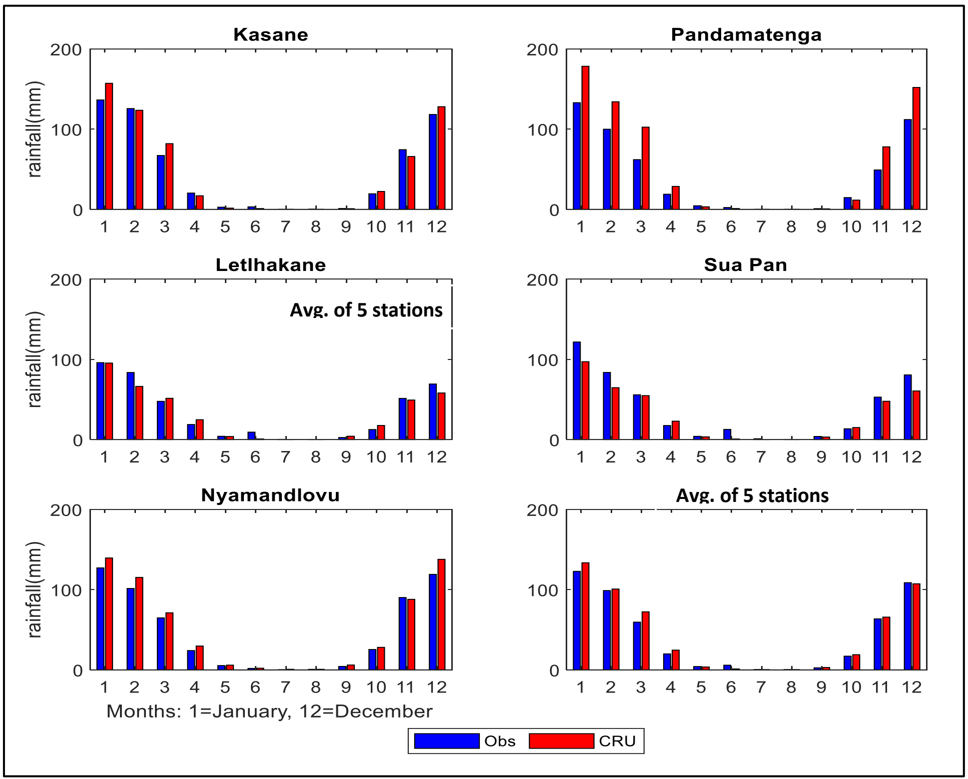


Figure 2.3: Mean monthly rainfall of climate (Obs) and virtual stations

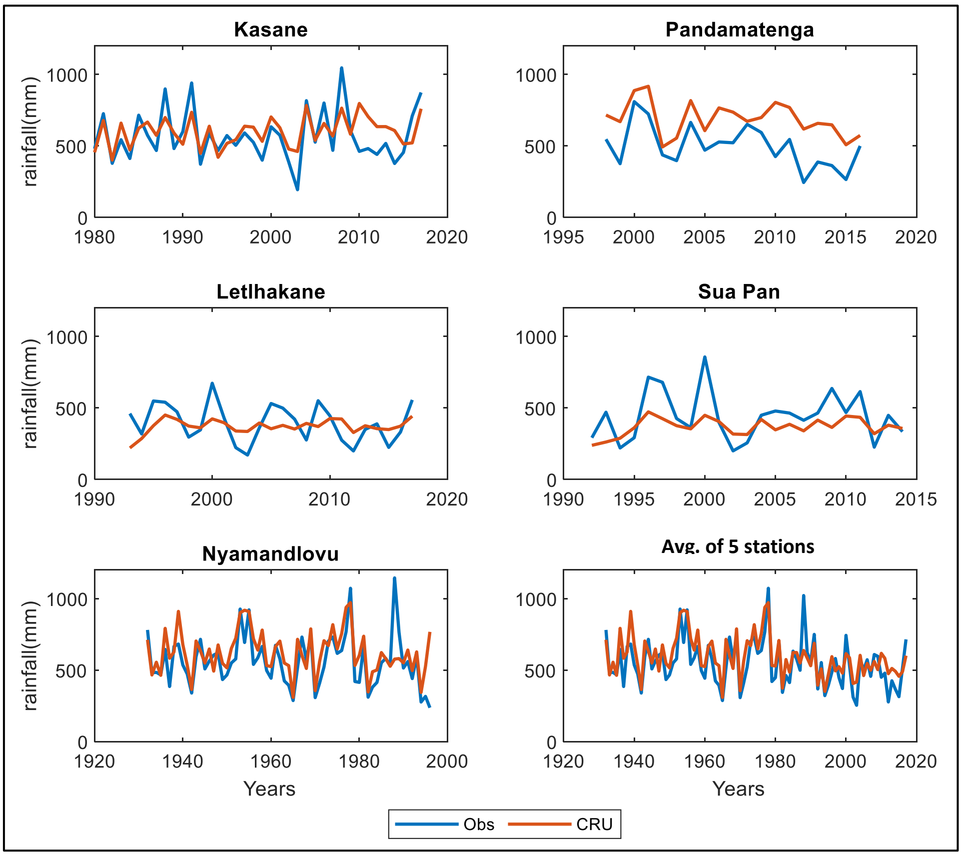


Figure 2.4: Annual rainfall of climate (Obs) and virtual stations

2.3.3. Spatial rainfall

Figure 2.2 shows increasing rainfall from the south (Botswana) to the north and north-eastern part of the EKK-TBA (Zimbabwe), ranging between mean annual rainfall of 327 and 680 mm/yr. The bulk of the rainfall barely exceeds 625 mm/yr. The rainfall values are reasonable given that the observed annual rainfall values recorded at Kasane and Nyamandlovu stations are about 568 and 564 mm respectively and are within the range of 525 and 625 mm depicted in Figure 2.2. Similarly, Letlhakane and Sua Pan rainfall values are reasonably represented by the interpolated rainfall from the CRU datasets as they also fall within the CRU range of 327 to 425 mm. It should be noted that long term mean annual rainfall data from climate stations do not show a statistically significant trend.

As pointed out earlier, there are only few stations for which data is available in the EKK-TBA. The reason for this could be two-fold, the first is that there are no additional monitoring stations in the basin and the second is that organisations are unwilling to provide data (climatic or meteorological data was impossible to obtain from Zimbabwe). The lack of adequate data restricts in-depth analysis and understanding of spatial rainfall (and other climate variables) trends in the EKK-TBA. However, the CRU datasets have shown that the CRU can be used as a source of data, which mitigates data unavailability.

2.4. Evapotranspiration

Monthly evapotranspiration (ET) for Botswana is generally higher than the ET for Zimbabwe with October having the highest values while June having the lowest, Table 2.5. Annual ET for the Letlhakane station in Botswana is 1 751 mm while the annual ET in the Gwayi Catchment on the Zimbabwean side of the EKK-TBA is 1 465 mm. The monthly ET based on CRU data is generally lower than the values at the Letlhakane station.

Table 2.5: Monthly evapotranspiration (mm) in the EKK-TBA

Months	Letlhakane Station	Letlhakane CRU	Nata Catchment	Boteti Catchment	Gwayi Catchment	Mean
Jan	171	161	141	158	127	151
Feb	150	142	126	139	108	133
Mar	154	144	130	144	119	138
Apr	129	123	114	127	106	120
May	116	111	104	116	95	108
Jun	97	92	88	100	81	92
Jul	103	98	93	107	92	99
Aug	131	125	118	134	123	126
Sep	158	151	142	161	156	154
Oct	185	175	163	185	175	177
Nov	179	168	153	171	154	165
Dec	179	167	145	165	129	157
Annual	**1 751**	**1 656**	**1 517**	**1 706**	**1 465**	**1 619**

3. TOPOGRAPHY AND SURFACE WATER DRAINAGE

3.1. Topography

The topography of the EKK-TBA is generally flat and ranges between 880 and 1 400 m amsl. A mountain range borders the Basin, running from the southeastern part to the east and northeastern parts of the Basin, Figure 3.1. Topographic gradients are highest in the east (~0.004) and shallowest in the central parts of the Basin towards the Makgadikgadi Pans (~0.0002). In the northeastern part of the Basin, rivers draining into the Zambezi River have incised steep valleys into the elevated ground, typical of the youthful stage of a river system.

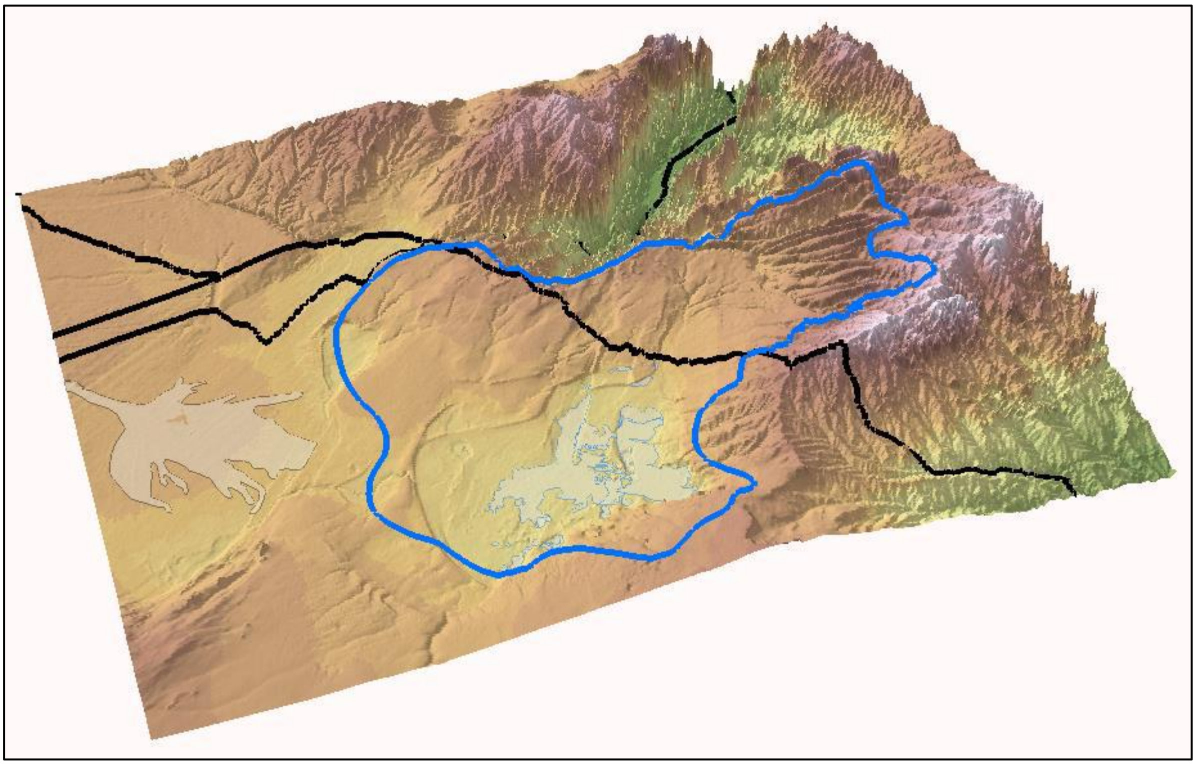


Figure 3.1: Digital Elevation Model (SRTM-30m) of the EKK-TBA and surroundings

The lowest part of the Basin lies in the south western part and is entirely in Botswana. This part is at an elevation of about 880 m amsl and is occupied by the Makgadikgadi Salt Pans.

3.2. Surface water drainage

The EKK-TBA covers part of the Okavango and Zambezi River Basins and is neighbouring the Limpopo River Basin on the southeastern side (Figure 3.2). The Okavango River starts from the highlands of Angola and flows through Namibia and terminates in the Okavango Delta in Botswana. The Zambezi River arises in Zambia and flows through eastern Angola, along the northeastern border of Namibia and the northern border of Botswana, then along the border between Zambia and Zimbabwe, and through Mozambique to the Indian Ocean. The Limpopo

River originates from South Africa and flows into Botswana, Zimbabwe and Mozambique to drain into the Indian Ocean. The EKK-TBA is linked to the Okavango River system on the west by the Boteti River which drains into the Makgadikgadi Pans (Figure 3.2). Similarly, on the eastern side, the Nata River, which originates from Zimbabwe, flows into the Makgadikgadi Pans. The Gwayi River in the eastern part of the EKK-TBA (in Zimbabwe), with the Khami and Umguza Rivers as tributaries in its upper reaches, flows northwest towards the Zambezi River. The Okavango and Zambezi River Basin Organisations are both key in the management of water resources in the EKK-TBA.

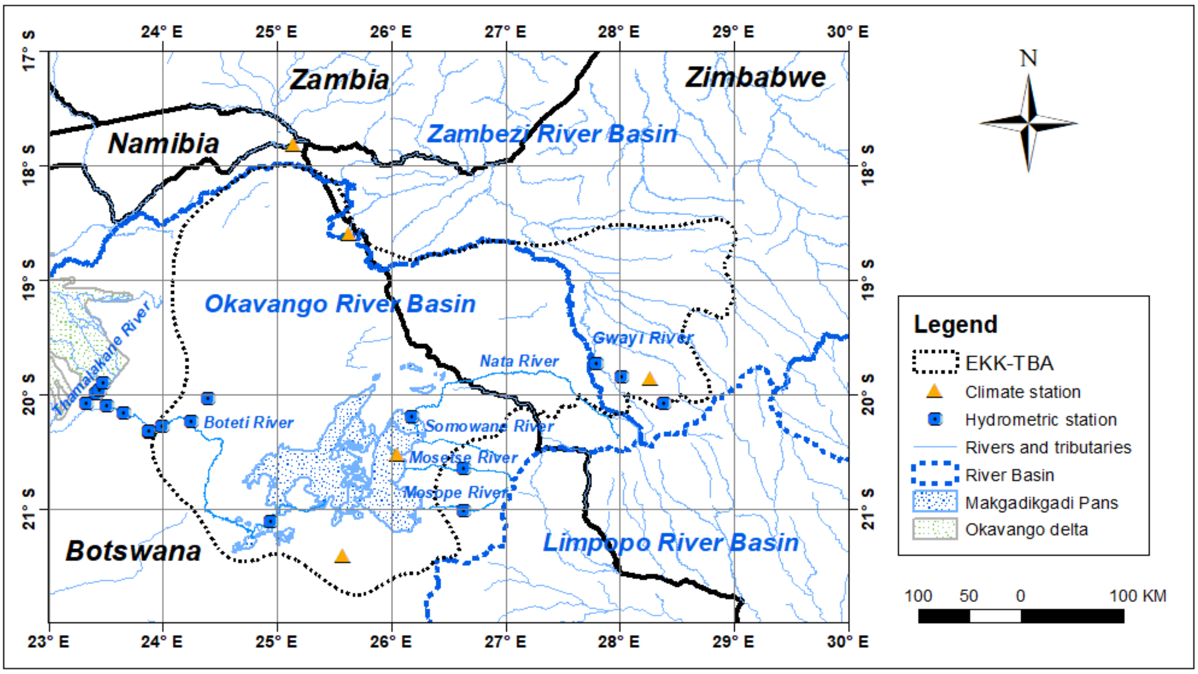


Figure 3.2: Surface water drainage in the EKK-TBA

3.2.1. Nata River

The Nata River, an ephemeral river, with flows only produced between December and March (Table 3.1), is mostly located in Zimbabwe (where it is also known as Manzamnyama River) and is the largest of the rivers draining into the Makgadikgadi Pans (MLWS and MLIT, 2018). In Zimbabwe, the Nata River is outside the Gwayi catchment, and has a mean annual runoff of 152.9 Mm^3 and drains an area of about 21 216 km^2 (DSM, 2000). The Nata River cannot be developed as a major water source in Botswana due to the relatively flat topography and generally low ephemeral flows (DWA, 2006; MLWS and MLIT, 2018). The only realistic development of the river could be an off-river storage system or could be developed for managed aquifer recharge.

As one of the major sand rivers in Botswana, the depth of sand exceeds 7 m in many sections along the Nata River channel (DSM, 2000). When the Nata River flows, it carries a substantial volume of water. Flow is highly variable: in 1948 the river did not flow at all but two years later, in 1950, the total annual runoff was 1 423.06 Mm^3 (*ibid*).

Table 3.1: Monthly streamflow of Botswana's EKK-TBA rivers

		Nata River	Boteti River	Thamalakane River	Khami River		Gwayi River
Runoff	**Station / Month**	**Nata Old Bridge**	**Same-dupe**	**Maun Bridge**	**Slights Weir**	**Porter**	**Gwayi Tjolotjo Weir**
Average Monthly Runoff (m3/s)	Jan	26.3	2.2	2.2	1.2	2.7	7.0
	Feb	20.3	2.1	2.5	1.0	3.1	9.3
	Mar	8.7	2.1	5	0.5	1.6	4.1
	Apr	1.4	2.7	6.4	0.1	0.4	0.5
	May	0.1	3.4	8	0	0.05	0.05
	Jun	0	6.7	11	0	0.02	0.03
	Jul	0	13.3	14.5	0	0.01	0.01
	Aug	0	16.5	14.9	0	0.01	0
	Sep	0	14.1	12.5	0	0	0
	Oct	0	10.1	8.7	0.1	0	0
	Nov	0.02	6	5.9	0.1`	0.01	0.8
	Dec	3.7	3.7	3.3	0.2	0.7	3.6
Average Annual Runoff	m^3/s	5.0	6.9	7.9	0.3	0.7	2.1
	Mm^3	158.7	217.9	249.4	16.8	43.7	131.4

3.2.2. Thamalakane River

The Thamalakane River (Figure 3.2) receives its flows from the Okavango River, and flows along the Thamalakane Fault in a southwesterly direction, acting as a collector channel for several rivers that receive outflow from the Okavango Delta (Gomoti, Santantadibe, Boro, Shashe and Nxotega), with the major flow coming from the Boro River. The Thamalakane River also provides a link between the Okavango and Boteti Rivers. The flow is concentrated between June and September, with the peak flow normally occurring between July and August (Table 3.1) during the dry period. The flow is generated from the highlands of Angola through the Okavango Delta in Botswana and does not coincide with the rainy season in Botswana. Figure 3.3 shows a weak declining trend in runoff between 1970 and 2016 for the Thamalakane River but clearly shows distinct wet and dry periods, with the latter running from 1993 to 2008.

3.2.3. Boteti River

The Boteti River (Figure 3.2) derives its flow from the Thamalakane River at the foot of the Okavango Delta and then flows towards the Makgadikgadi Pans. The flow generally occurs between June and October with the peak occurring in August (Table 3.1). The Boteti River has many gauging stations (10) compared to any other river in the EKK-TBA, Figure 3.2. Most stations, however, have incomplete data. Figure 3.4 also shows a weak declining trend in runoff between 1970 and 2016 as well as wet and dry periods, with the latter running from 1993 to 2008.

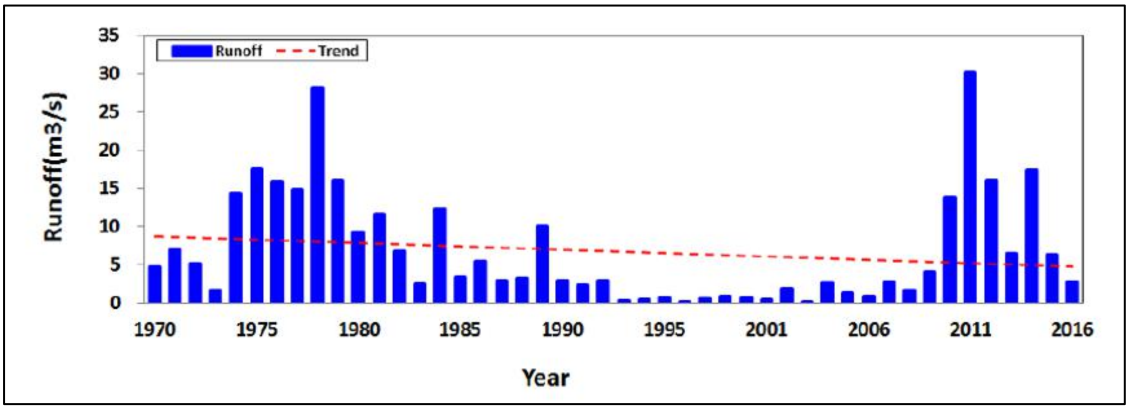


Figure 3.3: Flow of the Thamalakane River
Source: (MLWS)-Botswana and (MLIT) Korea (2018)

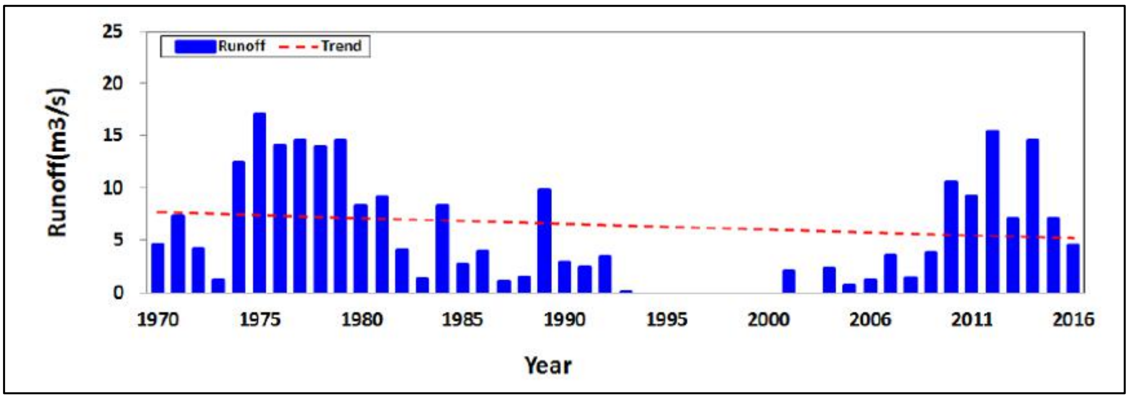


Figure 3.4: Flow of the Boteti River
Source: MLWS and MLIT (2018)

In 2010, the Boteti River flowed after some 20 years of no flow and the flow was captured by NASA[2] on 29th September 2010 as a historical newsworthy event (Figure 3.5). Note that the river stopped short of the Makgadikgadi Pans, which lies to the east in the image.


Figure 3.5: Boteti River flow
Source: NASA[2]

[2] https://earthobservatory.nasa.gov/images/46309/boteti-river-botswana

3.2.4. Gwayi River system

The Gwayi Catchment in Zimbabwe has 25 sub-zones including the Nyamandlovu area and is classified as hydrological zone A. The catchment covers an area of 87 960 km^2 (ZINWA[3]) and has an altitude ranging from 600 to 1 500m, Figure 3.6. The Gwayi River system, which flows through the EKK-TBA in the east, drains into the Zambezi River. The mean annual runoff for the Gwayi Catchment ranges between 4 and 36 mm (mostly between 4 and 10 mm within the EKK-TBA), Figure 3.6, and occurs between November and May, with the peak flow occurring between January and February. Compared to other catchments in Zimbabwe, the Gwayi Catchment has the lowest runoff of about 1.8 x 10^6 Ml/year and this is projected to significantly decrease by 2050 due to climate change (Davis and Hirji, 2014).

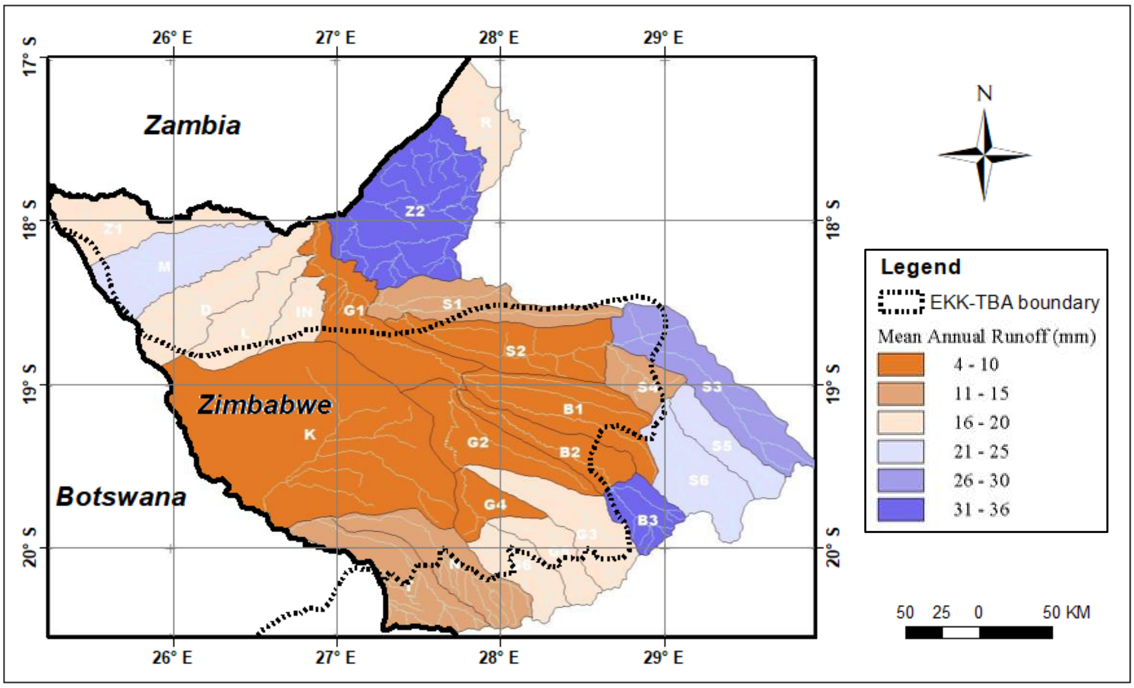


Figure 3.6: Mean annual runoff of sub-zones of the Gwayi Catchment
Source: modified after ZINWA[3]

The Khami River, which is a tributary of the Gwayi River, is gauged at two stations, the Slights Weir (upstream) and Porter (downstream). The Slights Weir has the longest time series (1951/52 to 2017/18) compared to the Porter station (1965/66 to 1987/88). The highest flow for the Slights Weir (Figure 3.7) was recorded in 2016/17, i.e. 3.9 m^3/s, followed by 1.6 m^3/s in 1954/55. There are also periods of low flows such as 1979/80 to 1986/87; 1989/90 to 1998/99 and 2015/16 which correspond to some of the worst drought periods experienced in southern Africa (Unganai and Kogan, 1998). These drought periods are also displayed in the Porter station time series flow (Figure 3.8).

[3] Zimbabwe National Water Authority (http://www.zinwa.co.zw/catchments/gwayi-catchment/)

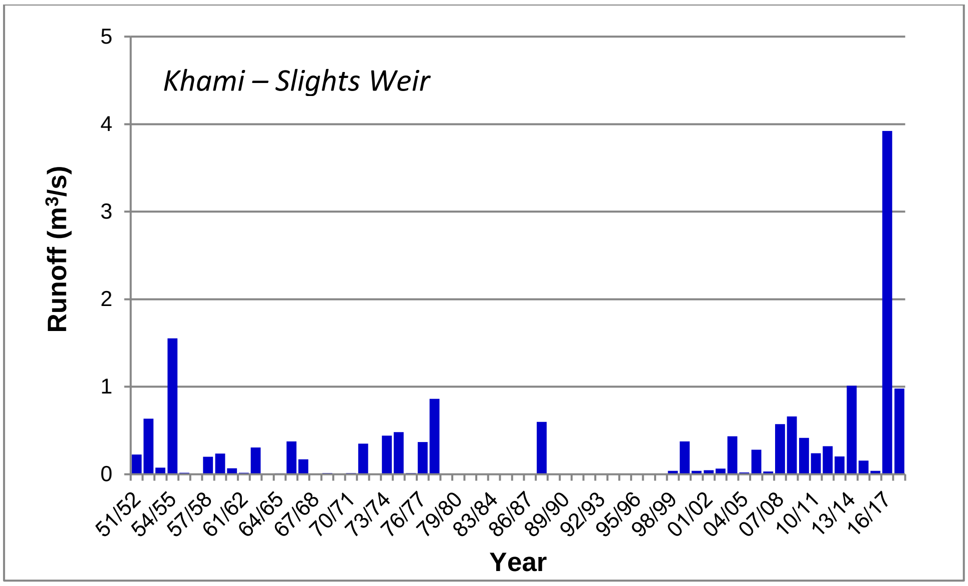


Figure 3.7: Flow for the Khami River at Slights Weir

Source: ZINWA

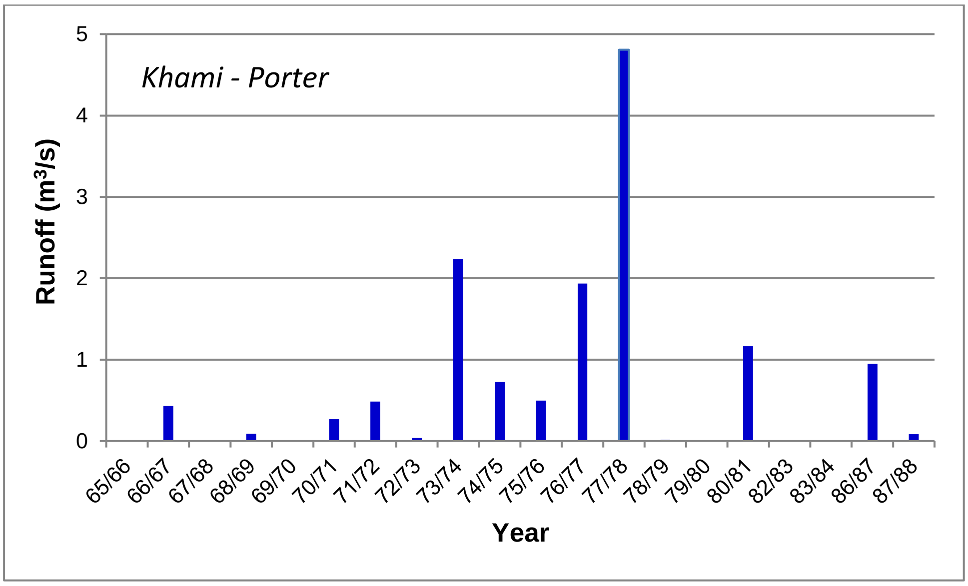


Figure 3.8: Flow for the Khami River at Porter

Source: ZINWA

The Gwayi River gauged at Tjolotjo Weir, which is downstream of the Khami River, has flows from 1953/54 to 1968/69 (Figure 3.9), with the 1954/55 year having the highest runoff of 13.5 m^3/s followed by 1958/59 and 1965/66 with 3.1 and 2.9 m^3/s, respectively. It is clear from this graph that runoff varies from year to year, with periods of high and low flows throughout the time series.

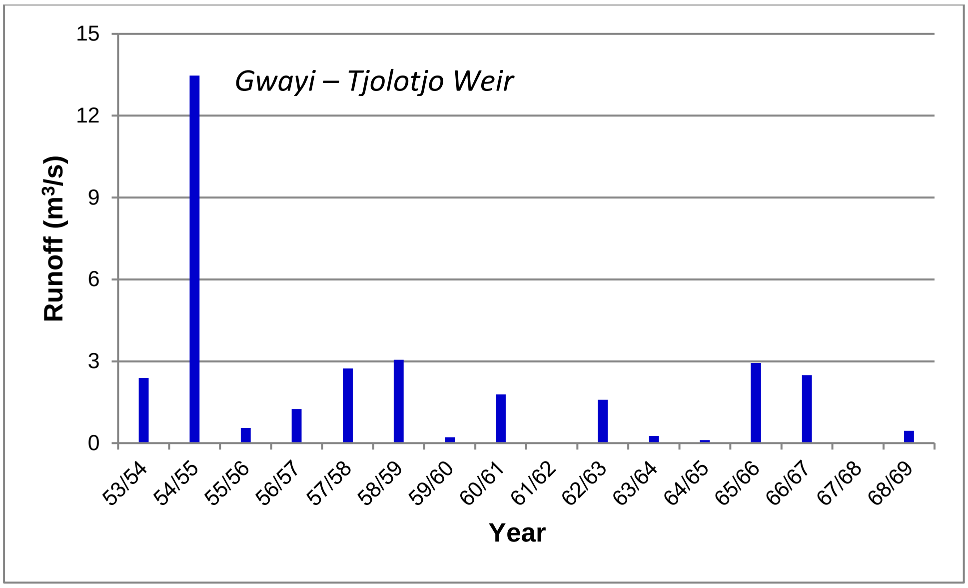


Figure 3.9: Flow for the Gwayi River at Gwayi Tjolotjo Weir
Source: ZINWA

3.2.5. The Makgadikgadi Pans

The Makgadigkadi Pans, occupying the lowest section of the Basin (880 m amsl), Figure 3.2 and Figure 3.10, form the discharge area of the surface drainage within the EKK-TBA.

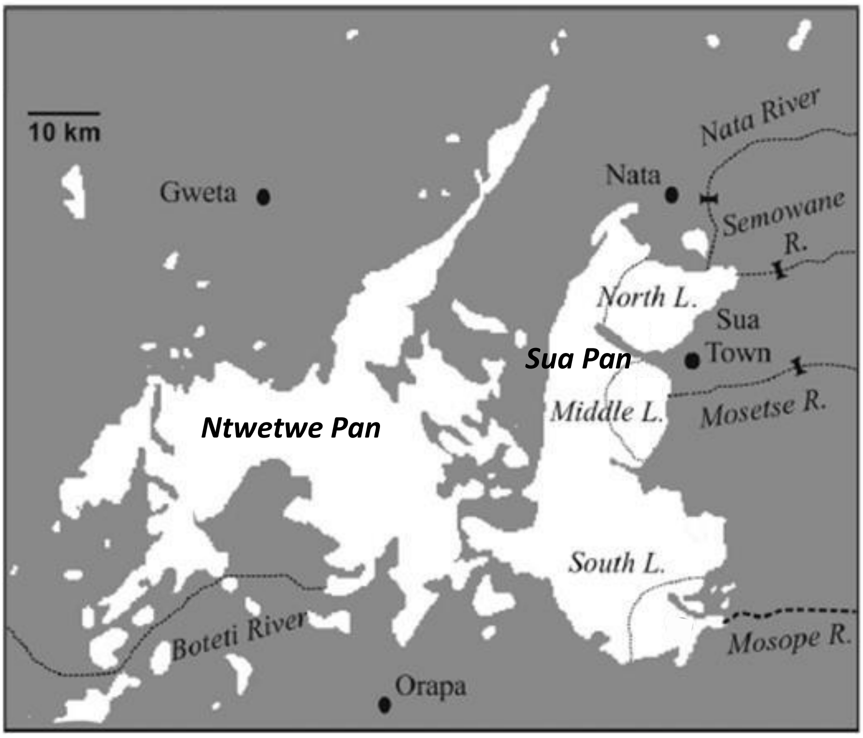


Figure 3.10: Rivers draining into the Makgadikgadi Pans
Source: modified after Eckardt et al. (2008)

The Pans are among the largest salt pans in the world and form an important destination for Botswana's tourism sector. The Pans are in part oriented along a Tertiary graben of the Pan African rift which in the past received water from the proto Zambezi resulting in a significant inland lake of around 66 000 km^2 in areal extent (Cooke, 1980). The surface water catchment area of the Makgadikgadi Pans extends into Zimbabwe in the east through the Nata River system. The Pans are also linked to the Okavango system in the northwestern side through the Boteti River. The Makgadikgadi wetland area is divided into the eastern Sua Pan and western Ntwetwe Pan. The eastern Sua Pan catchment receives inflows from the Nata River (with a catchment area of about 12 000 km^2), the Mosetse River (1 500 km^2), Semowane River (1 500 km^2), and Mosupe River (3 000 km^2). The northern end of Sua Pan undergoes the most pronounced seasonal flooding and drying and is subjected to significant subsurface brine extraction by the Botswana Ash (Pty) Ltd. company. The Ntwetwe Pan has a surface are of about 4 700 km^2 and is linked to an overflow from the Okavango Delta via the Thamalakane and Boteti Rivers.

3.3. Surface water quality

Land use plays a role in determining the quality of surface water in the area. The southern part of the EKK-TBA is a mining area, hosting the diamond mines of Orapa, Letlhakane and Damtshaa and the Soda ash and salt mine in Sowa town. In addition, the area has a significant number of livestock, mainly cattle and small stock (sheep and goats), particularly in communal areas. The main source of water is groundwater (from boreholes) and, occasionally, surface water from rivers and pans during wet periods. Commercial agriculture is also practiced, mainly in the Pandamatenga area, which is the grain basket of Botswana. These land use activities could be potential sources of surface water and groundwater pollution. Concentration of livestock in pans during wet periods has led to increased nitrates in rivers and groundwater from animal excreta. Agrochemicals (fertilisers and pesticides) from the Pandamatenga farms may also affect water quality of both surface water and groundwater. Leachates from mines will also contribute to the deterioration of groundwater at a local scale if not managed properly.

3.3.1. Water quality of the Thamalakane and Boteti Rivers

Table 3.2 presents a time series of pH measurements of river water samples taken by the Department of Water and Sanitation from March 2009 to November 2013 (Statistics Botswana, 2016). The tests were done at 32 points along the rivers, and were mostly carried out monthly, with the longest period between subsequent tests being four months (*ibid*). Water is considered acidic when the pH is below 5.6 and alkaline when the pH is above 7.0. The BOS 32: 2009 standard for irrigation water is between pH 6.5 and 8.4 and this standard was used as a proxy for environmental waters of the Thamalakane-Boteti Rivers (*ibid*). The recommended limit of pH 8.4 was exceeded in 2 of the 240 tests carried out, which were of May 2011 and April 2012. The recommended limit of pH 6.5 was exceeded in 93 of the 240 tests carried out (i.e. 39% of the tests) (Statistics Botswana, 2016). The source of the acidity was not identified and could pose problems to farmers relying on this water for irrigation.

Table 3.2: pH of Thamalakane-Boteti River Channel surface water: 2009-2013

Date (yr-mth)	No. of stations tested	No. below 6.5	No. above 8.4	% below 6.5	% above 8.4	Date (yr-mth)	No. of stations tested	No. below 6.5	No. above 8.4	% below 6.5	% above 8.4
09-Mar	7	0	0	0	0	**11-Mar**	8	0	0	0	0
09-Apr	7	0	0	0	0	**11-May**	16	0	1	0	6.3
09-May	7	0	0	0	0	**11-Aug**	14	3	0	21.4	0
09-Jun	6	0	0	0	0	**11-Oct**	14	0	0	0	0
09-Jul	6	0	0	0	0	**12-Jan**	13	13	0	100	0
09-Sep	6	0	0	0	0	**12-Mar**	11	11	0	100	0
10-Jan	6	0	0	0	0	**12-Apr**	8	0	1	0	12.5
10-Feb	6	0	0	0	0	**12-May**	11	1	0	9.1	0
10-Mar	7	0	0	0	0	**12-Aug**	5	5	0	100	0
10-May	7	6	0	85.7	0	**12-Sep**	7	7	0	100	0
10-Jun	6	6	0	100	0	**12-Dec**	11	0	0	0	0
10-Jul	6	3	0	50	0	**12-Mar**	6	0	0	0	0
10-Aug	6	5	0	83.3	0	**13-May**	10	10	0	100	0
10-Sep	6	6	0	100	0	**13-Aug**	4	4	0	100	0
11-Jan	9	9	0	100	0	**13-Nov**	4	4	0	100	0

Source: Statistics Botswana (2016) [4]

Table 3.3 shows that all samples were within the Botswana Bureau of Standard (BOS) limits except one sample that exceeded the limit for Manganese (Mn).

Table 3.3: Suitability of Thamalakane-Boteti River Channel water

Parameter	Number of tests done	Limit or guide range	Number over the limit or outside the range	Reference standard
TDS (mg/l)	229	2 000	0	BOS 463:2011
EC (µS/cm)	240	3 000	0	BOS 463:2011
K (mg/l)	21	100	0	BOS 32:2009
Ca (mg/l)	184	200	0	BOS 32:2009
Mg (mg/l)	184	100	0	BOS 32:2009
Mn (mg/l)	29	0.2	1	BOS 463:2011
Cl (mg/l)	142	350	0	BOS 463:2011
NO_3 (mg/l)	137	30	0	BOS 463:2011
SO_4 (mg/l)	137	200	0	BOS 463:2011

Source: Statistics Botswana (2016)

[4] The tests were undertaken by the Department of Water and Sanitation between March 2009 and November 2013

3.3.2. Water quality of the Gwayi River system

As part of developing a strategy for managing water quality and protecting water sources, the Ministry of Lands, Agriculture, Water and Rural Settlement of Zimbabwe, with the support of the World Bank, commissioned a study to conduct a rapid assessment of water quality in pilot areas using specialised tools and techniques (including Remote Sensing, Geographic Information Systems (GIS) and field sampling) as well as identifying pollution hotspots nationwide between March and April 2013. The water quality results for the Gwayi Catchment have not yet shown any major problems as they were all below the World Health Organisation (WHO) guidelines for drinking water (Murwira et al., 2014).

3.3.3. Water quality in the Makgadikgadi Pans

Although there are numerous small pans in the Makgadikgadi Pans area, there are two major distinct pans, known as Ntwetwe Pan and Sua Pan (Figure 3.10). The Sua Pan holds an estimated 8 013 Mm^3 of deep fossil brine (DEA and CAR, 2010). Botswana Ash (Pty) Ltd., which operates the Soda Ash mine in Sua Pan, pumps from over 90 well points in the northern basin of Sua Pan and aims to expand southward of their current well field (*ibid*).

At the river mouths with the Makagadikgadik Pans, the water is generally more saline compared to that found elsewhere in the Kalahari. During wet periods, the pans receive flood waters which pond for a few months of the rainy season to become temporary lakes. The floodwater in the pans and soil leaches have similar chemical composition with regards to Mg^{2+}, HCO_3^- and Ca^{2+}, although floodwaters are not as rich in K^+ as soil leaches, and these fresher waters are largely of the $Ca-HCO_3$ type (Eckardt et al., 2008). The salty floodwater is comparable with soil leaches from the saline pan margin ($Ca-Na-HCO_3$) (*ibid*). Early floods appear to dissolve pre-existing salts in riverbeds or pan margins as is the case with the Nata River, where high dissolved loads and $Na-Cl$ water type mark the first Nata River flood (*ibid*). Accumulation of salts is presumed to occur in dry seasons in areas of shallow groundwater discharge.

After high initial $Na-Cl$ water concentrations for Nata River flood water, the chemistry of seasonal inflow into Sua Pan can be characterised as being $Ca-HCO_3$ type, while concentrated lake waters produce $Na-Cl$ brines found in the pans. For this reason, mineral precipitation and dissolution may account for much of the initial flood water chemistry in the Nata River (Eckardt et al., 2008). It has also been found that soils in the catchment add much of the Ca^{2+}, HCO_3^-, Mg^{2+} and K^+ to floodwater while SO_4^{2-} in subsurface brines is probably derived from bedrock (possibly from igneous rocks and Proterozoic sedimentary rocks as well as Cambrian sea water (*ibid*). $Na^+$and Cl^- are thought to be provided by marine atmospheric sources and are subject to significant seasonal pan surface recycling (*ibid*). Analysis of groundwater from below the subsurface brines, close to the pan surface and beyond the pan margin will provide further information about the precise origin of the subsurface brine (*ibid*).

Calcium and magnesium contribute to calcite and dolomite precipitation in the lake pan environment. The deep-seated brine appears to be spatially homogenous in the Sua Pan and is pumped by BotAsh (Botswana Ash (Pty) Ltd.[5]) from a depth of 38 m to produce soda ash and salt ($NaCl$, Na_2CO_3, Na_2SO_4 and $NaHCO_3$). The TDS of brine in Sua Pan can be as high as 190 000 mg/l.

3.3.4. Surface water – Groundwater interaction

3.3.4.1. Boteti River

Mitiku (2019) investigated surface water – groundwater (SW-GW) interactions in the Boteti River system in Botswana using integrated hydrological modelling between the hydrological years of 2016 and 2017. The interactions were analyzed based on model results of water leakage into and out of the groundwater system. In their study, they established that interaction (exchange of water) occurred between the river and groundwater throughout the simulation period. The total loss of water from the Boteti River to the shallow Kalahari Aquifer system throughout the two hydrological years was 67 mm and the direct or indirect groundwater discharge to the Boteti River was 99 mm. As a result, the river was gaining water from the aquifer throughout the simulation period with a net water gain of 32 mm. The SW-GW interactions in the Boteti River area were found to be dependent on inflows from the Okavango Delta system.

For this study we carried out baseflow separation for streamflow at the Samedupe station on the Boteti River using the Nathan and McMahon method (1990) as applied by Ebrahim et al. (2019). The results and rainfall from the Maun station are plotted in Figure 3.11.

A baseflow index (BFI), determined as the ratio of baseflow to total streamflow was established at 0.299 (or 30%). This indicates that baseflow accounts for about 30% of the total river flow in the Boteti River, supporting the findings of Mitiku (2019), that there is indeed SW-GW interaction between the Boteti River and groundwater. No baseflow separation was carried out for the Nata River system as the hydrographs showed that there was no baseflow contribution in these ephemeral rivers.

[5] https://botash.bw/about-botash/

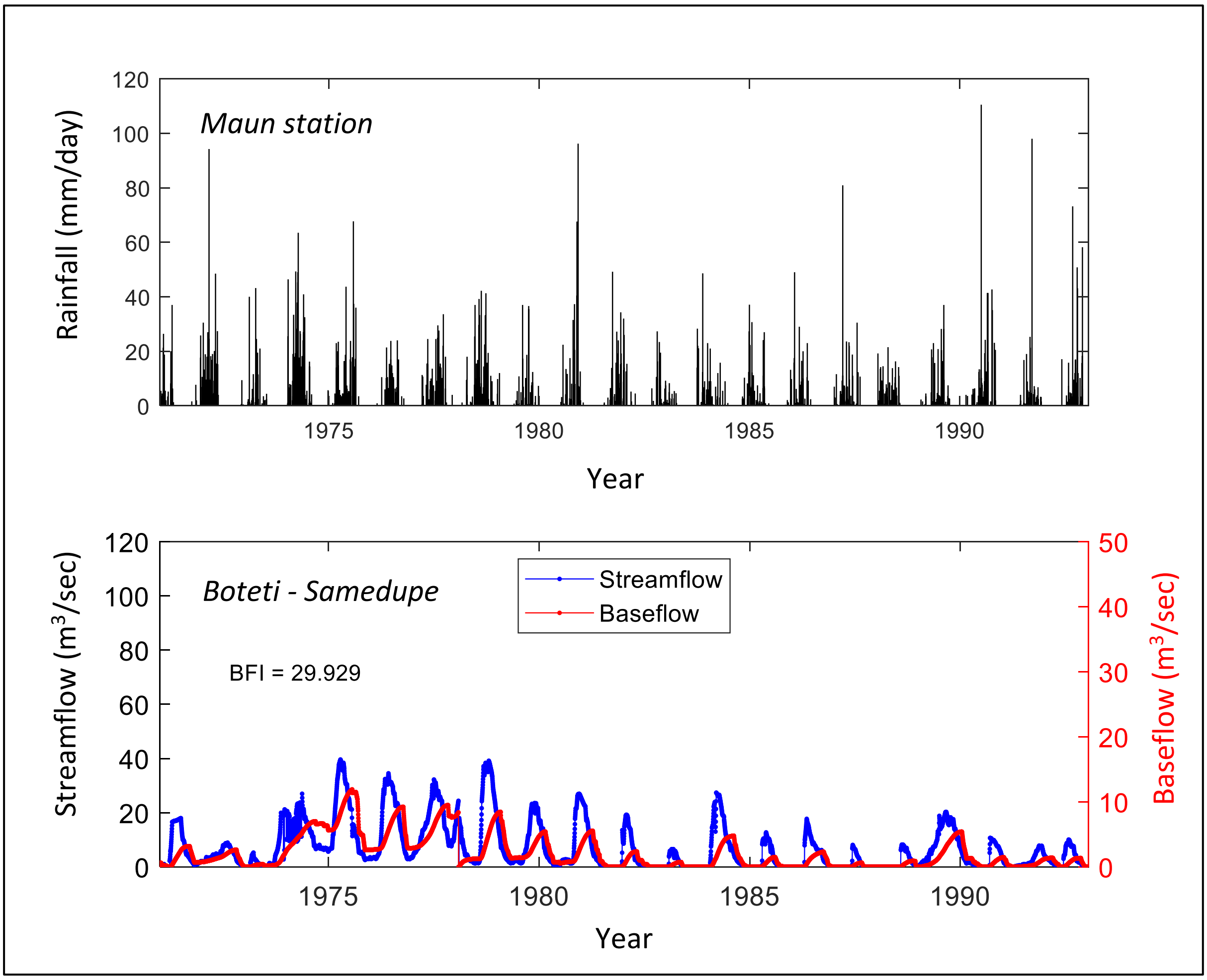


Figure 3.11: Baseflow separation for Boteti River flow at Samedupe station

3.3.4.2. Gwayi River System

Figure 3.12 and Figure 3.13 represent baseflow separation at three gauging stations of the Gwayi River System. BFI values are generally low: 9.8% for the Khami River at Slights Weir, 12.2% for the Khami River at Porter, and 11.3% for the Gwayi River at Tjolotjo Weir. The slightly higher BFI at the Porter station compared with the Slights Weir is likely the result of additional groundwater contribution from the Nyamandlovu aquifer. The baseflows are not sustained beyond a flood event. To obtain more insight into the streamflow and baseflow characteristics, daily rainfall data from the Nyamandlovu Police station were plotted with the flow hydrographs. The streamflow generally occurs in response to rainfall events. Note that there are also regulated releases from upstream reservoirs during the dry season.

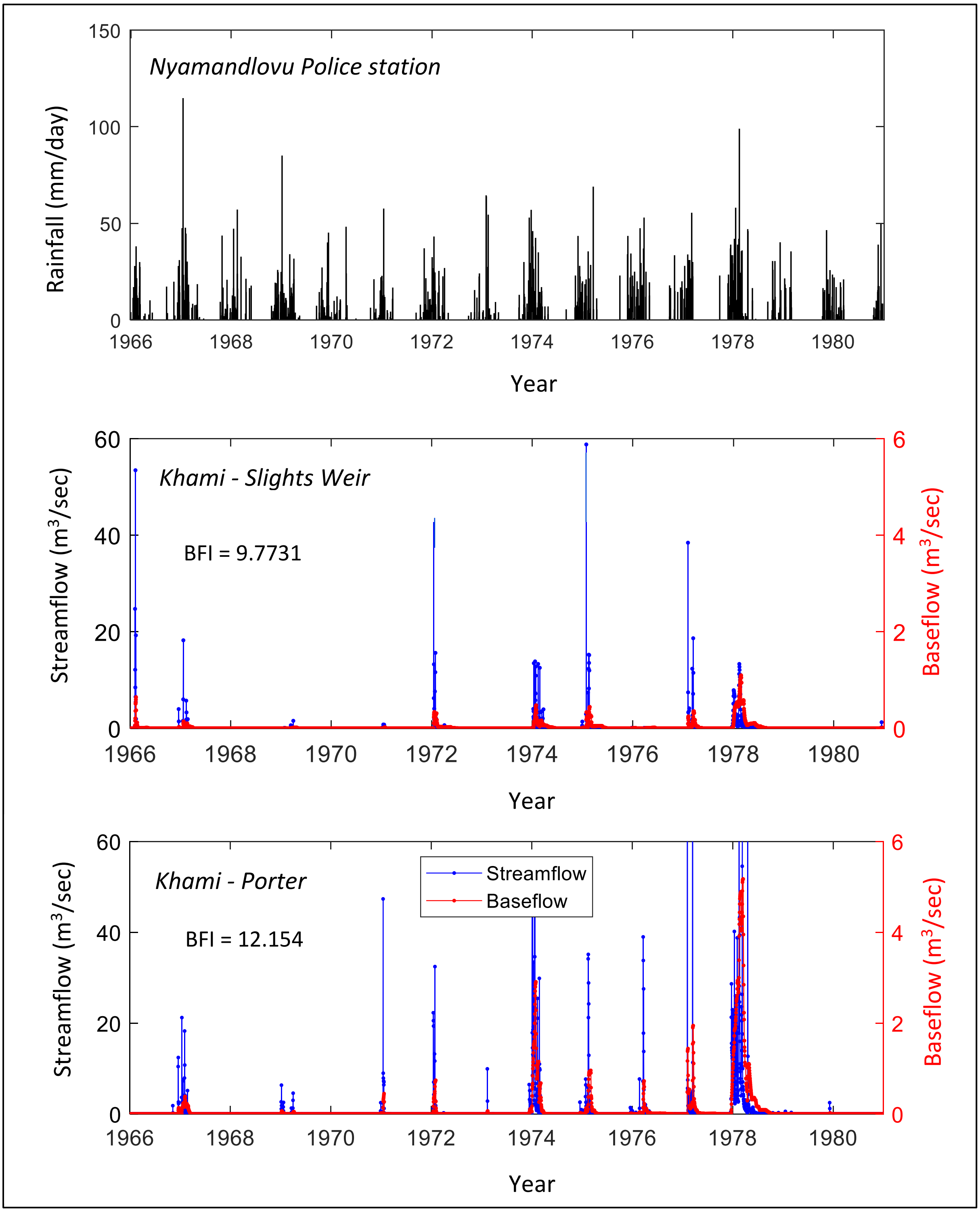


Figure 3.12: Baseflow separation Khami River at Slights Weir and Porter stations

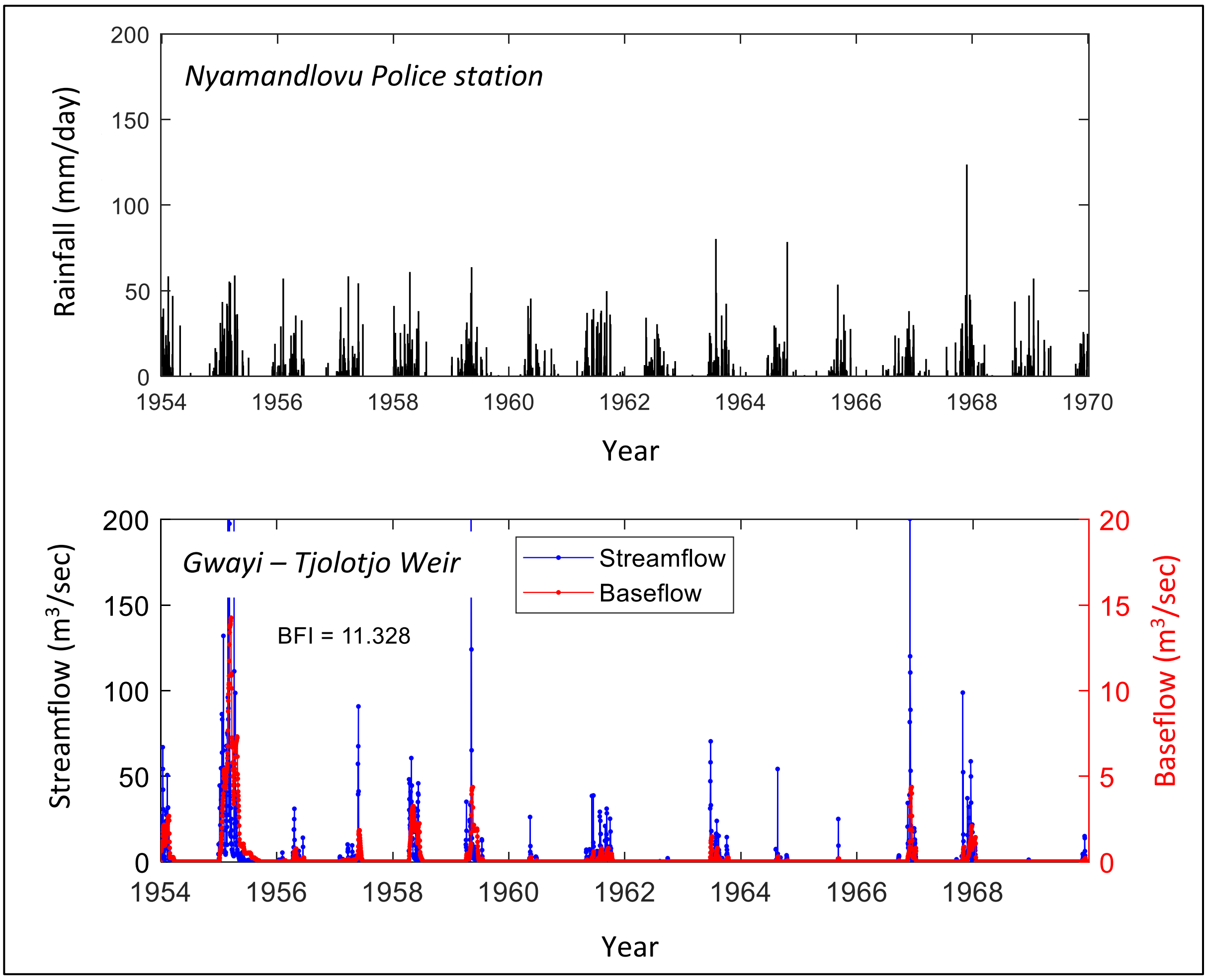


Figure 3.13: Baseflow separation Gwayi River at Tjolotjo Weir

4. STRATIGRAPHY AND STRUCTURAL GEOLOGY

4.1. Overview

The Karoo Basin is regarded as an intracratonic basin which forms part of the southerly extension of the northeast African structural feature (Visser, 1995). The Basin comprises a huge graben, with an areal extent of about 4.5 million km^2 and has several large inland basins on the Precambrian continental shield (Beasley, 1983; Johnson et al., 1996). The Basin formed as a result of subduction and orogenesis along the southern border of southern Africa in the then southern Gondwanaland and sediments of mainly fluviatile origin were deposited (Karoo Supergroup), Figure 4.1.

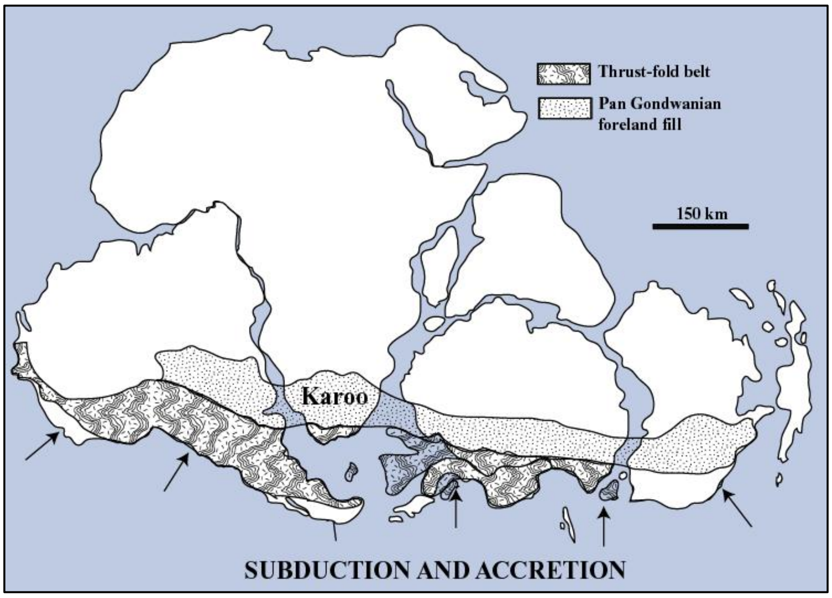


Figure 4.1: The breakup of Gondwana
Source: Nxumalo (2011)

In the mid- to late-Cretaceous the margins of southern Africa were uplifted whilst block-faulting in northern Botswana and subsidence of the newly formed interior Kalahari Basin to the north of the Kalahari-Zimbabwe Uplift Axis (occurring to the south of the EKK-TBA) took place thereafter (Haddon and McCarthy, 2005). Presumably, this uplifting resulted in the formation of horsts along the margins of the EKK-TBA, whereas the subsidence of the central part of the EKK-TBA created grabens and deep depressions. After the Karoo Supergroup, the Kalahari Group was deposited under alternating dry and wet climate conditions during the Quaternary period.

Figure 4.2 shows the current distribution of the Karoo aged basins in southern Africa. The sediments in the basins are comprised of a wide range of lithologies with varying thicknesses, which reach about 12 km in the southern part of the Main Karoo Basin in South Africa (Johnson et al., 2006).

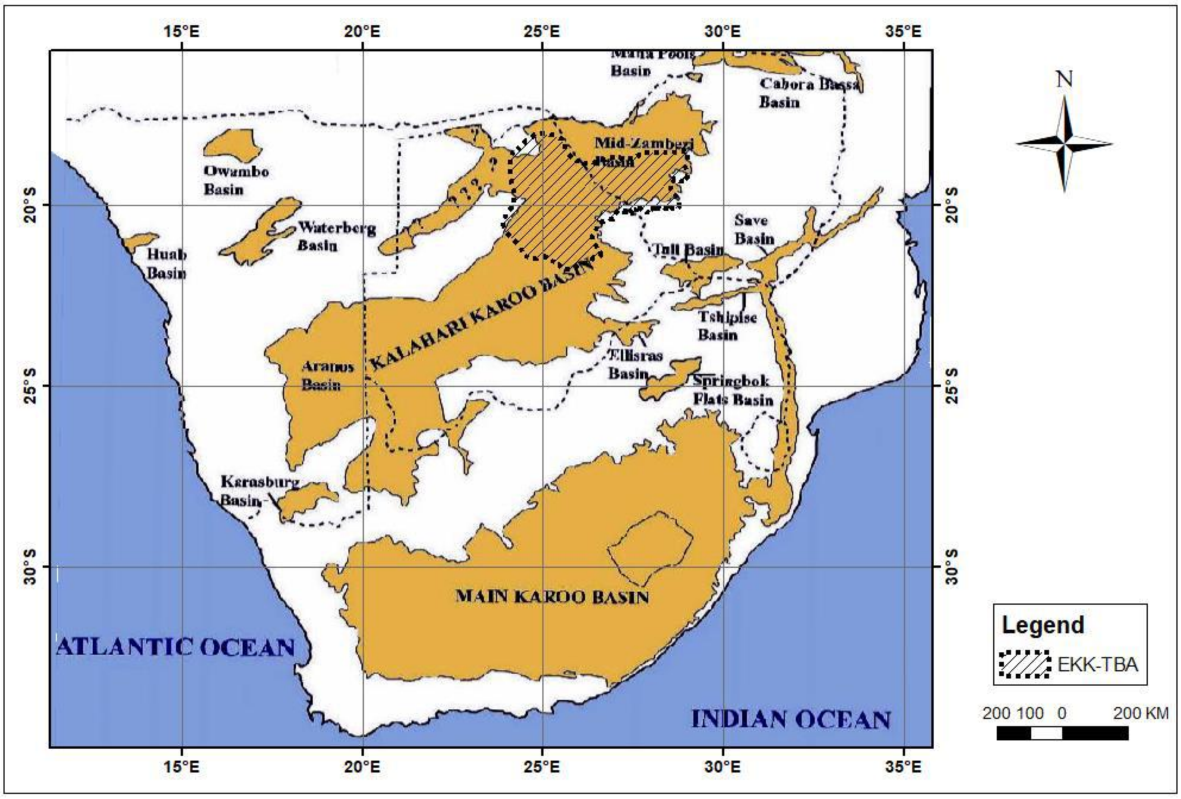


Figure 4.2: Distribution of Karoo-aged basins in southern Africa
Source: modified after Johnson et al. (1996)

4.2. Lithostratigraphy

4.2.1. Data Sources

Borehole data from the EKK-TBA was obtained from SADC-HGM (2010) and from the Zimbabwe National Water Authority to assist in constructing the lithological cross sections. In general, the boreholes are relatively shallow, often ranging from around 40 to 80 m, and drilled into the Kalahari Group deposits. There are few boreholes reaching a depth of 120m.

Borehole information with lithological contacts and thicknesses was also obtained for the wellfields located on the fringes of the Basin (Dukwi, Letlhakane, Maitengwe, Nyamandlovu and Orapa). These boreholes were drilled through the Upper Karoo formations and in some instances, reaching the deeper formations of the Ecca Group.

The 1:2 500 000 SADC geological map (Council for Geoscience, 2009) was used as the base map for the EKK-TBA study area, from which a simplified EKK-TBA legend was derived, Table 4.1. The EKK-TBA legend includes i) an Upper Karoo sequence with the Ntane and Forest Sandstone Formations (Stormberg Group), and the Stormberg/Batoka Basalt and ii) a Lower Karoo sequence containing the Dwyka Group, Ecca Group including the Mea Arkose and Wankie Sandstone Formations and the Beaufort Group. The various Archean and Proterozoic rocks have been grouped under Basement Complex.

4.2.2. Karoo Supergroup

The EKK-TBA straddles across the Mid-Zambezi and the NE Kalahari-Karoo Basins and is surrounded in the north, east and south by elevated Basement Complex of various metamorphic and intrusive rocks.

The Karoo Supergroup comprises the most prevalent lithostratigraphic unit in southern Africa and mainly consists of non-marine sequences deposited over a period of 120 million years between the Late Carboniferous and Early Jurassic (Schlüter, 2008). The depositional environments of the Karoo Supergroup are marine (tillite turbidites, shale), deltaic (shale, mudstone), fluvial (sandstone, siltstone, mudstone) and aeolian (sandstone) (*ibid*).

Table 4.1: Simplified EKK-TBA geological legend

	SADC Legend	**EKK-TBA Legend**	
Qa	Quaternary; alluvium, sand, gravel, calcrete	Quaternary sediments; alluvium, sand, gravel, calcrete	
Nk	Kalahari Group; Aeolian sand, sandstone	Kalahari Group; Aeolian sand, sandstone, limestone	
Jdr	Drakensberg Basalt, Lebombo Group	Basalt (Stormberg/Batoka)	**Upper Karoo**
Jc	Clarens Formation; sandstone, siltstone	Ntane/Forest Sandstone	
Tre	Elliot Formation; mudstone, sandstone	Mosolotsane Equiv. (Escarpment grit to Pebbly Arkose Fms, Figure 4.4); mudstones	
Trm	Molteno Formation; mudstone		
Pb	Beaufort Group; mudstone, sandstone	Beaufort Group; mudstone, sandstone	**Lower Karoo**
Pe	Ecca Group; shale, mudstone, sandstone, coal	Ecca Group (incl. Mea Arkose and Wankie Sandstone Fms); shale, mudstone, sandstone, coal	
Cd	Dwyka Group; tillite, mudstone, sandstone	Dwyka Group (Dukwi Formation); tillite, mudstone, coal, sandstone	
P1S	Palapye Group, Soutpansberg Group	Basement Complex	

The sediments originated from the erosion of the surrounding higher ground into the tectonically formed basins and were eventually capped by basaltic lava flows (Stormberg / Batoka Basalt). The sequence can be classified into two main units, the Lower Karoo and Upper Karoo. These can further be stratigraphically divided into the following groups or systems: (i) Dwyka Group, (ii) Ecca Group, (iii) Beaufort Group and (iv) Stormberg Group.

The lithostratigraphic units are briefly discussed below for each of the countries.

4.2.2.1. Lower Karoo

The Lower Karoo sequence comprises three groups: the basal Dwyka Group which is overlain by the Ecca Group and in turn by the Beaufort Group which forms the uppermost sequence.

4.2.2.1.1. Dwyka Group

Botswana

The Dwyka Group in the NE Kalahari-Karoo Basin is represented by the Dukwi Formation consisting of diamictites and overlies the basement (Smith, 1984).

Zimbabwe

The presence of the basal glacial beds of the Dwyka Group is found in practically all the Karoo sequences. The deposits comprise gravels, boulders, reworked tills and stoney clays that were irregularly deposited on the pre-Karoo floor (Stagman, 1978) and were intersected in boreholes drilled at Sawmills, Tsholotsho and Insuza valley *(ibid)*. Outcrops occur in the Mafungabusi area around Gokwe where the Group's thickness reaches 100 m. In Hwange, the glacial beds are overlain by Lower Wankie sandstone (60m) (Stagman, 1978; Beasley, 1983).

4.2.2.1.2. Ecca Group

Botswana

The Ecca Group in the NE Kalahari-Karoo Basin is subdivided into three formations: the lower Tswane Formation conformably overlying the Dukwi Formation, comprising grey and black mudstones and siltstones, the middle Mea Formation consisting of coarse-grained feldspathic sandstones (arkosic in nature); and the upper Tlhapana Formation containing carbonaceous mudstones and coal seams with subordinate sandstone and grey-brown mudstones (Smith, 1984).

Zimbabwe

The Ecca Group comprises three formations: Black Shale and Coal Group, Fireclay and Upper Wankie Sst. Formation. The Black Shale and Coal Group is a basal carbonaceous unit of black shale and coal seams, 70 m in thickness and overlain by a 30 m thick coarse gritty sandstone of the Upper Wankie Sandstone Formation. Around Hwange area, a 25 m thick Fireclay Formation is interbedded between the Black Shale and Coal Group and the Upper Wankie Formation (Stagman, 1978). A 120 m thick layer of Lower Madumabisa Mudstone Formation overlies the Upper Wankie Sandstone Formation and comprises dark grey shales and mudstones intercalated with thin layers of limestone and sandstone which forms the upper formation of the Ecca Group (Beasley, 1983; Stagman, 1978).

4.2.2.1.3. Beaufort Group Equivalent

Botswana

In the NE Kalahari-Karoo Basin, the Tlhabala Formation is the equivalent of the Beaufort Group and is approximately 90 m thick and consists of dark grey basal mudstone with minor carbonaceous partings, coaly streaks and siltstone lenses (Smith, 1984).

Zimbabwe
The Beaufort Group equivalent is represented by the commencement of the deposition of the Middle Madumabisa Mudstone Formation consisting of calcareous and nodular grey mudstones with an average thickness of 240 m (Stagman, 1978). The Upper Madumabisa Mudstone Formation with an average thickness of 180 m overlies the Middle Madumabisa Mudstones and consists of a lower succession of khaki coloured mudstones with numerous calcareous nodules and an upper part of well bedded grey and green siltstones and mudstones *(ibid)*. The Escarpment Grit, falling under Upper Karoo sequences (discussed under section 4.2.2.2.1) and which unconformably overlies the Upper Madumabisa Mudstones, caps off the deposition of the Beaufort Group.

4.2.2.2. Upper Karoo

There is no measurable angular discordance between the Lower Karoo Group and the Upper Karoo Group but the unconformity is widespread and well marked by a transgressive conglomerate (Stagman, 1978).

4.2.2.2.1. Stormberg Group

Botswana
In the NE Kalahari-Karoo Basin, the Upper Karoo sediments are represented by the Stormberg Lebung and the Lava Groups. The Lebung Group is divided into two sandstone formations: the underlying Mosolotsane Formation which is dominated by purplish muddy siltstones, sandstones, marls, and conglomerates; and the overlying widespread aeolian and uniform Ntane Sandstone Formation consisting of well sorted fine-grained porous sandstone (Smith, 1984).

Across the whole Kalahari-Karoo Basin, the Stormberg Lava Group, which correlates to the Drakensberg Group of the Main Karoo Basin in South Africa, overlies the Karoo Supergroup and consists of volcanic rocks such as finely crystalline dark grey, black, brown or purple amygdaloidal or massive basalts (Carney et al., 1994).

Zimbabwe
The Upper Karoo rocks comprising the Escarpment Grit, Ripple Marked Flags, Fine Red Marly Sandstone, Pebbly Arkose, Forest Sandstone and the Batoka Basalt outcrop extensively in the Middle Zambezi Basin and have an estimated total thickness of 3000 m (Stagman, 1978) and are discussed below.

Escarpment Grit: This forms the topmost layer of the Lower Karoo sequence and also the end of the Beaufort Group. The Grit is generally less than 20 m thick. It comprises ill sorted, coarse grained angular fragments of the Basement Complex rocks (Stagman, 1978).

Ripple Marked Flags: The Flags overlie the Escarpment Grit and comprise alternating layers of maroon and grey mudstones and flags and can attain thicknesses of up to 1200 m. The Flags mark the commencement of deposition of the Upper Karoo sediments. The Flags are correlated to the Molteno Stage of the Main Karoo Basin in South Africa (Stagman, 1978).

Fine Red Marly Sandstone: The formation comprises unfossiliferous slightly calcareous fine grained sandstone with alternating layers of siltstone reaching a total thickness of approximately 70 m (Stagman, 1978).

Pebbly Arkose: The Pebbly Arkose has a thin basal layer containing hardened fragments of the underlying sandstone. This is overlain by a coarse grit containing isolated pebble bands, which change upwards into sandstone.

Forest Sandstone: The formation exhibits desert derived aeolian red sandstones deposited over sub-aqueously formed basal beds of pale sandstone that grades upwards into white sandstone (Stagman, 1978). The Forest Sandstone rests directly on the Basement Complex at the margins of the Basin such as around Nyamandlovu (45 km NW of the City of Bulawayo).

Batoka Basalt: The Batoka Basalt, representing voluminous extrusion of tholeiitic basaltic lava, marked the end of deposition of the Upper Karoo and consequently that of the Karoo Supergroup. The basalt is of the plateau type and was formed through the superimposing of several flows with little or no unconformity between successive flows. The Basalt is intercalated with sandstone at its base and this is most conspicuous in the Nyamandlovu area where it overlies the Forest Sandstone and baked it into a red to brick red colour. The Basalt weathers into prismatic columnar jointing and rounded spherical boulders. The Basalt forms the mighty Victoria Falls along the Zambezi River. The Basalt is equated to the Drakensburg Formation of the Main Karoo Basin in South Africa, the Stormberg Lava Group in the main Kalahari-Karoo Basin of Botswana and the Kalkrand Formation in the Aranos Basin of Namibia.

4.2.3. Kalahari Group

The Kalahari Group is ubiquitous throughout the EKK-TBA and is generally unconsolidated and thus presenting a primary porosity aquifer. The Kalahari Group is of the Tertiary to Quaternary periods and generally has the same characteristics of aeolian in origin.

Botswana

The Kalahari Group deposits are extremely widespread in the area and attain considerable thicknesses that can be well over 150 m. This unit comprises a discordant and highly variable sequence of white to pink coloured aeolian loose to poorly consolidated sands, silcrete, conglomerate, limestone and calcrete intercalations of variable proportions, subordinate to minor ferricrete, silcretized/calcretized sandstones and mudstones (Smith, 1984).

Zimbabwe

The Kalahari System is represented by the extensive sand deposits known as the Kalahari Group deposits. The deposits are most widespread and rest on the Bakota Basalt or unconformably on the Forest Sandstone or Basement Complex (Sunguro, 1991). The Kalahari sands are pink or buff coloured structureless aeolian sands with well rounded quartz grains that have frosted surfaces (Beasley, 1983). The grains were derived from the Forest Sandstone. The aeolian sands are indicative of a long period of aridity over the large portion of southern Africa over which they were deposited *(ibid)*. The Kalahari Group deposits have a bed of concretionary ironstone and frequently chalcedonic or indurated sandstone. The ironstone is a hard blackish conglomerate-like rock composed of sand and angular fragments of the underlying rocks *(ibid)*. The upper portion of the Kalahari Group has a pisolitic structure and is composed of pellets of impure limonite (Stagman, 1978). The sandstone represents cemented Kalahari Group deposits which is often hollow due to decayed plant matter (stems and roots) buried during sediment deposition (Sunguro, 1991). The hollow sandstone is sometimes referred to as the Pipe Sandstone and has good groundwater potential (Stagman, 1978; Sunguro, 1991).

The thickness of the Kalahari Group deposits varies from 0-270m and is deepest in the central portions of the basin (Haddon, 2005) which mostly lies in Botswana and follows an East–West strike coinciding with the central part of the EKK-TBA, Figure 4.3.

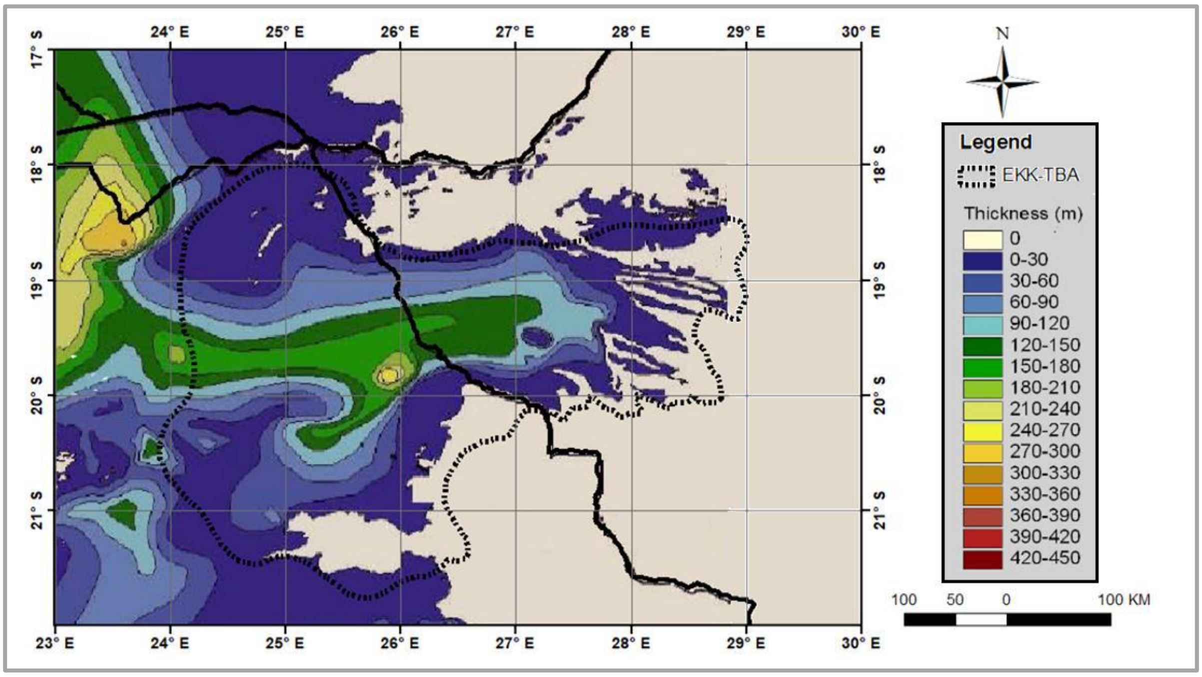


Figure 4.3: Kalahari Group isopach map

Source: modified after Haddon (2005)

4.2.4. Lithological correlation

Figure 4.4 shows a correlation of the lithostratigraphic units of the Aranos Basin stretching from northwestern South Africa into southeastern Namibia, into the main Kalahari-Karoo Basin (NE, Central and SW) in Botswana and the Mid Zambezi Basin in Zimbabwe. It should, however, be noted that there is sparse hydrogeological data and information in the public domain on the western sections of the EKK-TBA in Botswana and a postulation of the geological setting of NW EKK-TBA has been made instead. Likewise, in Zimbabwe, the eastern section covering the Hwange National Park to the border with Botswana also has limited data and therefore information from the Nyamandlovu to Sawmills area has been used.

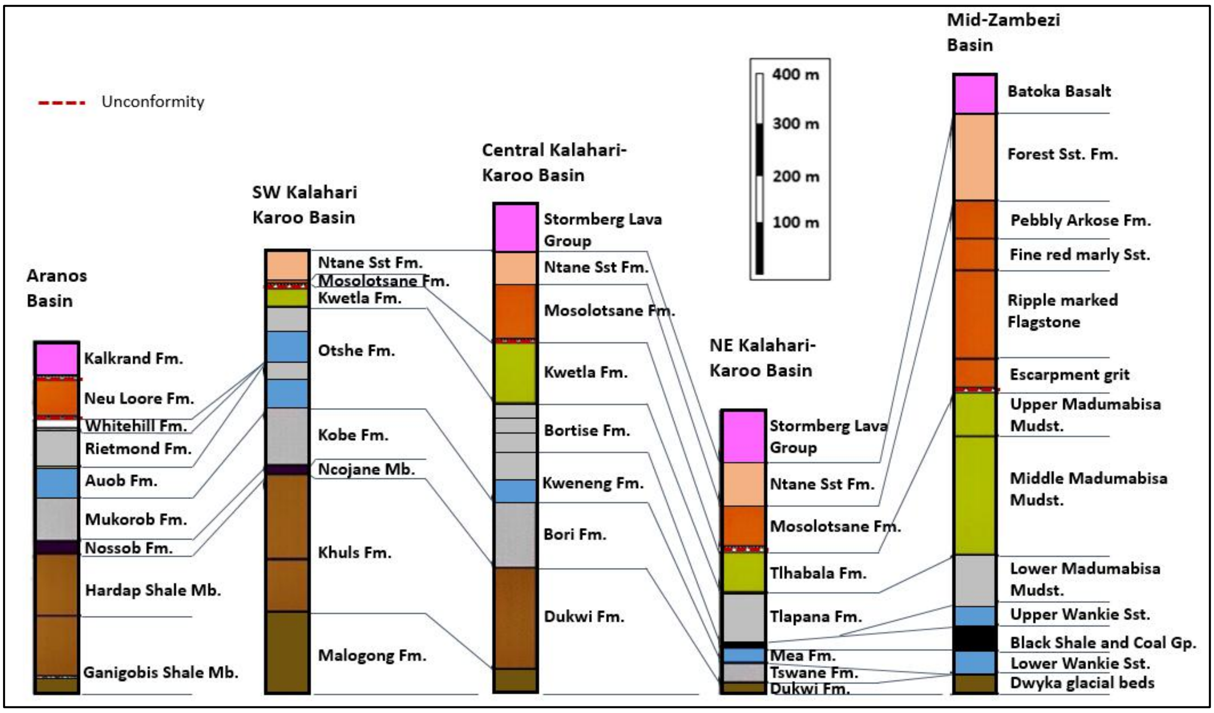


Figure 4.4: Correlation of Karoo Supergroup lithostratigraphic units

Source: modified after Catuneanu et al. (2005)

4.3. Surficial geology

Figure 4.5 shows the surficial and structural geology of the EKK-TBA. The Kalahari Group covers the majority of the EKK-TBA and is only absent in the eastern and southern fringes of the basin where it has been eroded away. The Ntane/Forest Sandstone Formations and the Stormberg/Batoka Basalt outcrop in the southern and eastern parts of the Basin. The deeper Mea Arkose Formation outcrops in the southeast. The Basement Complex forms the southeastern to eastern border of the EKK-TBA.

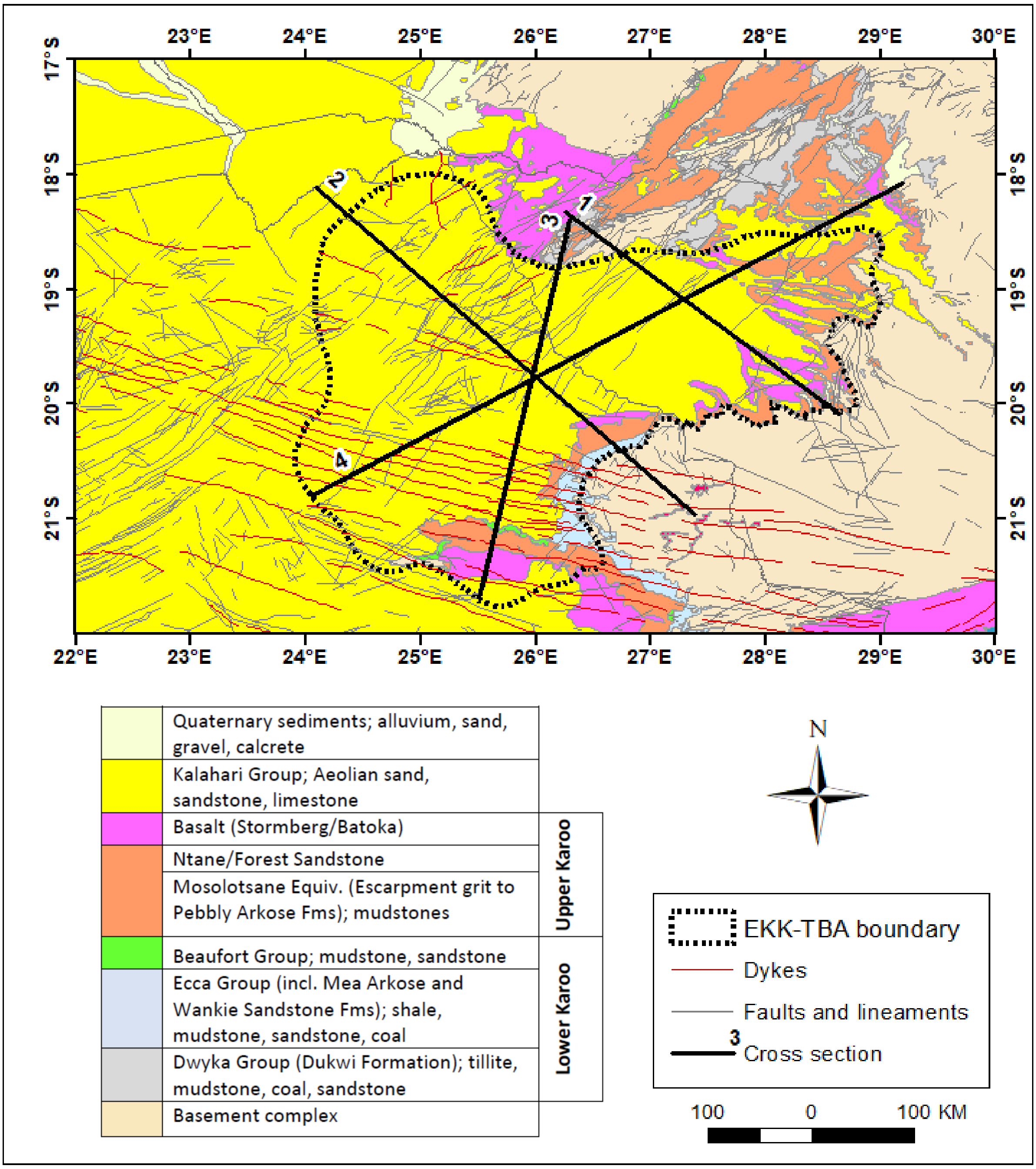


Figure 4.5: Geology of the EKK-TBA and surroundings
Source: modified after Council for Geoscience (2009)

4.4. Pre-Kalahari lithological outcrops

Figure 4.6 presents a pre-Kalahari map showing the areal extent of the Karoo Supergroup formations. The Stormberg / Batoka Basalt covers the greater portion of the Basin, with the Ntane / Forest Sandstone outcropping in the eastern and central southern portions of the Basin. Precambrian interlayered metasedimentary rocks occur in the western sections of the

Basin whereas Precambrian mafic to ultramafic extrusive rocks occur in the central western part of the Basin.

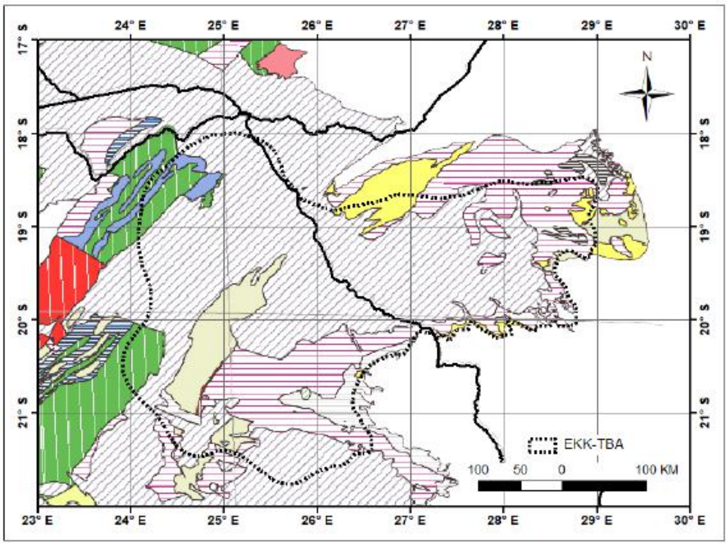


Figure 4.6: Pre-Kalahari Formations
Source: modified after Council for Geoscience (2009)

4.5. Dyke intrusions

Dykes of various ages and types have been recognized in southern African countries. They are mainly Mesozoic / Jurassic dykes (Karoo dolerite) but Proterozoic occurrences involving dykes and/or sills, and the remnants of late Archean dyke swarms have also been identified in Zimbabwe (Wilson et al., 1987; Mekonnen, 2005).

The Okavango Dyke Swarm crosses the southwest of the study area (Figure 4.5). It is a giant swarm consisting of a group of Karoo Jurassic dykes (circa 180 million years), trending east-southeast across Botswana and Zimbabwe, spanning a region nearly 2 000 kilometres long and 110 kilometres wide. The mean dyke thickness is about 17 m. This N110°E-oriented dyke swarm intruded the Archaean basement terrains and the entire Permo-Jurassic Karoo sedimentary sequences (Wilson et al., 1987; Mekonnen, 2005).

The Karoo dykes are mainly composed of tholeiitic mafic rock and are related to the Jurassic volcanism (the Drakensberg or Stormberg Basalts) that followed after the deposition of the Karoo Supergroup sedimentary succession and was responsible for one of the largest outpourings of flood basalt in the World during a period of extensive magmatic activity that took place over almost the entire southern African subcontinent that accompanied one of the phases in the Gondwanaland break-up.

The Karoo intrusive patterns are regarded as inherited brittle basement fabrics associated with a previous (Proterozoic) extensional event. The Okavango N110°E dyke swarm is thus a polyphase intrusive system in which total dilation caused by Karoo dykes is 12.2% (6 315 m of cumulative dyke width) (Le Gall et al., 2005).

4.6. Structural geology

Dominantly SW-NE trending normal faults and less dominant NW-SE faults have been reported on geological maps on the southern borders of the NE Kalahari-Karoo Basin in Botswana and on the northern border of the Mid-Zambezi basin in Zimbabwe, Figure 4.5. The faults resulted in block faulting and compartmentalisation of the formations and this has had an effect on the groundwater dynamics and the groundwater quality.

This network of faults and structural lineaments is well developed in the basement rocks and are mainly Pan-African in age and older. However, these structures have been reactivated during the Mesozoic extensional regime resulting in the formation of several discrete fault-controlled sub-basins or grabens in which the Karoo succession was deposited (Catuneanu et al., 2005, Modie, 2000, Key et al., 1998, Smith 1984). The EKK-TBA therefore has, in general, a horst and graben morpho-tectonic style, the horsts corresponding to the Basement Complex highlands and the grabens to the Karoo sedimentary basins.

Four broadly inferred cross sections were constructed across the EKK-TBA (see Figure 4.5). The cross section lines were selected to better understand the role of the horst and graben tectonics on the spatial distribution of the main lithostratigraphic units. The sections are based on an analysis of the geological and structural maps and on an analysis of the lithostratigraphy, complemented and validated by available geological information obtained from borehole logs where available, albeit scanty. Note that since there was limited lithological data to utilise, the cross sections are more of an inference based on the pre-Kalahari map (Figure 4.6) by the Council for Geoscience (2009) and the correlation of the lithostratigraphic units of the Aranos Basin (in Namibia), SW-Central-NE Kalahari-Karoo Basin (in Botswana), Mid-Zambezi Basin (in Zimbabwe) and the Cahora-Bassa Basin (in Mozambique) (Figure 4.4) by Catuneanu et al. (2005).

4.6.1. Geological cross-section 1

Figure 4.7 shows cross section 1 which runs across the Mid-Zambezi basin in Zimbabwe from NW to SE (Figure 4.5). The section illustrates the graben structure of the basin. In the NW the fault-controlled basement horst is outcropping and, in the SE, the Karoo sediments resting on the Basement Complex are dipping towards the centre of the graben structure. The Basalt and part of the underlying sedimentary formations were eroded away along the margins of the basin. The total thickness of the entire Karoo filling the graben (especially the lower Karoo) is not precisely known since there are no boreholes that penetrate the whole sequence.

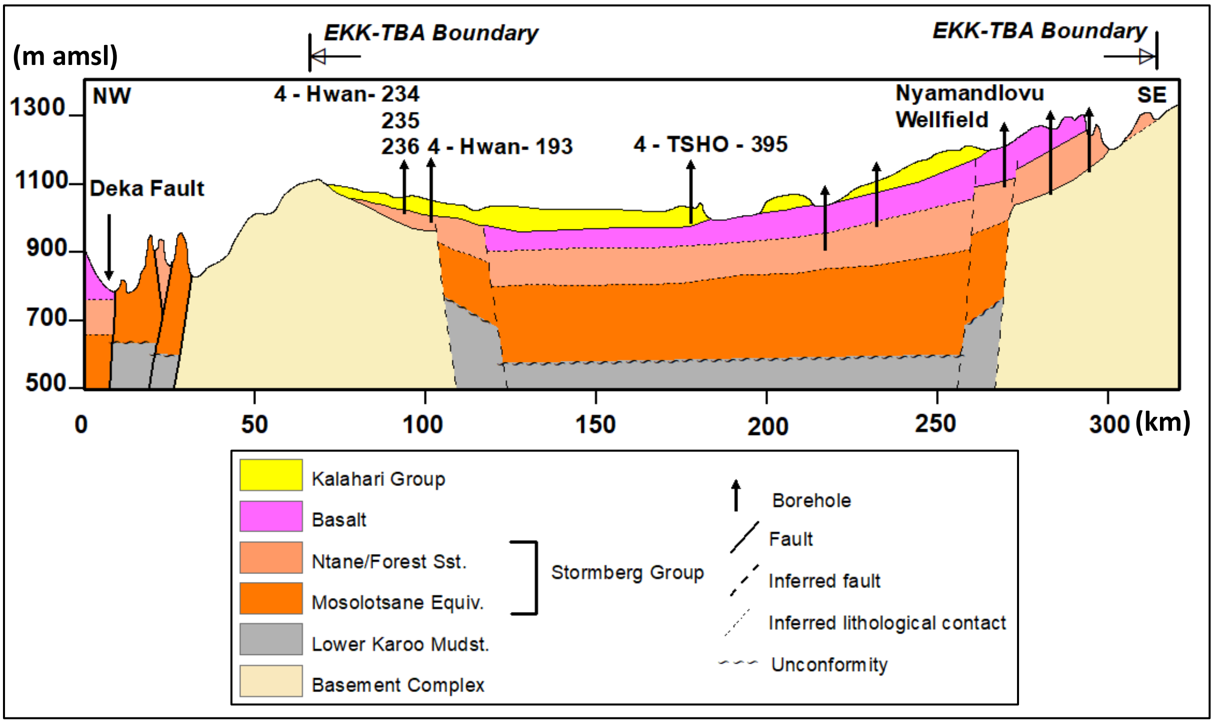


Figure 4.7: Cross section 1

4.6.2. Geological cross-section 2

Error! Reference source not found. represents cross section 2 which runs across the eastern K alahari-Karoo Basin from NW to SE and illustrates the tectonic style (horst and graben) of the basin coupled with massive block faulting, depicting that the formations are structurally controlled. The basement horst in the middle of the section is the southern extension of the faulted basement that is outcropping in cross section 1. However, without depths to the lithological contacts, the vertical displacement along faults cannot be accurately estimated.

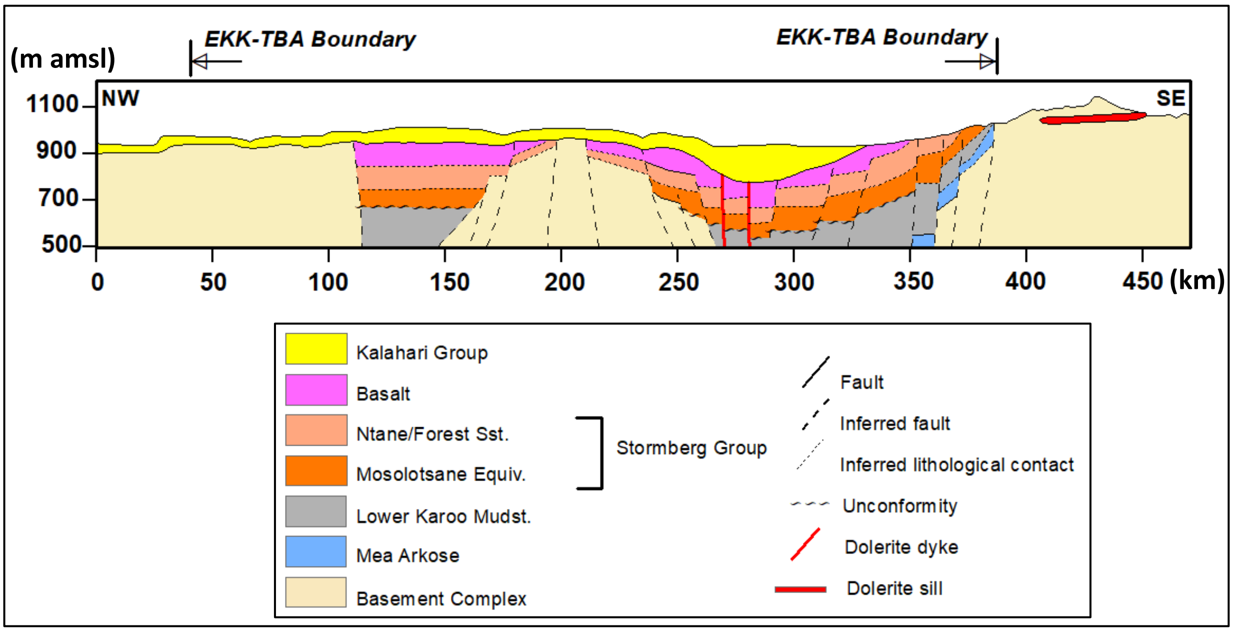


Figure 4.8: Cross section 2

4.6.3. Geological cross-section 3

Figure 4.9 shows cross section 3 which runs from Letlhakane Wellfield in the SW to the NE of the EKK-TBA. The cross section depicts a general horst and graben morpho-tectonic style, the horsts corresponding to the Basement Complex - highlands and the grabens to the Karoo sedimentary intra-basins seen in the other cross sections. Massive block-faulting is evident in the cross section.

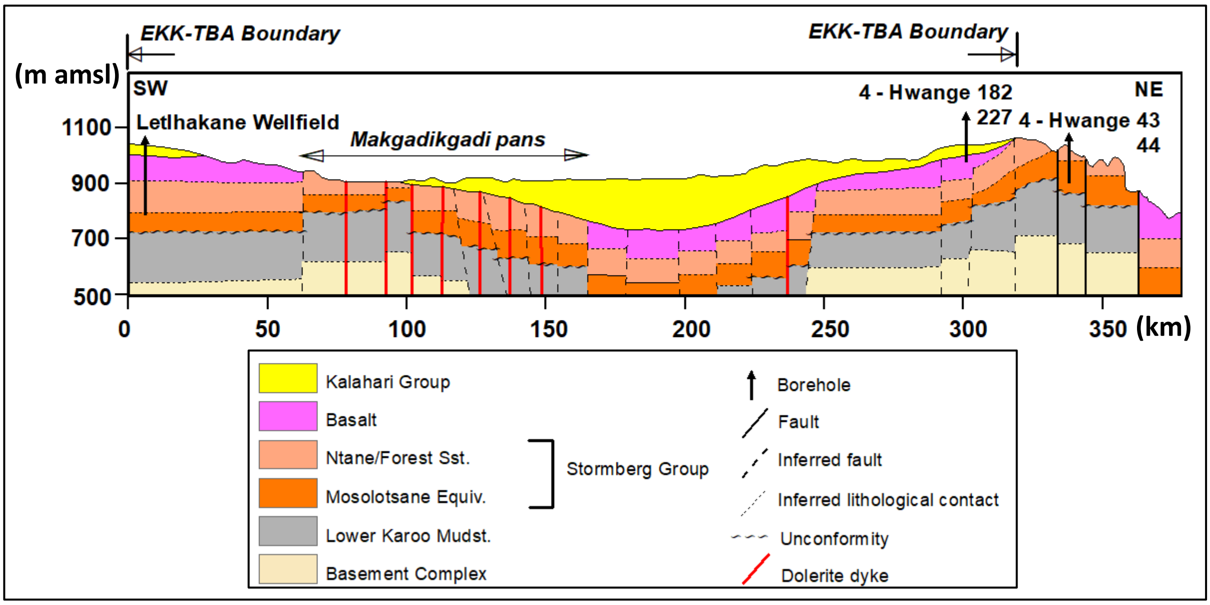


Figure 4.9: Cross section 3

Following the uplift around the margins of southern Africa in the mid- to late-Cretaceous, surface water drainage patters in southern Africa were dominated by several rivers flowing southeastwards from Angola via the Limpopo River (proto-Limpopo) to the Indian Ocean and westwards via the Kalahari and Karoo Rivers (Haddon and McCarthy, 2005). The block-faulting in northern Botswana and subsidence of the newly formed interior Kalahari Basin to the north of the Kalahari-Zimbabwe Uplift Axis (near the southeastern EKK-TBA boundary) may have caused back-tilting of the drainage away from the proto-Limpopo River and into the Kalahari Basin resulting in water ponding into a great lake west of the Kalahari-Zimbabwe Uplift Axis (Cooke, 1979; Haddon and McCarthy, 2005). Relics of this great lake are represented by the Makgadikgadi Pans. The Pans occur between approximately 65 and 160 km along cross section 3 over an uplifted area where the basalt was eroded, exposing the underlying Ntane/Forest Sandstone and the Lower Karoo mudstones, Figure 4.6. The mudstones divide the Ntane/Forest Sandstone into two parts.

The Ntane/Forest Sandstone is underlain by mudstones of the Mosolotsane Formation which form an aquiclude that allows subsurface discharge of groundwater from the Ntane/Forest Sandstone into the Makgadikgadi Pans, albeit at a very slow groundwater movement. From approximately 105 to 165 km along cross section 3, the Ntane/Forest Sandstone Formation is in direct hydraulic contact with the Kalahari Group deposits and groundwater from both aquifers discharges into the Makgadikgadi Pans. There is also the possibility of groundwater discharging into the Makgadikgadi Pans through faults from the deeper aquifers.

4.6.4. Geological cross-section 4

Figure 4.10 represents cross section 4 running from SW-NE and parallel to the graben structure. Cross section 4 intersects cross sections 2 and 3 around the centre of the EKK-TBA and cross section 1 in the northeastern part of the Basin.

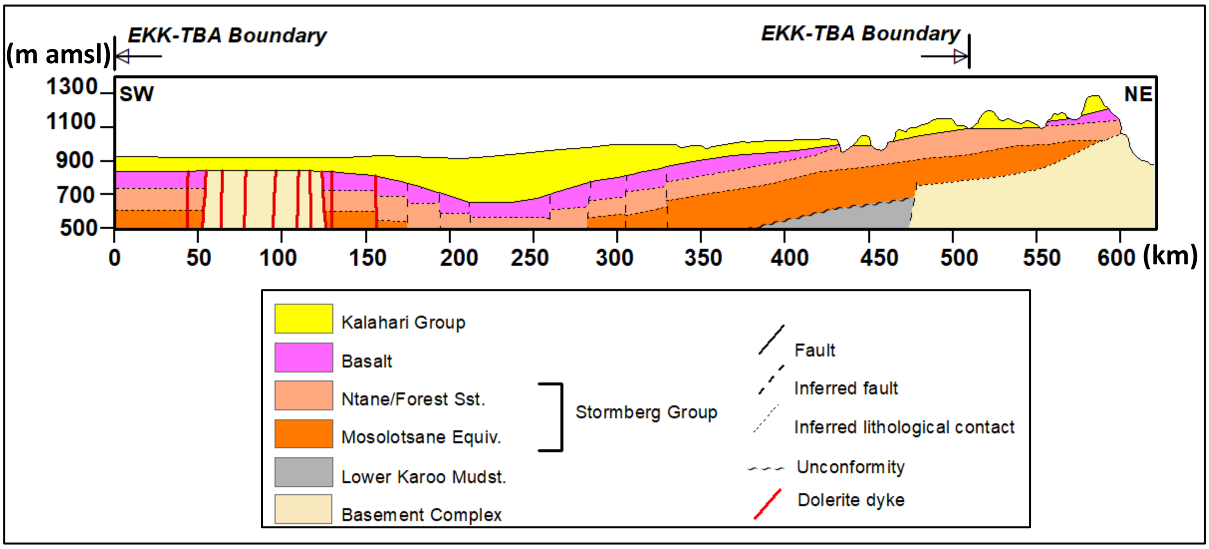


Figure 4.10: Cross section 4

The cross section shows the existence of Precambrian mafic to ultramafic extrusive rocks, sub-cropping in the south-western part of the basin, which are overlain by Kalahari Group deposits. Along the cross section, from the southwest to the northeast, the extrusive mafic to ultramafic rocks attain a subsurface width of about 75 km, and the rocks control the spatial distribution of the Karoo Supergroup Formations. The basalt extends for almost 295 km from the Precambrian extrusive rocks northeastwards into Zimbabwe where it is absent towards the margins of the EKK-TBA. The Kalahari Group deposits are deepest at between 200 and 260 km along the cross section. The Precambrian mafic to ultramafic extrusive rocks are presumed to control groundwater flow from the northern and western sections of Botswana's EKK-TBA. The groundwater flow on the western side of the extrusive rocks is very likely sluggish, which results in high salinity build up. As also pointed out in section 6.1.3, the high salinity will invalidate refreshening of the aquifer from any potential recharge along the contact zones. Groundwater flows southwestwards from Zimbabwe and then southwards towards the Makgadikgadi Pans where it discharges through subsurface drainage.

4.7. Conceptual geological model

A fence diagram was built using the cross sections in order to illustrate the litho-structural set up of the EKK- TBA, Figure 4.11. The figure shows the role played by structural geology in the spatial distribution of the rock formations within the Basin. The Karoo sediments after having been deposited in a graben structure surrounded by basement highlands or horsts, underwent several tectonic episodes that resulted in complex block faulting. It is inferred that the Kalahari Group deposits are generally averaging 70 m in thickness, but an E-W trough is running through the EKK-TBA where the Formation can reach a thickness of 270 m in places.

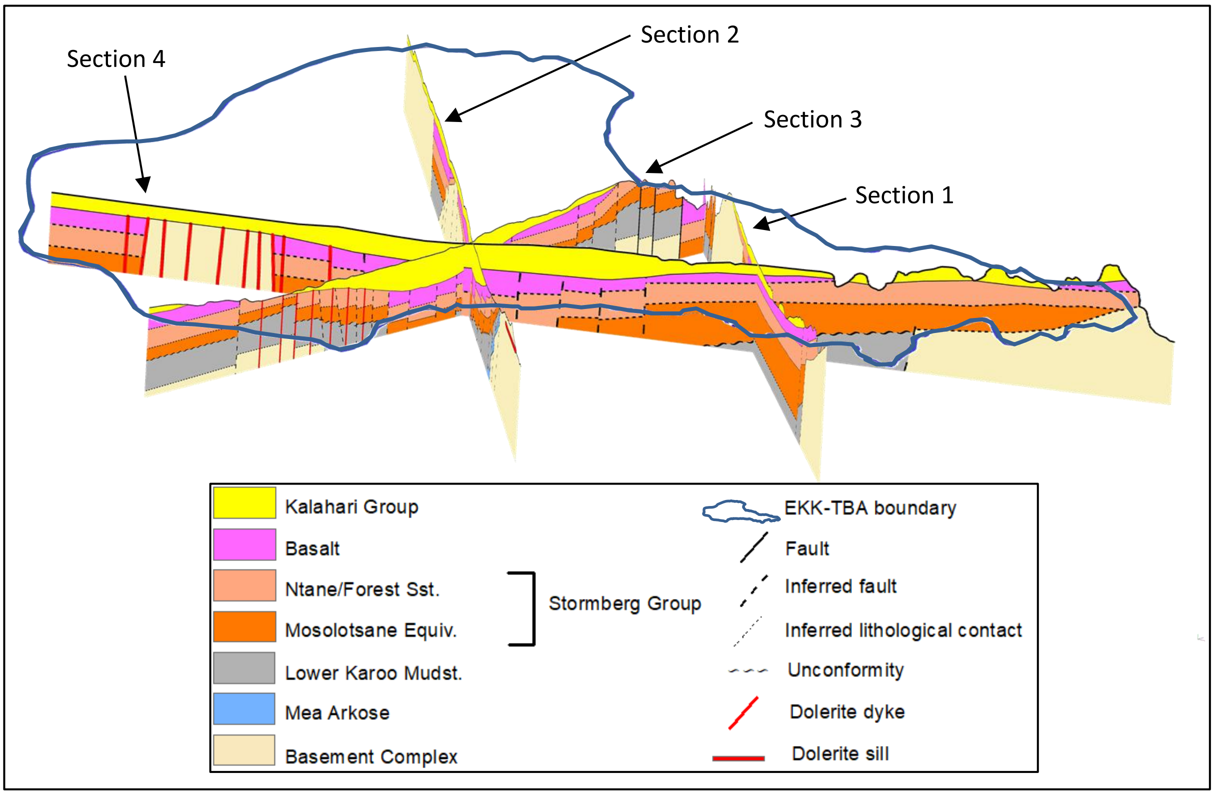


Figure 4.11: Geological fence diagram

5. LOCAL HYDROGEOLOGICAL PERSPECTIVE

Hydrogeological data is available on the wellfields developed along the southern to the eastern fringes of the EKK-TBA and it is scanty for the rest of the Basin. It is for this reason that the hydrogeological assessment was designed to start from the local perspective of wellfields before inferring on the regional hydrogeological perspective.

Wellfields existing in the EKK-TBA are shown in Figure 5.1. The wellfields have been classified into public sector (Water Utilities Corporation (WUC) in Botswana and ZINWA in Zimbabwe) and private sector (diamond mining companies) owned and managed wellfields. The Department of Water and Sanitation (DWS) in Botswana is obligated with monitoring the aquifers but rarely do so due to limited resources (Farr, 2017). WUC owns and manages potable water wellfields used for human consumption whereas diamond owned and managed wellfields are for both potable water and saline water used for human consumption and for mining operations respectively.

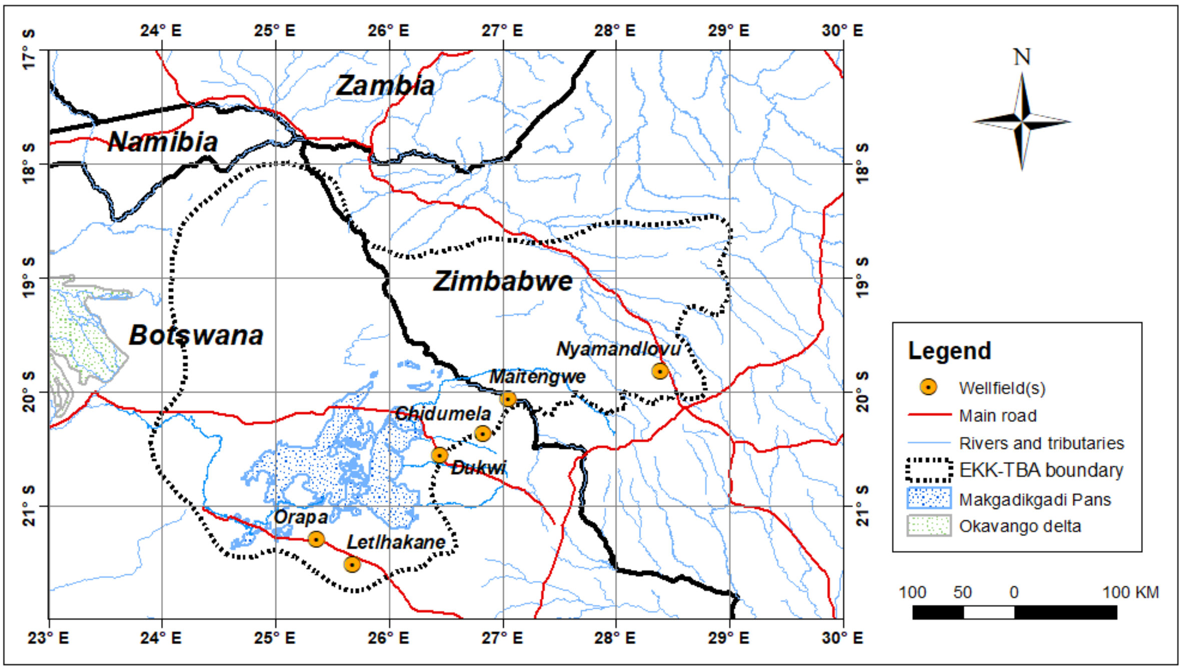


Figure 5.1: Approximate location of EKK-TBA Wellfields

5.1. Public owned and managed wellfields

Several potable wellfields were developed within the Botswana part of the EKK-TBA, some of which have since been decommissioned due to deteriorating water quality and/or drastically reduced yields. Zimbabwe has only one wellfield, the Nyamandlovu Sandstone Aquifer Wellfield. The main wellfields are briefly discussed below.

5.1.1. Dukwi Regional Wellfield

The Dukwi Regional Wellfield lies in the southeastern margin of the EKK-TBA in Botswana and about 130 km northwest of the town of Francistown, Figure 5.1. It comprised the Dukwi Wellfield Phase I, Dukwi Wellfield Phase II, Chidumela Wellfield and Soda Ash Botswana Boreholes which were developed between 1992-1995. The Chidumela Wellfield, Dukwi Wellfield Phase I and Soda Ash Botswana Boreholes were decommissioned in 2008 due to deterioration in the groundwater quality (Legadiko, 2015). The Dukwi Wellfield Phase II covering an area of approximately 480 km^2 and comprising 4 production boreholes is currently the only operational wellfield. It supplies an average of 30 m^3/h per borehole to Sowa Town, Soda Ash Botswana Mine, Nata and Dukwi Villages as well as the Dukwi Refugee Camp and Quarantine Camp (Legadiko, 2015).

5.1.1.1. Lithostratigraphy and structural geology

The stratigraphic units of the Dukwi area are presented in Table 5.1 and the general geology of the area is shown in Figure 5.2.

Table 5.1: Lithostratigraphy of the Dukwi area

Age	Stratigraphic Unit			Lithology
	Supergroup	Group	Formation	
Recent to Tertiary		Kalahari		Calcrete and silcrete underlying variously consolidated sands
Post Karoo Intrusives				Dolerite dykes and sills
Late Carboniferous to Early Jurassic	Karoo	Stormberg	Drakensberg	Amygdaloidal and vesicular basaltic lava flows
		Lebung	Ntane	Fine to medium grained sandstones and siltstones
			Ngwasha	Red to purple mudstone and sandstone
			Pandamatenga	White coarse sandstone
		Ecca	Upper Tlapana	Variegated non-carbonaceous fine-grained massive mudstones
			Lower Tlapana	Dark carbonaceous shales, mudstones & coal
			Mea Arkose	Fluvio-deltaic sandstone with insubordinate coal, white, gritty arkoses and sub-arkoses
		Dwyka	Dukwi	Grey varved mudstone and shale, sandstones and tilloids
Archaean Basement	Mosetse River Gneiss Group			Quartz, feldspar gneisses, migmatites and granitic gneisses
	Greenstone Belt Rocks			Chlorite-talc schists and amphibolites, characteristically green

Source: Legadiko (2015)

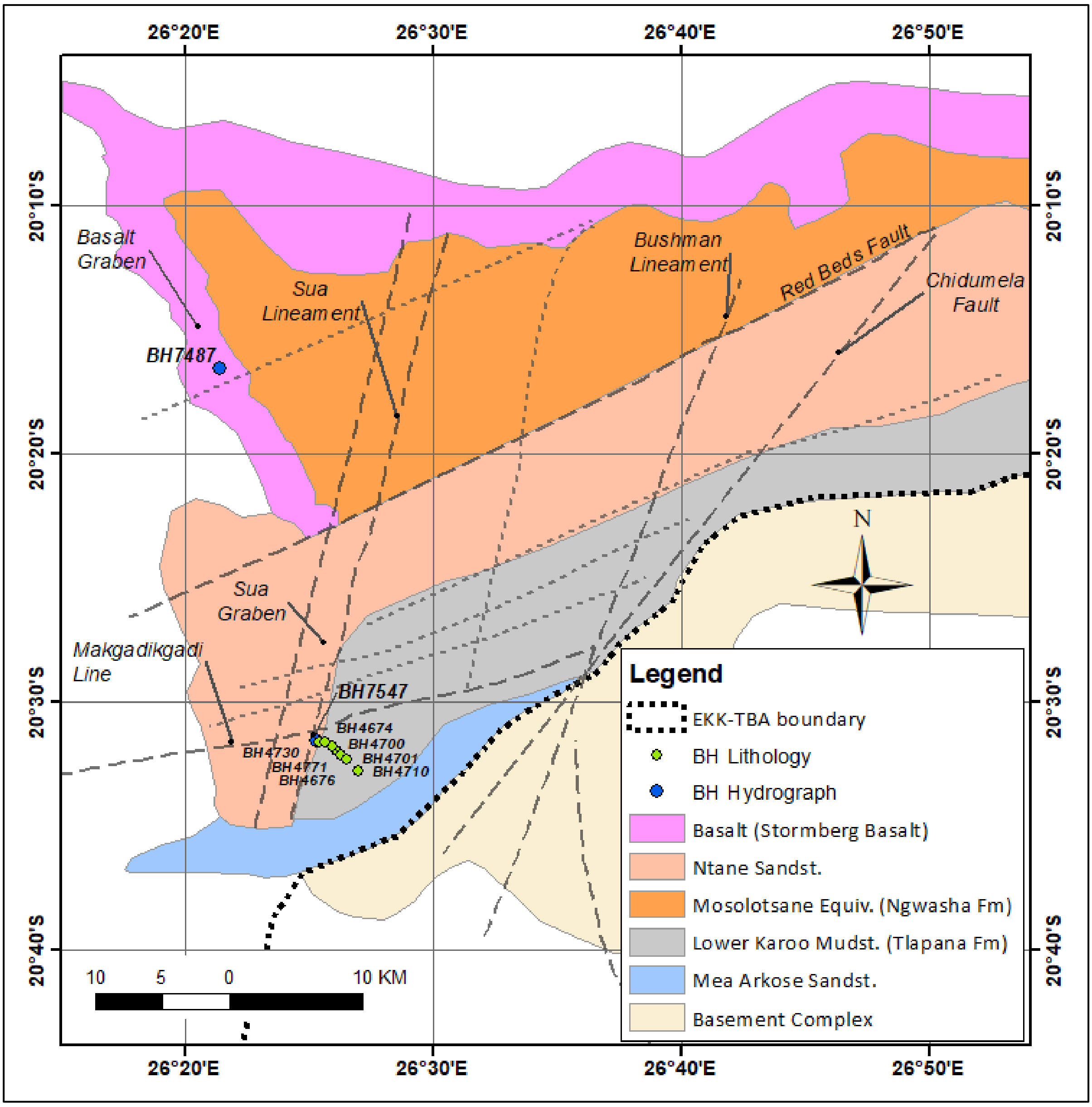


Figure 5.2: Geology of the Dukwi area

Source: modified after DWA (2000b)

The stratigraphy is strongly structural controlled by faults and dykes. The Dukwi Formation of the Dwyka Group uncomformably overlies the Archaean basement and forms the basal layer of the Karoo sediments and was deposited under glacial conditions (DGS, 1973). The Dwyka Group is in turn uncomformably overlain by rocks of the Ecca Group. The Mea Arkose Formation, comprising white, gritty arkoses and sub-arkoses forms the basal strata of the Ecca Group and uncomformably overlies the Dukwi Formation and has an average thickness of 58m within the Dukwi and Chidumela Wellfields. The Tlapana Formation consisting of non-carbonaceous mudstones, siltstones and carbonaceous mudstones uncomformably overlies the Mea Arkose formation and has an average thickness of about 93 m (DWA, 2000b). The Tlapana Formation is subdivided into the Lower Tlapana and Upper Tlapana Formation (see Table 5.1). The Lebung Group comprises the Pandamatenga, Ngwasha and Ntane Sandstone

Formations. The Pandamatenga consists mainly of fine- to medium-grained calcareous sandstone and mud-flake breccias and conglomerates, whereas the overlying Ngwasha Formation is typified by heavily oxidised sedimentary rocks and consists of red thick muddy siltstones with calcareous nodules. The Ntane Sandstone Formation is characterised by coarse, gritty, cross-bedded sandstones changing upwards to thinly bedded, medium to coarse-grained quartzitic sandstones of cream-brown to red colour of aeolian deposition. The Stormberg Group, overlying the Lebung Group is represented by amygdaloidal and vesicular basaltic flows. The basalt occurs in a narrow graben that is lineament controlled to the west of the Ngwasha Formation and outcrops mainly in the northern sections of the wellfield, Figure 5.2. Within the basalt graben, 30 m of highly weathered tuffaceous lava is present (Legadiko, 2015). Post Karoo intrusions are dominated by the dolerite intrusions which occurred after the deposition of the Karoo Supergroup and are not ubiquitous within the Dukwi Wellfield. These doleritic dykes of the post Karoo intrusions generally exhibit a preferential trend or orientation towards WNW. The Kalahari Group deposits, representing the most recent formation, are widely distributed within the EKK-TBA but are mostly absent in the Dukwi area.

5.1.1.2. Hydrogeology

5.1.1.2.1. Hydrostratigraphy

The main aquiferous unit is the Mea Arkose Formation and its middle to lower sections are reported to be the most productive horizons (Jennings, 1974). The average thickness of the Mea Arkose Formation was estimated at 58m with yields around 400 m^3/d (DWA, 2000b; Figure 5.3). The underlying Dukwi and overlying Tlapana, Pandamatenga and Nwasha Formations do not form any significant aquifer units. The Mea Arkose aquifer is confined by the mudstones of the Tlapana Formation (up to 30m thickness) in the north and outcrops in the southern part of the Dukwi area where it is unconfined. The Ntane Sandstone overlying the Ngwasha Formation (up to 24m thickness), has very little groundwater potential within the Dukwi Wellfield and where significant yields have been encountered, the groundwater has been established to have very high Total Dissolved Solids (TDS) that render the groundwater not suitable for human consumption (Legadiko, 2015). The basalts and doleritic contact zones have groundwater which is saline and is thus not suitable for human consumption as well. The overlying Kalahari Group deposits and other recent formations are generally thin and have localised ephemeral perched aquifers that are exploited by hand dug wells particularly along the Semowane River. Note that the faults and dykes heavily influence the hydrogeology of the area and have resulted in compartmentalised aquifer zones.

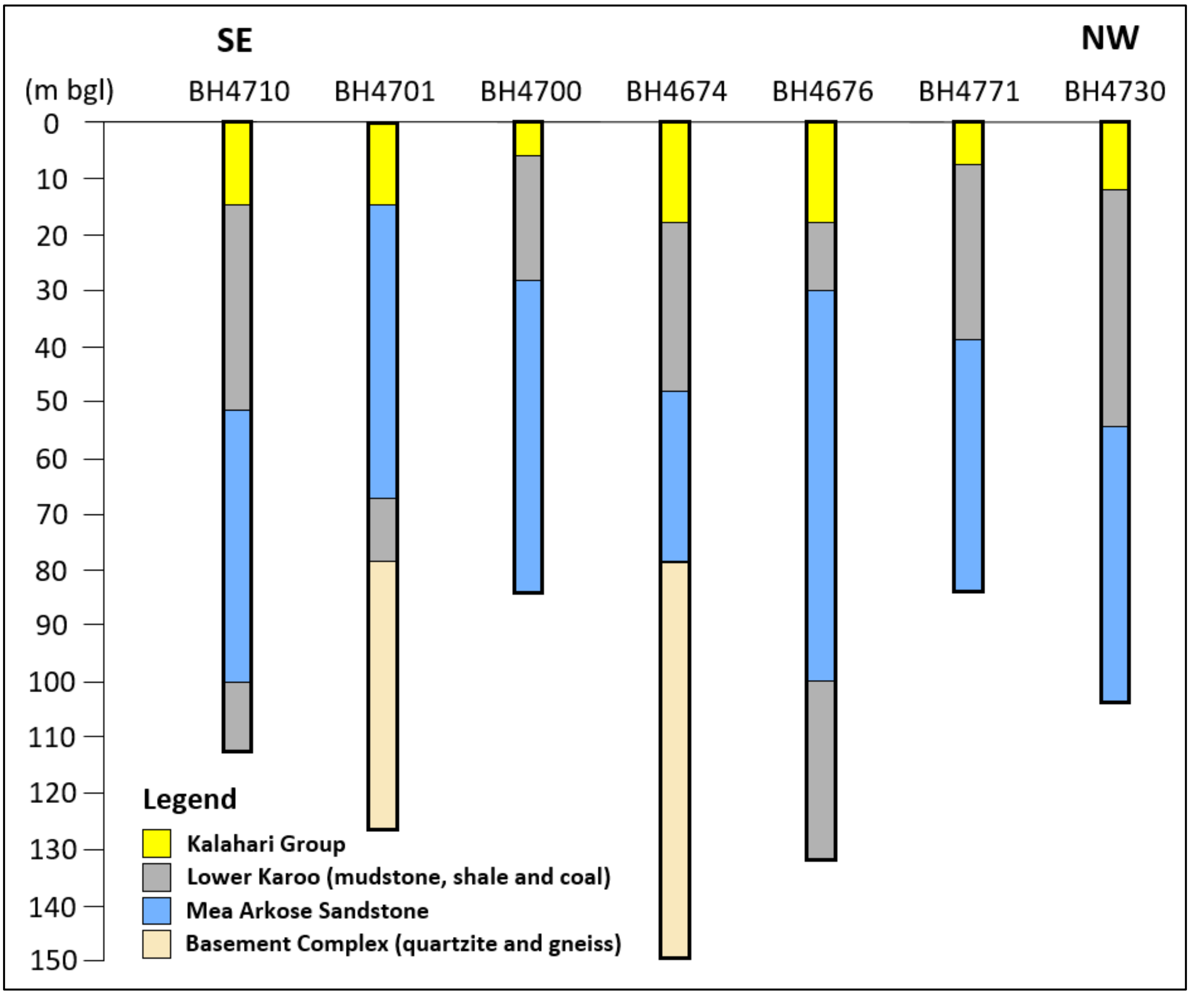


Figure 5.3: Borehole Lithological Logs showing the position of the Mea Arkose Formation
Source: modified after Legadiko (2015)

5.1.1.2.2. Groundwater levels and flow

Groundwater level monitoring is manually conducted by the DWA for 28 boreholes. Years of exceptionally high rainfall resulted in elevated groundwater levels and diminished rainfall resulted in lowered groundwater levels, BH7 547 in Figure 5.4. BH 7547 shows a rapid rise in groundwater levels between August 1999 and April 2001, which coincides with an exceptionally wet year (650 mm for 1999/2000) and low abstraction rates. It is most likely that the rapid rise in groundwater level is due to indirect recharge since the borehole is located next to the Sua lineament Figure 5.2. BH 7487 is located furthest north of the wellfield (Figure 5.4) and was rarely affected by the wellfield abstraction from July 2001 to the end of 2009 wherefrom the effect of increased abstractions and diminished annual rainfall took effect (Legadiko, 2015).

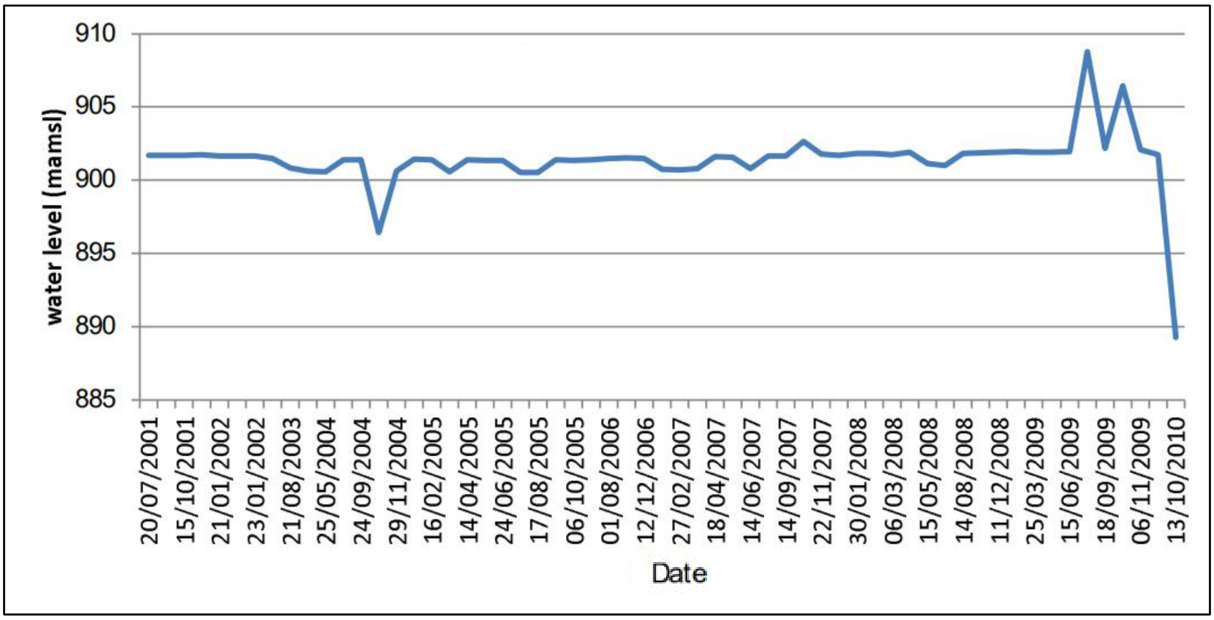


Figure 5.4: Groundwater level response to rainfall and abstraction Dukwi

Top: BH 7547 and Bottom: BH 7487; Note the response to high rainfall and low abstraction in BH 7547 and low rainfall and increased abstraction in BH 7487 towards the end of the monitoring period

Source: Legadiko (2015)

Groundwater flow within the Dukwi Wellfield is generally structural controlled and as such the flow directions highly vary (Legadiko, 2015). Groundwater gradients in some of the compartments have been established to be very low, in the order of $5x10^{-4}$ *(ibid)*. The regional groundwater flow direction is deduced to be in a southwesterly direction towards the Makgadikgadi Pans, and this notation is confirmed by the steady-state groundwater heads established by DWA in 2000, Figure 5.5. Figure 5.6 shows that the general groundwater flow direction in the Dukwi Wellfield has remained southwestwards over a period of 20 years despite the 5-10m drop in groundwater levels caused by pumping.

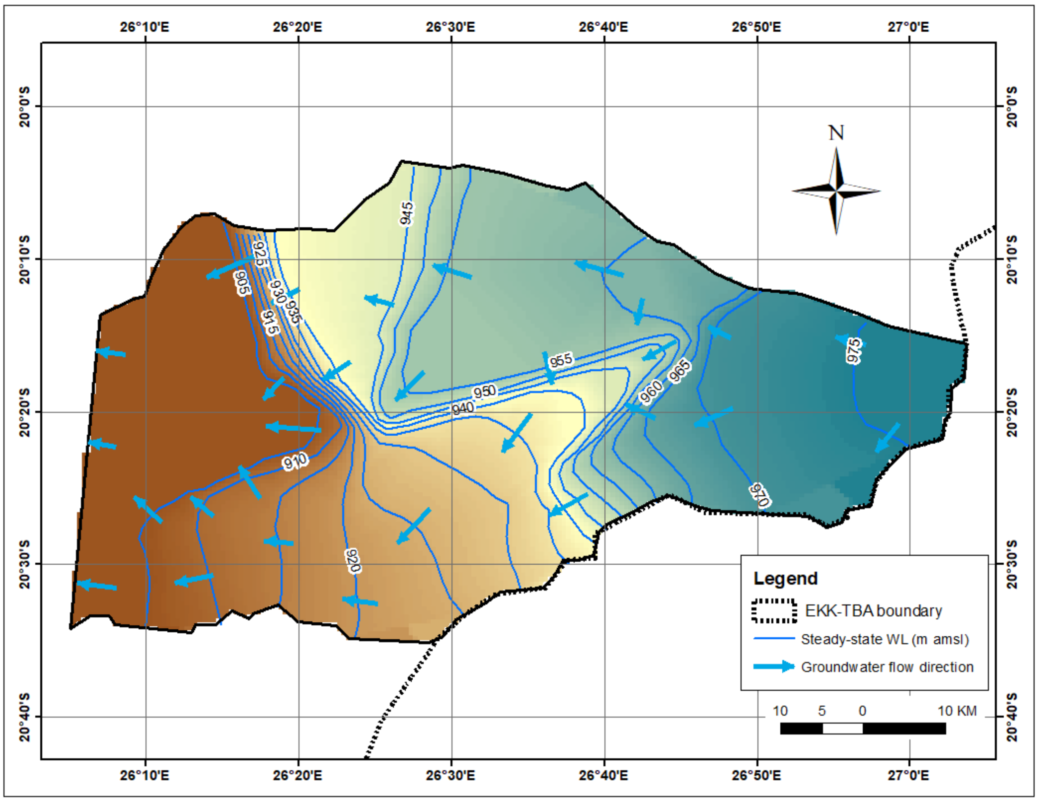


Figure 5.5: Steady-State calibrated groundwater levels prior to abstraction in 1995
Source: modified after Legadiko (2015)

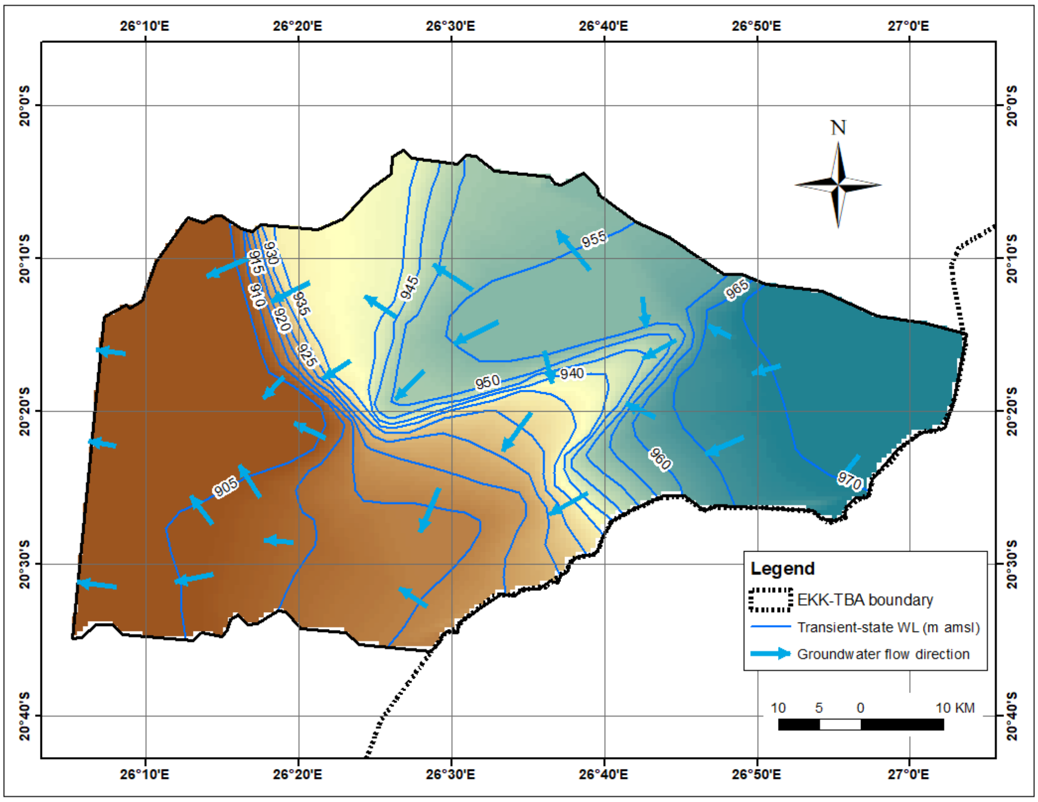


Figure 5.6: Transient-State calibrated groundwater levels as at January 2014
Source: modified after Legadiko (2015)

5.1.1.2.3. Groundwater chemistry

Table 5.2 shows the results of chemical analysis of groundwater from the Dukwi Wellfield. The water quality falls within the maximum allowable range of chemical parameters of the Botswana Bureau of Standards (BOS 32:2000; Table 5.3) and hence the groundwater can broadly be considered suitable for human consumption (Legadiko, 2015). The decommissioning of Dukwi Phase I due to deteriorating groundwater quality and the potability of Dukwi Phase II groundwater gives credence to the supposition that the aquifer is compartmentalized. The potability of Dukwi Phase II groundwater has been attributed to its proximity to the recharge zone *(ibid)*.

Table 5.2: Physico-chemical analysis of groundwater samples Dukwi Wellfield

Parameter	Units	BH 7678	BH 7675	BH 7687	BH 7674
Electrical Conductivity	µS/cm	1516	1377	1488	1530
TDS	mg/l	985.4	895	967.2	994.5
pH		7.62	7.25	7.21	7.16
Sodium	mg/l	167	238.10	238	254
Potassium	mg/l	0.52	2.20	3.28	2.39
Calcium	mg/l	28.09	94.34	11.28	97.42
Magnesium	mg/l	6.59	44.53	46.50	44.42
Iron	µg/l	300.2	NM	10.11	23.65
Manganese	µg/l	109.4	1.61	2.26	1.94
Chloride	mg/l	217.02	216.55	229.2	107.1
Alkalinity	mg/l	381.57	345.33	389.78	360
Nitrate	mg/l	0.8	0.43	0.94	NM
Sulphate	mg/l	125.41	112.49	121.92	115.15
Turbidity	NTU	0.19	0.24	0.16	0.14
Aluminium	µg/l	NM	NM	NM	0.84
Cadmium	µg/l	2.56	2.64	2.56	2.60
Chromium	µg/l	5.42	NM	NM	NM
Cobalt	µg/l	4.72	3.86	3.95	3.76
Copper	µg/l	1648.29	NM	35.28	26.37
Nickel	µg/l	5.66	0.99	0.62	1.14
Zinc	mg/l	0.61	NM	NM	NM
Bromide	µg/l	0.90	0.94	1.02	0.60

NM = Not Measured; Samples from November 2014

Source: Legadiko (2015)

The groundwater quality of the Dukwi Wellfield has been classified into three types which are Type I: Ca-Mg-HCO_3, TDS < 1 000 mg/l, Type II: Na-HCO_3, TDS between 1 000 mg/l and 1 500 mg/l, and Type III: Na-Cl, TDS >1 500 mg/l (often > 5 000 mg/l).

Table 5.3: Botswana drinking water classification

Parameter	Units	Class I: Ideal	Class II: Acceptable	Class II: Maximum Allowable
TDS	mg/l	450	1000	2000
pH		6.5-8.5	5.5-9.5	5.0-10
Sodium	mg/l	100	200	400
Potassium	mg/l	25	50	100
Calcium	mg/l	80	150	200
Magnesium	mg/l	30	70	100
Iron	mg/l	0.03	0.3	2.0
Manganese	mg/l	0.05	0.1	0.5
Zinc	mg/l	3.0	5.0	10
Chloride	mg/l	100	200	600
Nitrate	mg/l	45	45	45
Fluoride	mg/l	0.7	1.0	1.5
Sulphate	mg/l	200	250	400
Turbidity	NTU	0.5	5.0	10

Source: Botswana Bureau of Standards (BOS 32:2000)

5.1.1.2.4. Groundwater recharge

Groundwater recharge zones were delineated using a variety of techniques which included piezometry, numerical modelling, satellite imagery, review of geology and hydrochemistry. It was established that recharge of the Mea Arkose aquifer mainly occurs in areas where the aquifer is unconfined in the eastern to south-eastern parts of the area, along the contact between the Mea Arkose Formation and the Basement Complex, and along certain stretches of the major rivers such as the Mosetse River (DWA, 1995).

Analysis of radiocarbon (^{14}C or C-14) results confirmed the zonation of the recharge area in which 0-10 percent modern carbon (pmC) with lighter oxygen-18 (^{18}O or O-18) values represents older groundwater, recharged under cooler conditions, whereas 50-88 pmC with heavier ^{18}O values represents younger groundwater recharged under evaporative conditions (elevated temperatures).

Table 5.4 shows the yearly recharge rates and recharge classification for the various hydrogeological zones used by the DWA in the numerical groundwater model of 2000.

Table 5.4: Groundwater recharge zones

Recharge Classification	Recharge Zone					
	Mea Arkose Outcrop		Basement Contact		Ntane Sandstone Outcrop	
	Recharge (mm/yr)	Area (km^2)	Recharge (mm/yr)	Area (km^2)	Recharge (mm/yr)	Area (km^2)
High Recharge	6	105	3	200	0.3	1 000
Medium Recharge	5		2.5		0.25	
Low Recharge	4		2		0.2	

Source: DWA (2000a; 2000b)

5.1.1.2.5. Hydraulic characteristics

The hydraulic characteristics of the various aquifer units are shown in Table 5.5. Pumping tests revealed that the Mea Arkose aquifer transmissivities in the area are highly variable, ranging from 1.5 m^2/d to 1 760 m^2/d with a mean value of 572 m^2/d and that the Dukwi Wellfield Phase II is located in a zone of high transmissivity with a mean transmissivity of 1523 m^2/d. The storativity (matrix and fracture) ranges from 0.0001 to 0.08 with a mean value of 0.007 (DWA, 2000a and 2000b).

Table 5.5: Hydraulic characteristics hydrogeological units Dukwi Wellfield

	Hydrogeological Unit											
	Mea Arkose Outcrop			Basement-Mea Contact			Ntane Sst Outcrop		Makgadikgadi Line			Major Faults
Recharge Classification	S	T (m^2/d)	K (m/d)	S	T (m^2/d)	K (m/d)	S	T (m^2/d)	S	T (m^2/d)	K (m/d)	T (m^2/d)
High Recharge	0.002	1618	0.001	0.002	48	0.001	0.002	1618	0.008	290	0.001	0.8
Medium- Low Recharge	0.001	48	0.001		48			48				

Source: DWA (2000a and 2000b) and Legadiko (2015)

5.1.2. Letlhakane Wellfield

The Letlhakane Wellfield comprises 5 production boreholes, ranging in depth from 120-250m and lies in the southern fringes of the EKK-TBA in Botswana, Figure 5.1. It supplies groundwater to the Letlhakane Village.

5.1.2.1. Lithostratigraphy and structural geology

The stratigraphic units of the Letlhakane area are presented in Table 5.6.

Table 5.6: Lithostratigraphy of the Letlhakane Area

Age	Stratigraphic Unit			Lithology
	Supergroup	Group	Formation	
Recent to Tertiary		Kalahari		Calcrete and silcrete underlying variously consolidated sands
Post Karoo Intrusives				Dolerite dykes and sills
Mesozoic	Karoo	Stormberg	Drakensberg	Basaltic lava flows
		Lebung	Ntane	Fine to medium grained sandstones and siltstones
			Mosolotsane	Fluvio-lacustrine siltstones and mudstones with sandstones

Source: DWA (1993)

The Ntane Sandstone overlies Mosolotsane fluvio-lacustrine sediments which comprise siltstones and mudstones with intercalations of sandstones. A 3-5m thick fluviatile layer forms the basal layer of the Ntane Sandstone. The upper layer of the Ntane Sandstone consists of 48-140 m thick aeolian quartzitic sandstones which are interbedded with siltstones (Geoflux, 2005). The Ntane Sandstone is overlain by amygdaloidal basaltic lava flows of varying thickness (35-124m) and the basalt in turn is overlain by the Kalahari aeolian fine grained sands comprising calcretes and silcretes varying in thickness from 8-23m.

The formations are intruded by post Karoo dykes emplaced into pre-existing WNW striking fault planes and are part of the Okavango Dyke Swarm (DWA, 2000c). Post Karoo faulting is ubiquitous in the area, with most of the faults striking NE-SW, NW-SE and E-W and the Letlhakane River is structurally controlled (DWA, 1993).

5.1.2.2. Hydrogeology

5.1.2.2.1. Hydrostratigraphy

The Ntane Sandstone (equivalent to the Forest Sandstone in Zimbabwe) forms the main aquifer in the Letlhakane area, with yields varying from 0.5-90 m^3/hr. The basalt generally forms a confining layer to the Ntane Sandstone and can be high yielding where fractured, attaining yields of up to 45 m^3/hr (Geoflux, 2005). Figure 5.7 shows a generalized overview of the hydrogeological units within the Letlhakane Wellfield (Figure 5.9). The contact zone between the basalt and Ntane Sandstone presents a good groundwater occurrence zone with yields ranging from 8-26 m^3/hr (*ibid*).

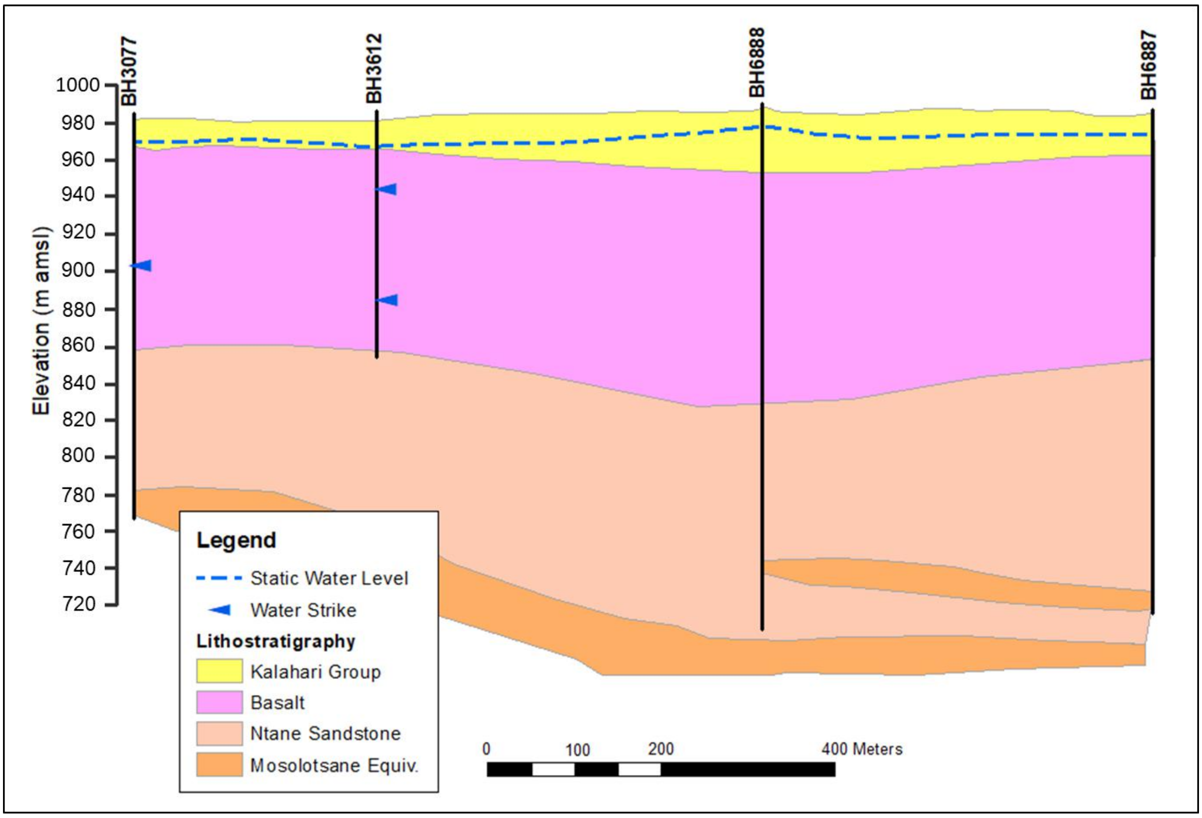


Figure 5.7: Hydrogeological units within the Letlhakane Wellfield
Source: modified after DWA (2000c)

5.1.2.2.2. Groundwater levels and flow

Groundwater level monitoring was commenced in April 1992 in 3 boreholes and an additional 2 boreholes were added in May 1995 (DWA, 2000c). Groundwater levels are measured on a daily basis in the production boreholes before the pumps are switched on and soon after the pumps are switched off. The measurements are archived into a well monitoring database called MELLMON at the DWS head office in Gaborone. Figure 5.8 shows groundwater level fluctuations in two of the boreholes (BHs 3077 and 3613). The groundwater levels have largely been unchanged for the greater part of the time and are only of late showing a conspicuous drop as a result of low rainfall and increased abstraction.

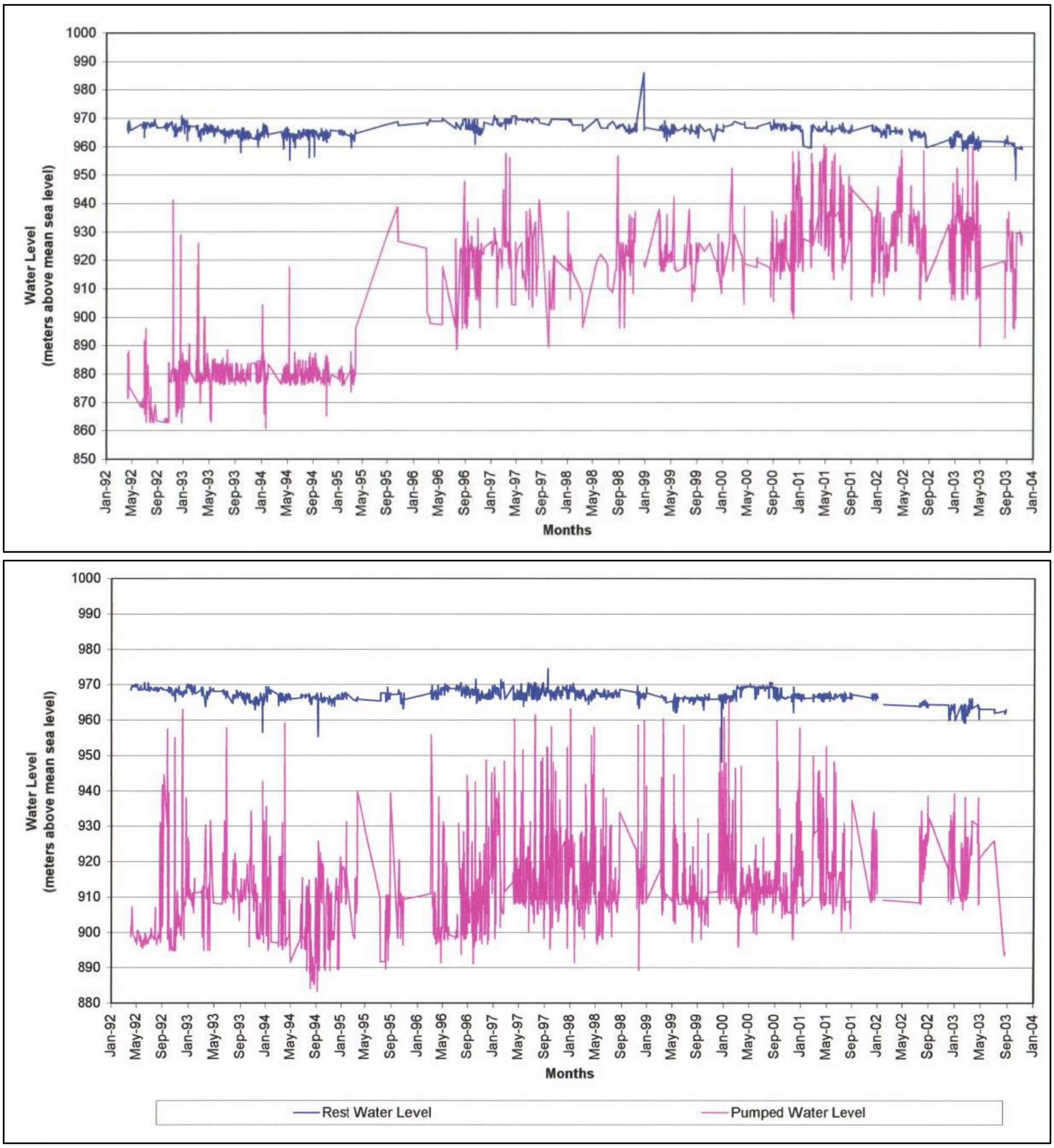


Figure 5.8: Letlhakane Wellfield production BHs groundwater level fluctuations
Top: BH 3077 and Bottom: BH 3613
Source: Geoflux (2005)

The groundwater is deduced to flow north to northwest, Figure 5.9, but this might not be reflective of the regional flow because of limited spatial distribution of monitoring boreholes. It would therefore be misleading to come to a conclusion based on very scanty data and this calls for an expanded well designed monitoring network that can definitively provide information on the groundwater dynamics.

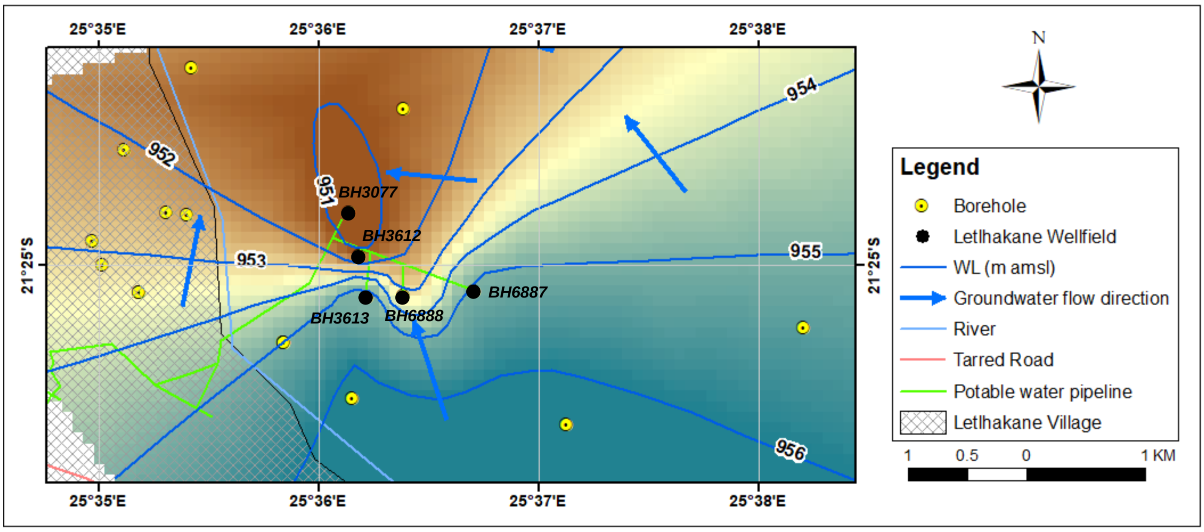


Figure 5.9: Letlhakane Wellfield piezometry and groundwater flow

Source: modified after Geoflux (2005)

5.1.2.2.3. Groundwater chemistry

The groundwater quality (Table 5.7) is generally considered potable (BOS 32:2000) (Table 5.3) though elevated nitrate concentrations have been recorded and these have been attributed to leaching of nitrate from cattle pens and posts along fracture and/or fault zones during seasons of high rainfall (Kefentse, 2004) and this is indicative of the susceptibility of the groundwater to pollution from surface sources.

Table 5.7: Results of physico-chemical analyses of Letlhakane Wellfield groundwater

	WELLFIELD BH				NEW BH				
Parameter	**3077**	**3612**	**3613**	**6888**	**10142**	**10143**	**10144**	**10145**	**10146**
Sampling date	16/04/04	16/04/04	16/04/04	16/04/04	28/01/05	04/02/05	19/02/05	26/02/05	05/03/05
EC (µS/cm)	1640	1650	1300	1260	1900	880	1200	1480	1070
TDS (mg/l)	998	936	760	768	1040	690	900	1070	700
pH	7.67	7.88	7.71	8.29	7.30	7.50	7.40	7.10	7.30
Na (mg/l)	242.7	249.4	168.5	217.1	282.8	146.0	229.0	281.5	137.6
K (mg/l)	6.0	5.2	4.21	4.7	7.8	26	4.3	4.8	1.5
Ca (mg/l)	56.8	53.7	56.2	50.4	54.6	60.0	50.0	67.0	74.1
Mg (mg/l)	19.1	42.6	39.6	20.2	32.2	25.2	28.8	36.8	37.1
Fe (mg/l)	0.1	0.0	0.1	0.2	0.253	0.114	0.172	0.025	0.029
Mn (mg/l)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cl (mg/l)	210.7	246.9	150.9	130.0	317.2	78.5	220.3	222.6	104.4
NO_3^- (mg/l)	41.3	38.4	25.9	22.8	83.5	22.6	57.1	44.3	15.2
F (mg/l)	0.0	0.0	0.0	0.0	0.7	0.8	0.7	0.8	1.2
HCO_3^-(mg/l)	502.9	525.8	533.5	433.6	414.6	493.9	428.8	589.3	502.0
CO_3^{2-} (mg/l)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO_4^{2-} (mg/l)	54.6	54.6	24.6	79.3	33.6	18.0	28.2	60.5	18.3

Source: Geoflux (2005)

Geoflux (2005) reckons that the main potential source of groundwater pollution could be the Letlhakane Mine situated upgradient of the wellfield, the sewerage system of the prison which is located within the wellfield and from cattle waste in cattle posts and pit latrines.

The TDS generally increases in a southwesterly direction, Figure 5.10, based on the available (limited) measuring points. An even spatial distribution of measuring points would have provided a clear picture on the evolution of the groundwater chemistry. Overall, the groundwater chemical type is adjudged a Na-Cl, HCO_3 type of water (Geoflux, 2005).

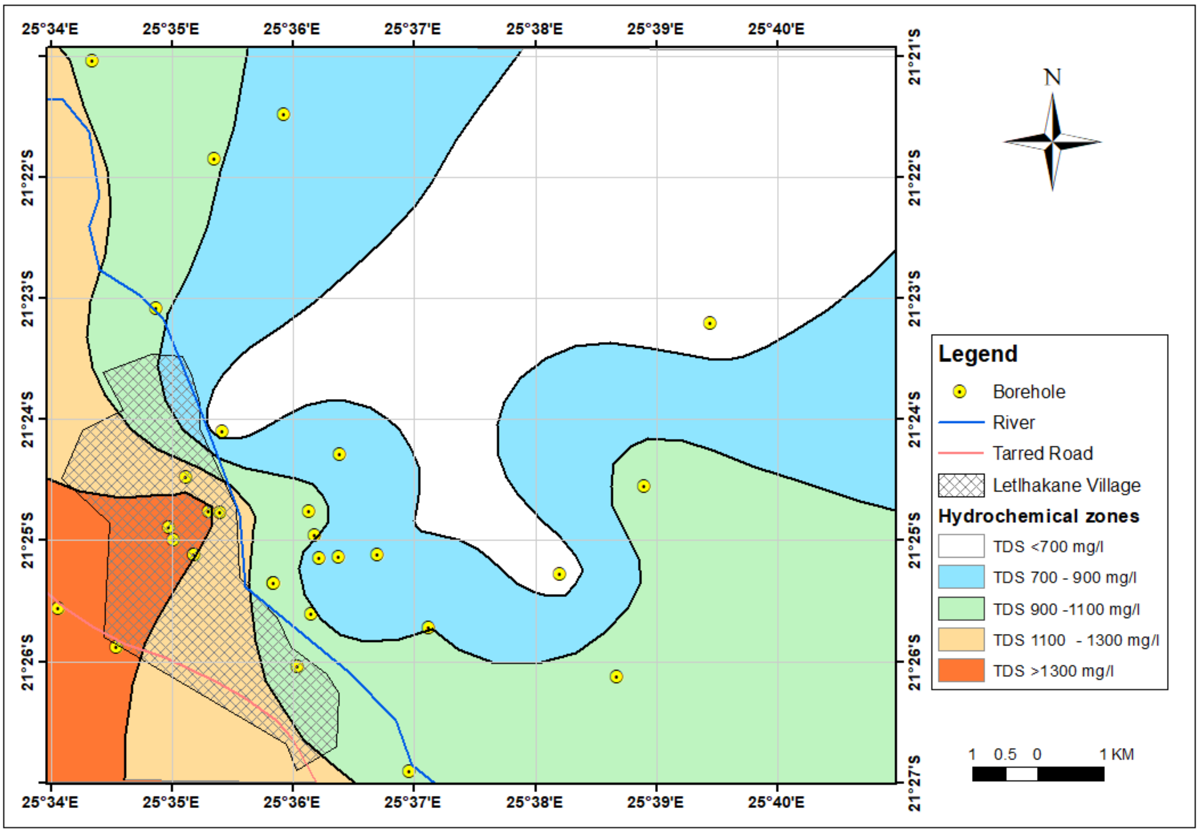


Figure 5.10: TDS of groundwater around Letlhakane Wellfield
Source: modified after Geoflux (2005)

5.1.2.2.4. Groundwater recharge

Direct groundwater recharge from rainfall is very unlikely where the basalt is compact and unfractured. Nevertheless, preferential recharge can take place along fault or fractured zones as evidenced by the low TDS values of boreholes close to the Letlhakane River (DWA, 1993). Geoflux (2005), using the chloride mass balance method, estimated the groundwater recharge at 2.69 mm/yr by considering the 1990 annual chloride deposition of 478 mg/m^2/yr at the Letlhakane station and chemical analyses results presented in Table 5.7.

5.1.2.2.5. Hydraulic characteristics

The transmissivity values for the wellfield range from 10-60 m^2/d (Geoflux, 2005). Table 5.8 shows the hydraulic characteristics of the various formations.

Table 5.8: Hydraulic characteristics boreholes Letlhakane Wellfield

<table>
<tr><th>Formation</th><th>Thickness (m)</th><th>Yield (m3/hr)</th><th>Water Strike Depth (m bgl)</th><th>Transmissivity (m2/d)</th></tr>
<tr><td>Kalahari Group</td><td>8-23</td><td>7-8</td><td>10-36</td><td>-</td></tr>
<tr><td>Basalt</td><td>35-124</td><td>Up to 45</td><td>9-142</td><td>-</td></tr>
<tr><td>Ntane Sandstone</td><td>48-140</td><td><0.5-89.5</td><td>14-245</td><td rowspan="2">10-60</td></tr>
<tr><td>Basalt-Ntane Sandstone Contact Zone</td><td>-</td><td>8-26</td><td>12-143</td></tr>
<tr><td>Mosolotsane</td><td>-</td><td>Up to 45</td><td>184-258</td><td>-</td></tr>
</table>

Source: Geoflux (2005)

5.1.3. Maitengwe Wellfield

The Maitengwe Wellfield comprises 9 production boreholes, ranging in depth from 110-200m (DWA, 2002), and it lies on the border with Zimbabwe, Figure 5.1. It supplies groundwater to the Northeastern District which previously obtained groundwater from the unreliable crystalline basement and sand river aquifers that barely met the water demand (*ibid*).

5.1.3.1. Lithostratigraphy and structural geology

Exploration boreholes in the Maitengwe area intersect the Kalahari and the Karoo sedimentary succession down to the Ecca (Tlapana and Mea Arkose Formations), WSB (2003), Table 5.9. Figure 5.11 shows the Pre-Kalahari geology of the area.

Table 5.9: Lithostratigraphy Maitengwe Wellfield

<table>
<tr><th rowspan="2">Age</th><th colspan="3">Stratigraphic Unit</th><th rowspan="2">Lithology</th></tr>
<tr><th>Supergroup</th><th>Group</th><th>Formation</th></tr>
<tr><td>Upper Cretaceous to Recent</td><td></td><td>Kalahari</td><td>Kalahari Group</td><td>Alluvium, lacustrine deltaic duricrust, residual soil & sand</td></tr>
<tr><td colspan="4">Post Karoo Intrusives</td><td>Dolerite dykes and sills</td></tr>
<tr><td>Jurassic</td><td rowspan="6">Karoo</td><td>Stormberg</td><td>Drakensberg</td><td>Basaltic lava flows</td></tr>
<tr><td rowspan="3">Triassic</td><td rowspan="3">Lebung</td><td>Upper Ntane</td><td>Aeolian sandstone</td></tr>
<tr><td>Lower Ntane</td><td>Fluvial sandstone</td></tr>
<tr><td>Ngwasha</td><td>Mudstones and minor sandstones, red beds</td></tr>
<tr><td rowspan="2">Permian</td><td rowspan="2">Ecca</td><td>Lower Tlapana</td><td>Mudstones</td></tr>
<tr><td>Mea Arkose</td><td>Arkose</td></tr>
<tr><td>Archaean</td><td colspan="3">Mosetse Complex</td><td>Granite-Greenstone</td></tr>
</table>

Source: WSB (2003)

The Mea Arkose Formation is deposited on top of the Archean (Pre-Karoo) basement and is overlain by the Lower Tlapana Formation (max 120m thickness) and the Ngwasha Formation (max 130m thickness) comprising mudstones and minor sandstones. The overlying Ntane Sandstone ranges in thickness from 2-76m and has an average thickness of about 60m. Overlying the Ntane Sandstone is the Stormberg Basalt which has a thickness ranging from around 35m to about 300m, with an average thickness of 108m. The basalt is strongly controlled by the Bushman Lineament, a major fault running north to southwest, with a thicker basalt unit in the western side of the fault than on the eastern side, Figure 5.11. The basalt thickens towards the northwest, reaching thicknesses of about 300m. In the eastern part of the wellfield, the basalt is considerably thinner and more deeply weathered and is absent along the southern margins. The Kalahari Group in the area is generally less than 50 m thick (with an average thickness of 23m) and thickens north-west and northwards towards Zimbabwe (DWA, 2002).

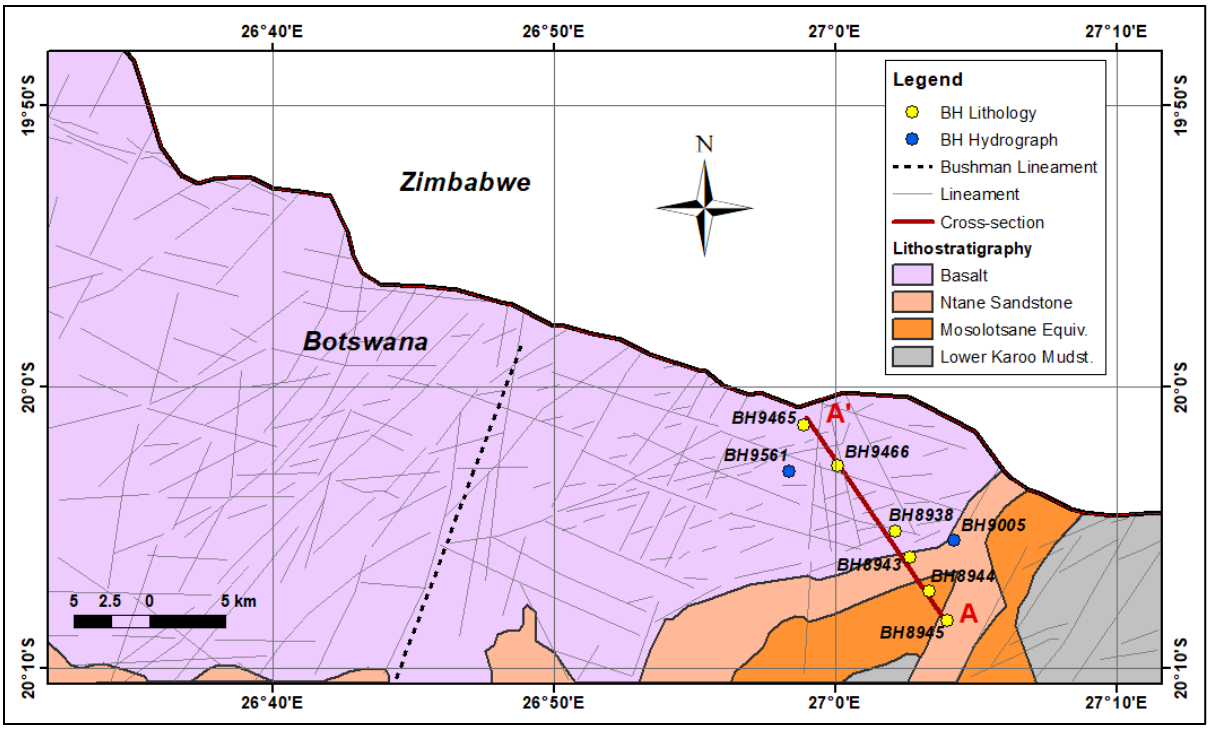


Figure 5.11: Pre-Kalahari geology of the Maitengwe area
Source: modified after DWA (2002)

Variations in elevation of the Ntane Formation and the basement depth are indicative of faulting and vertical displacement along the southern margin of the graben structure. This is clearly seen in southeast-northwest geological cross-section through the wellfield, Figure 5.11 and Figure 5.12.

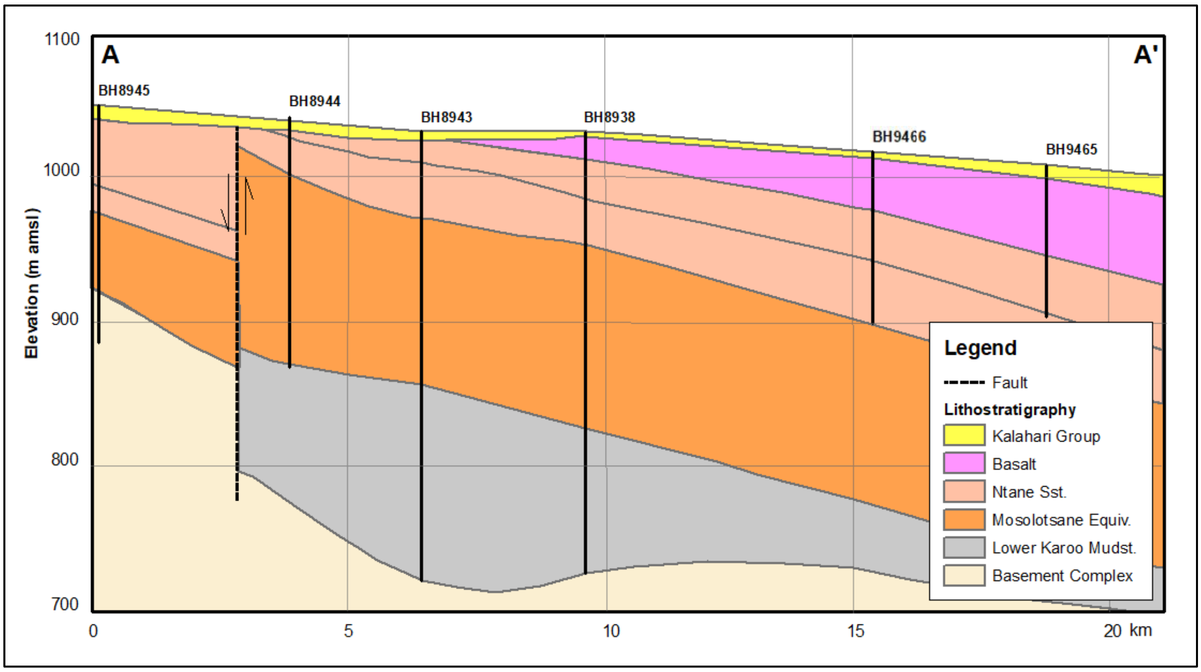


Figure 5.12: SE-NW geological cross-section (A-A') through Maitengwe Wellfield
Source: modified after DWA (2002)

5.1.3.2. Hydrogeology

5.1.3.2.1. Hydrostratigraphy

The Mea Arkose Formation has been identified as a potential confined aquifer. It is overlain by an aquitard comprising mudstones and siltstones intercalated with sandstone (DWA, 2002). The Upper Ntane Sandstone overlying the mudstones and siltstones forms the main aquifer, with yields varying from 24-240 m^3/d (DWA, 2002). The aquifer exhibits semi-confined to confined dual porosity conditions and becomes confined when moving towards the central portions of the basin. The basalt overlying the Ntane Sandstone forms both an aquiclude and aquitard and where it is deeply weathered and fractured (aquitard), localised high yields (200-1 000 m^3/d) can be obtained (DWA, 2002; United Nations, 1989). The overlying Kalahari Group does not constitute an aquifer since no groundwater has been encountered in boreholes drilled through it (DWA, 2002).

5.1.3.2.2. Groundwater levels and flow

Limited groundwater level monitoring was carried out in Maitengwe Wellfield in 1999 (January – March) and typical hydrographs from 2 of the 26 monitoring network boreholes (BH 9005 and BH 9561) are presented in Figure 5.13. BH 9005 clearly shows a declining water level and hence the need for effective groundwater management. Confined aquifer condition of the Ntane Sandstone at BH 9561, which is further away (down-gradient) from the recharge area, is likely the reason why there is no change visible for the groundwater level during the same, relatively short, monitoring period (Figure 5.11 and Figure 5.12).

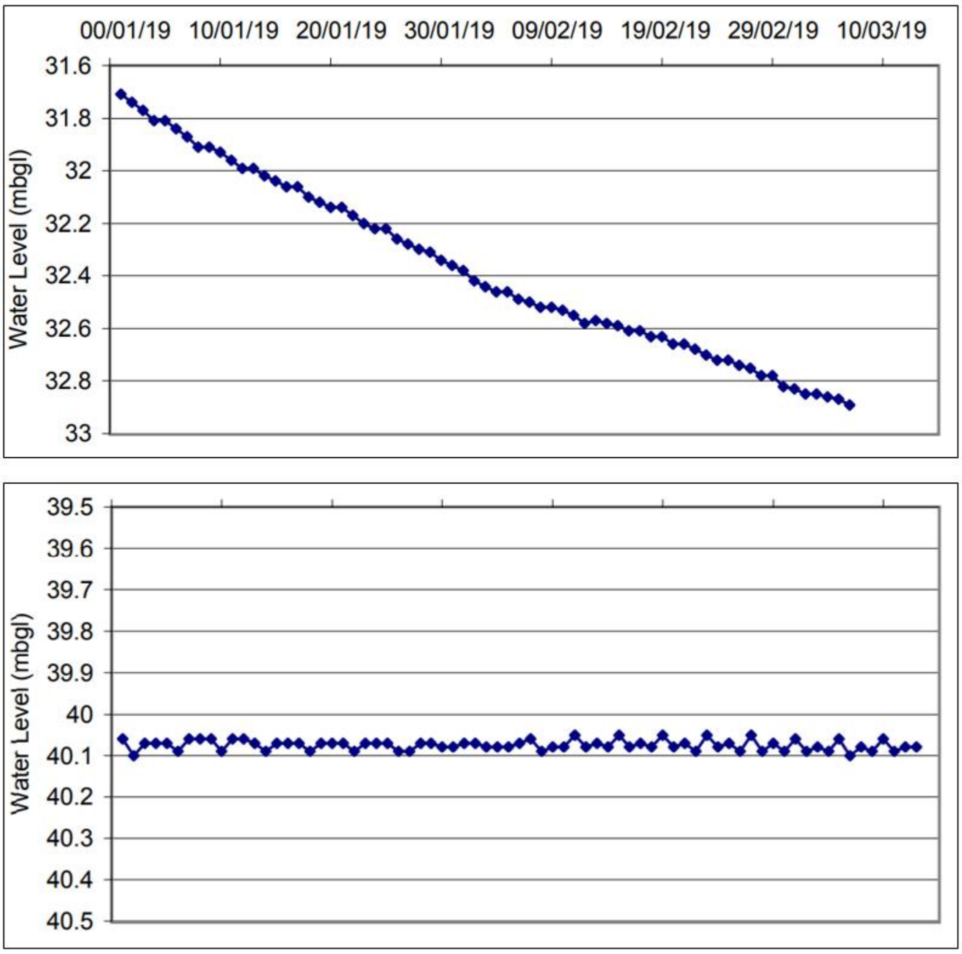


Figure 5.13: Groundwater hydrographs Maitengwe
Top: BH 9005 and Bottom: BH 9561
Source: DWA (2002)

Groundwater level information from the Maitengwe Wellfield shows that groundwater flows northwest towards the central portions of the basin and then southwest towards the Makgadikgadi Pans, Figure 5.14.

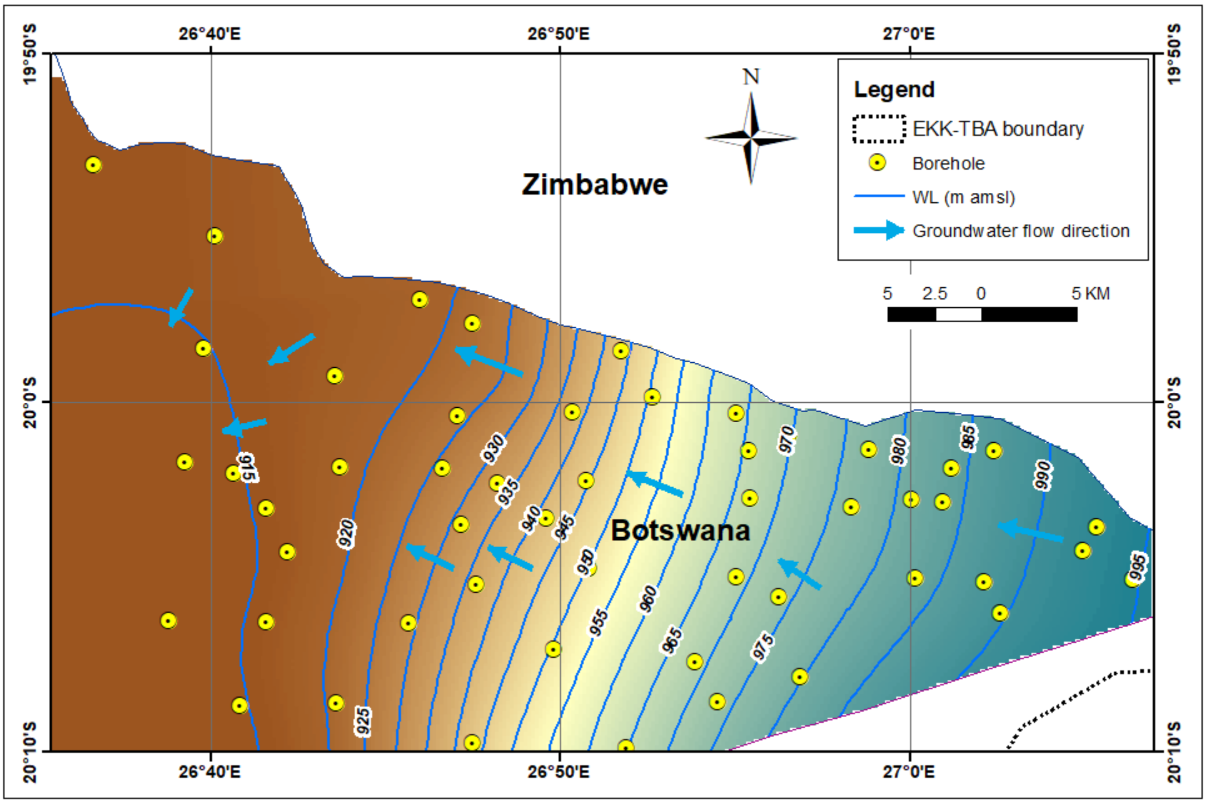


Figure 5.14: Maitengwe Wellfield piezometry and groundwater flow

Source: modified after DWA (2002)

5.1.3.2.3. Groundwater chemistry

Groundwater from the Upper Ntane Sandstone shows a progressive deterioration in water quality towards the northwest, in the direction of deepening of the aquifer and within less than 20km along the flow paths from the recharge zone (DWA, 2002). The groundwater was classified into five hydrochemical zones, Figure 5.15:

- Eastern Zone: $CaHCO_3$ type waters with TDS generally below 500 mg/l
- North Central Zone: Na-$CaHCO_3$ type waters with TDS increasing westwards from 500mg/l to 1 000mg/l
- South Central Zone $NaHCO_3$ type waters with TDS ranging from 500 to 1 000mg/l
- Transition Zone: TDS from around 1 000 mg/l in the east to 2 000 mg/l in the west; $NaHCO_3$ waters in the east and NaCl waters to the western side
- Western Zone: NaCl waters progressively becoming more saline to the northwest with TDS >70 000mg/l

Note that the area with low salinity $CaHCO_3$ type waters typically represents the recharge area.

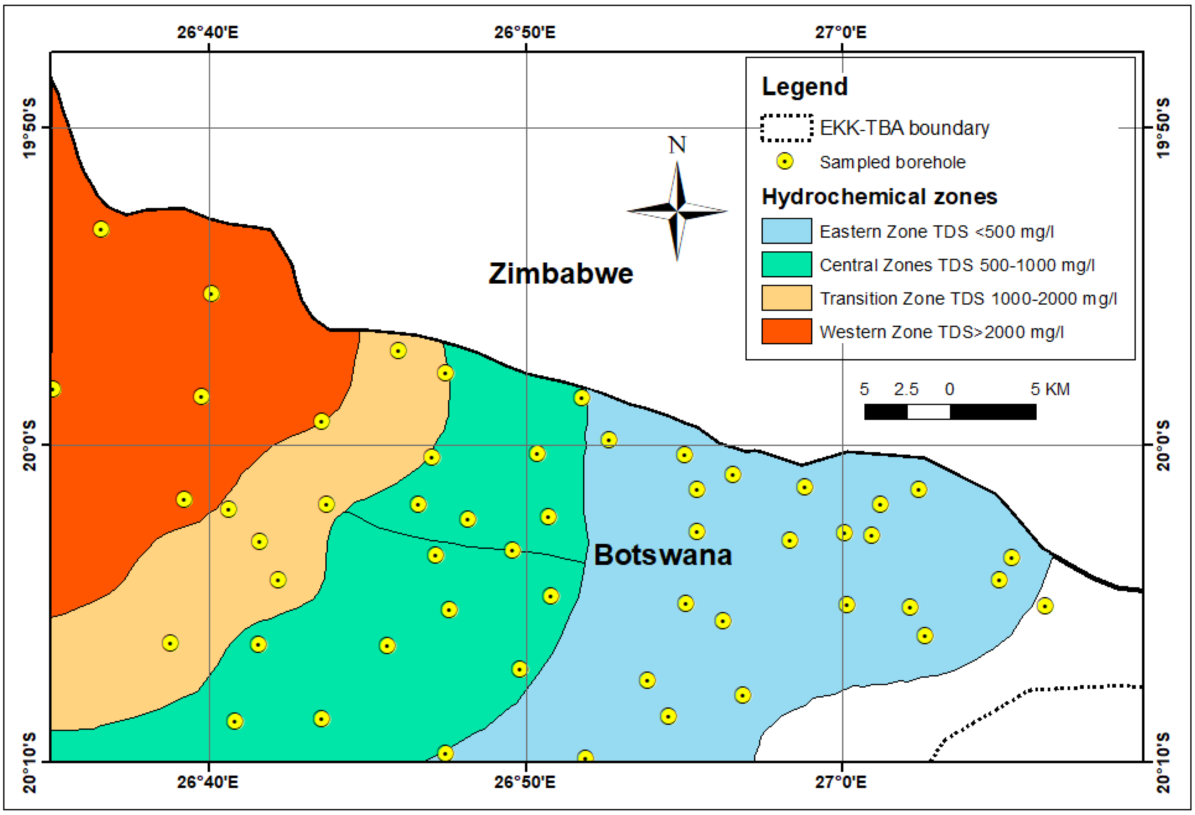


Figure 5.15: Upper Ntane Sandstone hydrochemical zones
Source: modified after DWA (2002)

5.1.3.2.4. Groundwater recharge

Groundwater recharge investigations of the Ntane Sandstone Aquifer were conducted within the Maitengwe Wellfield area (~125 km^2) using the CMB and Carbon-14 dating methods. CMB yielded recharge rates of 9-14 mm/yr and 10 mm/yr was considered reasonable (DWA, 2002). Carbon-14 (C-14) dating provided a wide range of recharge rates, varying from 2-37 mm/yr. The higher recharge rates were attributed to (indirect) recharge from the Maitengwe River (*ibid*). Groundwater from the Ntane Sandstone had C-14 age dating of 350-1 200 years, whereas that from the Ngwasha Formation (equivalent to the Mosolotsane Formation) had ages varying from 4 000-8 000 years making it considerably older than that of the overlying Ntane Sandstone and hence the two aquifers are not hydraulically connected within this particular area (*ibid*).

5.1.3.2.5. Hydraulic characteristics

Average transmissivities and storage values of the Ntane Sandstone Aquifer for the production boreholes are presented in Table 5.10. The transmissivity values range from 2-400 m^2/d and are mostly <10 m^2/d and the hydraulic conductivities range from 0.1-10 m/d. Late specific storage (S Late) ranges from 1E-6 to 8E-3 with an average of 2.2E-4/m.

Table 5.10: Hydraulic characteristics Ntane Sandstone - Maitengwe Wellfield

BH	T (m^2/day)	S early	S Late
9465	126	0.0000165	0.00111
9466	406	0.00014	0.00113
9467	262	0.0000225	0.00191
9468	56	0.000057	0.00533
9469	140	0.000013	0.00275
9470	30	0.0000268	0.00134
9471	114	0.000725	0.00265
9472	10	0.00012	0.000531
9473	34	0.00006	0.00277
9474	245	0.000424	0.00233
9933	32	0.0000027	0.00063
9934	45	0.00002	0.001
9935	48.5	0.000008	0.0008
9961	16	0.0000011	0.0000014
9960	30	0.0000003	0.000002

Source: WSB (2003)

5.1.4. Nyamandlovu Wellfield

The Nyamandlovu Wellfield lies towards the southeastern margin of the EKK-TBA in Zimbabwe, Figure 5.1. The wellfield was developed in 1992 in response to the dire water situation faced by the City of Bulawayo (second largest city in Zimbabwe) resulting from the 1991/92 severe drought.

5.1.4.1. Lithostratigraphy and structural geology

The lithostratigraphy of the Nyamandlovu area is presented in Table 5.11 and the geology of the area and surface water drainage are shown in Figure 5.16.

Table 5.11: Lithostratigraphy of the Nyamandlovu area

System	Description	Geological age
Quaternary	Alluvium, ferricrete, and colluvium	Pleistocene and Recent
Tertiary	Kalahari Group: loosely consolidated. Has a bed of concretionary ironstone and frequently chalcedonic or indurated sandstone	Late Tertiary
Karoo System	Constitutes basalt overlying Forest Sandstone which is the main aquifer	Late Triassic for Basalt Upper Triassic for the Sandstone
Intrusive Rocks	Granites	Precambrian
Bulawayan	Volcanic greenstones, lying outside the Nyamandlovu area	Early Precambrian

Source: Beekman and Sunguro (2015)

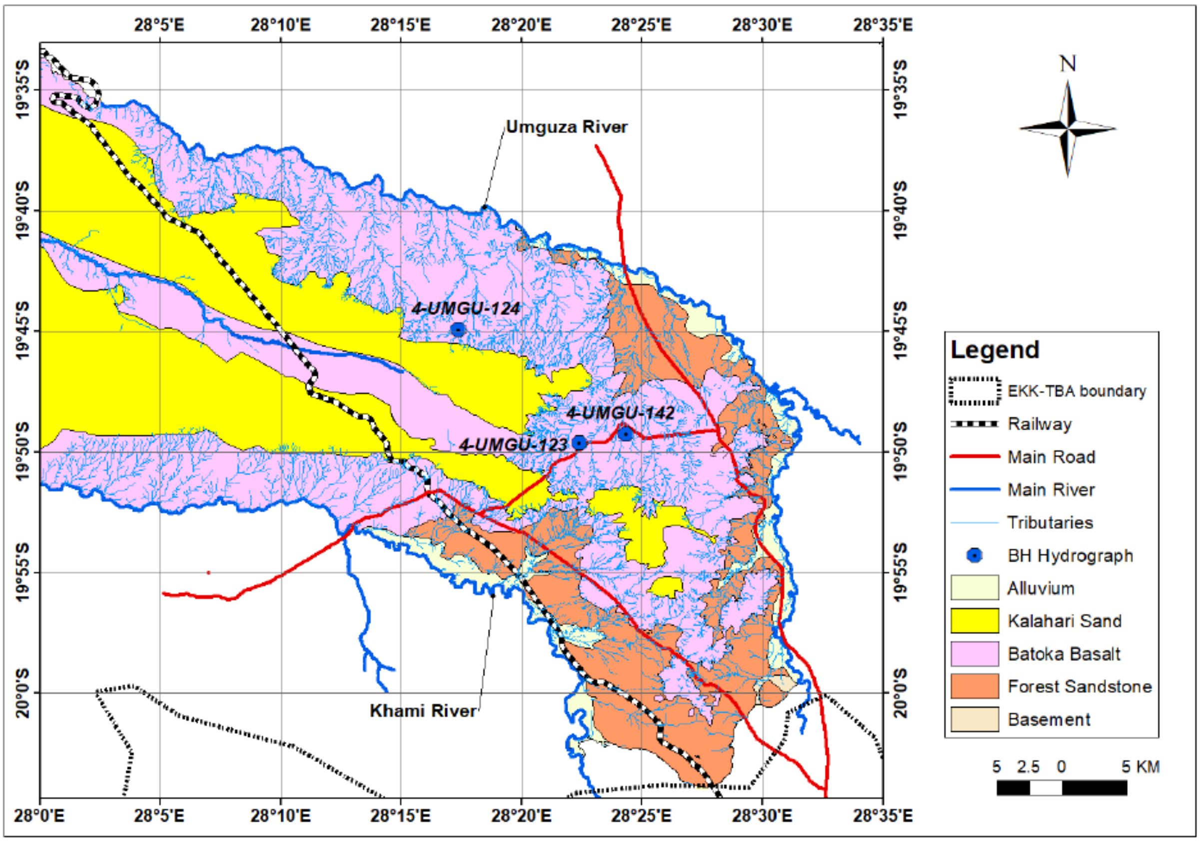


Figure 5.16: Geology of the Nyamandlovu area
Source: modified after Beekman and Sunguro (2015)

The Forest Sandstone lies directly on top of basement rocks and has an average thickness of 100m within the Nyamandlovu Wellfield and thickens with the deepening of the basin to the northwest (Beekman and Sunguro, 2015). The Batoka Basalt, which overlies the Forest Sandstone, is absent in the south-eastern fringes of the basin and also thickens towards the northwest and west. Its thickness within the area is usually less than 50m *(ibid)*. The thickness of the overlying Kalahari Group varies from 0-70m and also thickens towards the deeper parts of the basin (northwards and westwards). Note that the tributaries of the Khami and Umguza Rivers are exposing underlying formations through headward erosion of the Kalahari Group. The Formations in the Nyamandlovu area have undergone little structural deformation and faulting which is unlike the wellfields in the southern part of the Basin such as the Dukwi and OLDM Wellfields in which the formations are strongly structurally controlled.

5.1.4.2. Hydrogeology

5.1.4.2.1. Hydrostratigraphy

The Forest Sandstone (equivalent to the Ntane Sandstone in Botswana) constitutes the major aquifer from which the Nyamandlovu Wellfield was developed to augment water supplies to the City of Bulawayo. Borehole yields range from 2-20 m^3/hr (Martinelli and Hubert, 1996; Beasley, 1983; Beekman and Sunguro, 2015). Local farmers also rely on groundwater from the aquifer (abstracted through own boreholes), for agricultural purposes (cropping and livestock). The Batoka Basalt overlies the Forest Sandstone and forms a confining layer in certain places and has been eroded or fractured and faulted in others thereby giving rise to water table and leaky conditions. In areas where the basalt is not fractured, it forms a bedrock (aquiclude) for the Kalahari Group deposits. Interconsult (1986) reckons that yields from Kalahari Group deposits vary between 8-90 m^3/d, with borehole depths ranging from 30-70m.

Within the Nyamandlovu area, the Kalahari Group does not form a significant aquifer for the volume of abstractions required for urban water supplies or intensive irrigation due to its limited thickness and yields. Along major river channels, the Kalahari Group has been eroded away exposing underlying basalt.

5.1.4.2.2. Groundwater levels and flow

A groundwater level monitoring network was set up in 1989 with initially around 79 boreholes. Recent communication with ZINWA staff indicates that monitoring is erratic, particularly after 2016 due to lack of resources.

Figure 5.17 shows three hydrographs of monitoring boreholes that represent groundwater level responses to rainfall and abstraction in the area: 4-UMGU-123 in the more confined part (down-gradient) of the aquifer; 4-UMGU-124 in the (semi)unconfined part of the aquifer and 4-UMGU-142 a production borehole of the wellfield (Beekman and Sunguro, 2015). Over the period of 1989 to 2015, the monitoring revealed the following trends:

- From 1989 to 1998, when systematic monthly monitoring started over the whole Nyamandlovu area, water levels declined on average by about 4 m and in the wellfield which was established in 1992/93, in certain areas, the groundwater levels have even declined by up to 12 m; the average annual rainfall of ~420 mm (excluding 1997/98 for which there were no data) over this period could not compensate for the abstractions; clearly, drought conditions prevailed;
- From 1998 to the end of 1999, water levels remained more or less the same;
- From 2000 to 2002, which includes increased rainfall from Cyclone Eline since 22nd February 2000, water levels increased by ~2 m on the average;
- From 2002 to 2006, water levels remained more or less the same;
- From 2006 to 2015, water levels declined by 2 to 3 m

Note that over the period of 2006 to 2009 there were no water level data available.

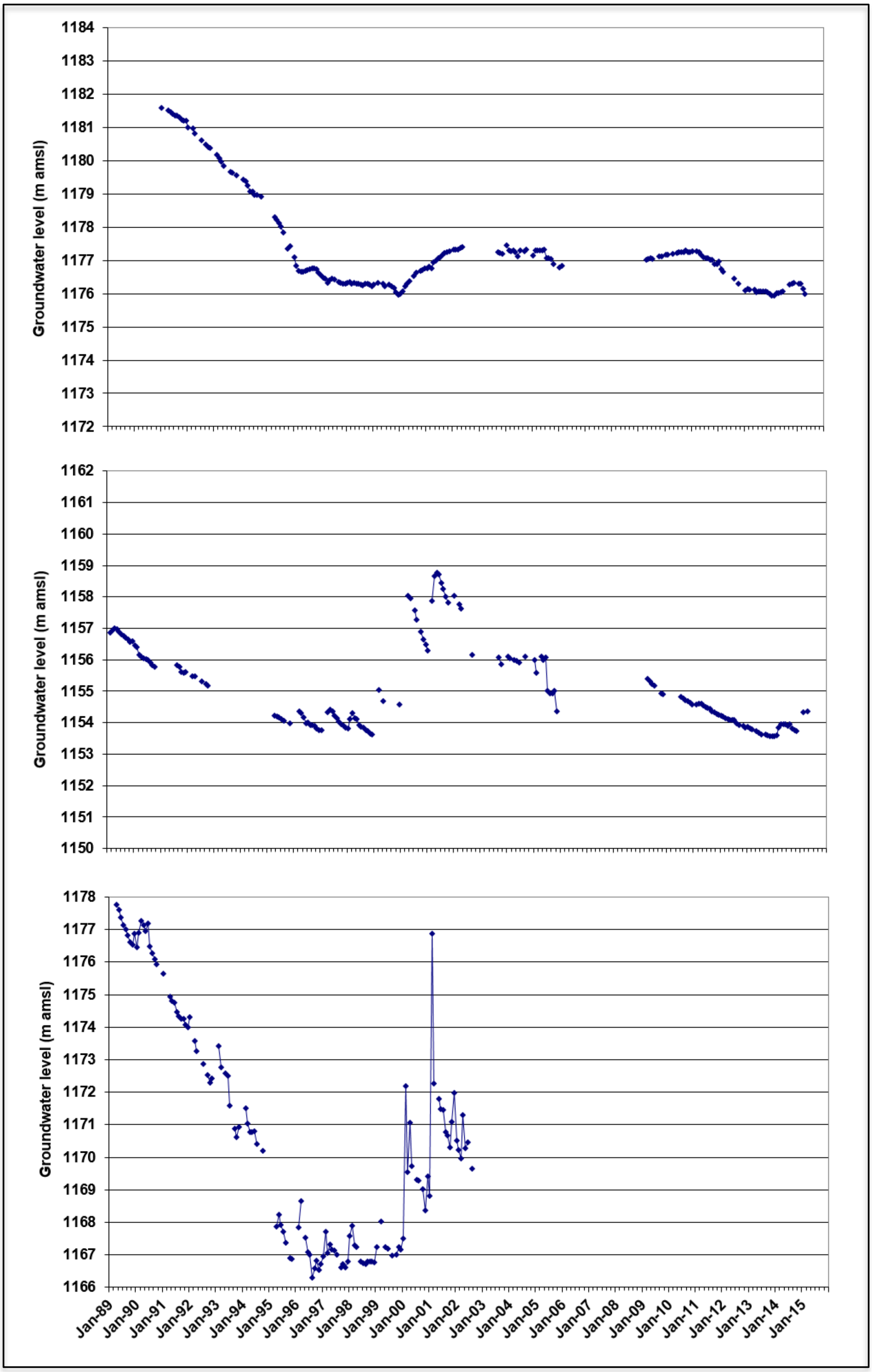


Figure 5.17: Groundwater hydrographs Nyamandlovu area

Top: BH 4-UMGU-123; Middle: BH 4-UMGU-124; Bottom: BH 4-UMGU-142

Source: modified after Beekman and Sunguro (2015)

Groundwater within the Nyamandlovu area flows in a northwesterly to northerly direction and mimics the (subdued) topography as shown in Figure 5.18 for the year 1999.

In the Kalahari Group deposits, water levels (measured below ground level) are generally >20m and borehole yields generally lie between 100-1000 m^3/d (Interconsult, 1986).

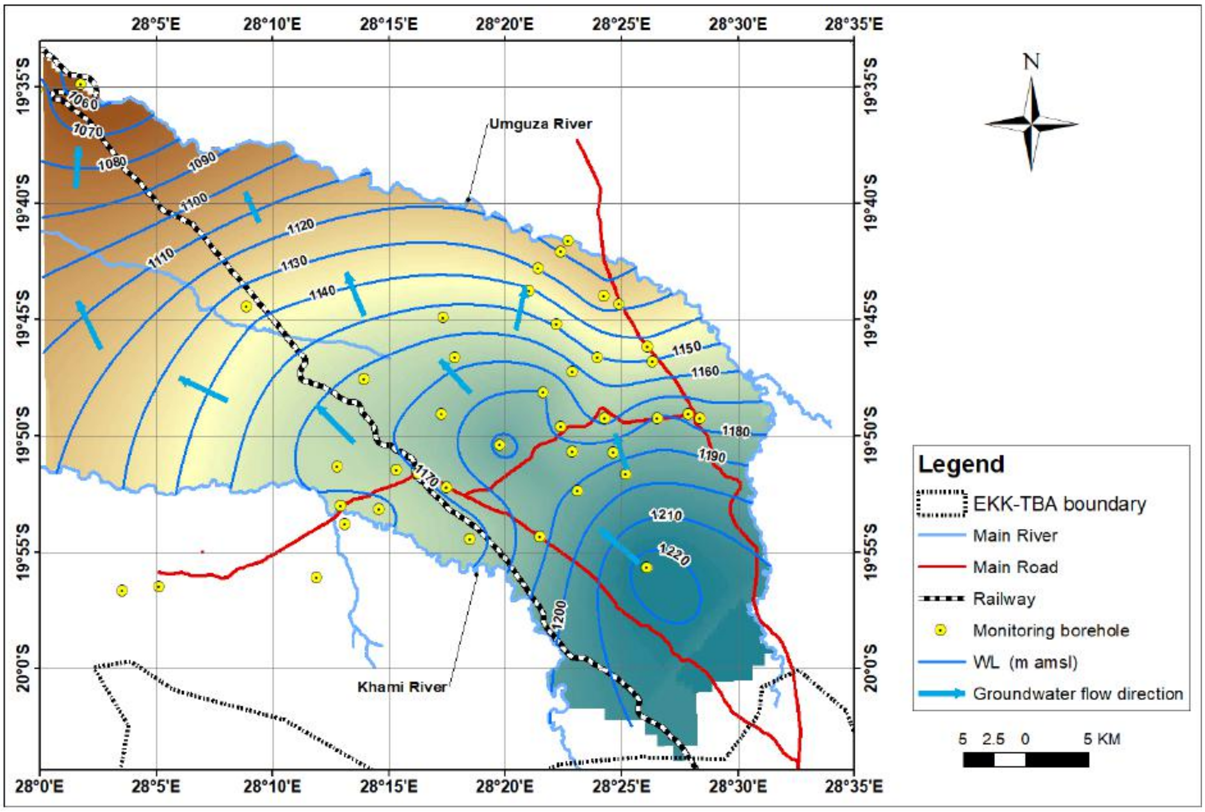


Figure 5.18: Piezometry and groundwater flow directions in the Nyamandlovu area
Source: modified after Beekman and Sunguro (2015)

5.1.4.2.3. Groundwater chemistry

The groundwater quality of the Nyamandlovu (Forest) Sandstone Aquifer is generally good with relatively low electrical conductivity (EC) of 300-500 µS/cm in the Nyamandlovu Wellfield (Sunguro, 1991; Larsen et al., 2002; Table 5.12) and is compliant with the Zimbabwe guideline for drinking water (Table 5.13). Isolated high nitrate levels were recorded in boreholes belonging to certain Nyamandlovu farmers and the nitrate levels were correlated to poorly constructed boreholes that allowed leakage into the aquifer along the borehole casing (Sunguro, 1991). Nielsen (2000) sampled groundwater from 24 boreholes across the Nyamandlovu Aquifer in December 1999 for major cation and anion chemistry and ^{14}C, ^{13}C, ^{3}H, ^{2}H and ^{18}O analysis. Away from the recharge area in the direction of flow, the groundwater is aging and changes its composition from a relatively young (~85 pmC) fresh Ca-HCO_3 water type to an older (<1 pmC: >20 000 years after 20 km) and sightly more mineralized Na-HCO_3 water type, the latter water type suggesting the refreshening of a salt water aquifer (Nielsen, 2000; Larsen et al., 2002).

Table 5.12: Groundwater composition Nyamandlovu area

Water type (#BHs)		pH	O_2	EC	Ca	Mg	Na	K	SiO_2	HCO_3	Cl	NO_3	F	SO_4
			(mg/l)	(µS/cm)	<---------------------(mg/l)--------------------->									
$Ca\text{-}HCO_3$ (18)	Min	6.6	0.6	346	28	11	8.9	0.4	15	206	2.1	0.4	0	0
	Max	7.2	6.4	1042	99	32	33	3.4	35	534	26	72	0.5	27
	Avg	6.9	2.9	678	68	20	19	1.6	28	375	11	18	0.1	3.7
$Na\text{-}HCO_3$ (4)	Min	9.1	0.2	465	0.5	0	87	0.7	6.2	27	11	0	0.1	1.3
	Max	9.4	2.2	1079	45	0.2	155	2.0	10	458	30	1.4	5.3	267

Source: based on Larsen et al. (2002)

Table 5.13: Zimbabwe guideline for drinking water quality

Parameter	Guideline value*	Parameter	Guideline value*
Colour (TCU)	15	Arsenic	0.05
Turbidity (NTU)	5	Cadmium	0.005
pH	6.5-8.5	Chromium	0.05
Hardness (as $CaCO_3$)	500	Cyanide	0.1
Iron	0.3	Fluoride	1.5
Manganese	0.3	Lead	0.05
Sulphate	400	Mercury	0.001
Chloride	250	Selenium	0.01
Total Dissolved Solids	1 000	Zinc	5
Nitrate	10	F. coli/100 ml	0
		T. coli/100 ml	0

* Note: All units, except pH, in mg/l unless stated otherwise
Source: WHO Guideline for drinking water (1984)

5.1.4.2.4. Groundwater recharge

Several groundwater recharge investigations were carried out related to the Forest Sandstone utilising various methods that ranged from CMB, WTF, Darcian Flownet, ^{14}C age dating to groundwater modelling (Sibanda and Nonner, 2009; Beekman and Sunguro, 2015). For the CMB method, recharge varied from 2.6-38.5 mm/yr (harmonic mean of 18.4 mm/yr), WTF from <4 – 49 mm/yr and groundwater modelling from 2 to 40 mm/yr or an average of 14.6 mm/yr over a recharge area of 960 km^2 (Beekman and Sunguro, 2015). High recharge rates appear to occur along preferential paths such as fracture and fault zones (*ibid*). The average annual recharge amounts to 2.6% of the average annual rainfall of 560 mm/yr. In Figure 5.19, calculated recharge based on the WTF method is plotted against rainfall for 10 boreholes with fitted lines through the data of each borehole (aquifer conditions are unconfined to leaky). The figure shows a threshold value of ~350 mm/yr rainfall below which there is hardly any recharge in the Nyamandlovu area and that there is a wide range in recharge rates at an average rainfall of 560 mm/yr. The data also shows that it is not likely that recharge in the area will be higher than 30mm/yr.

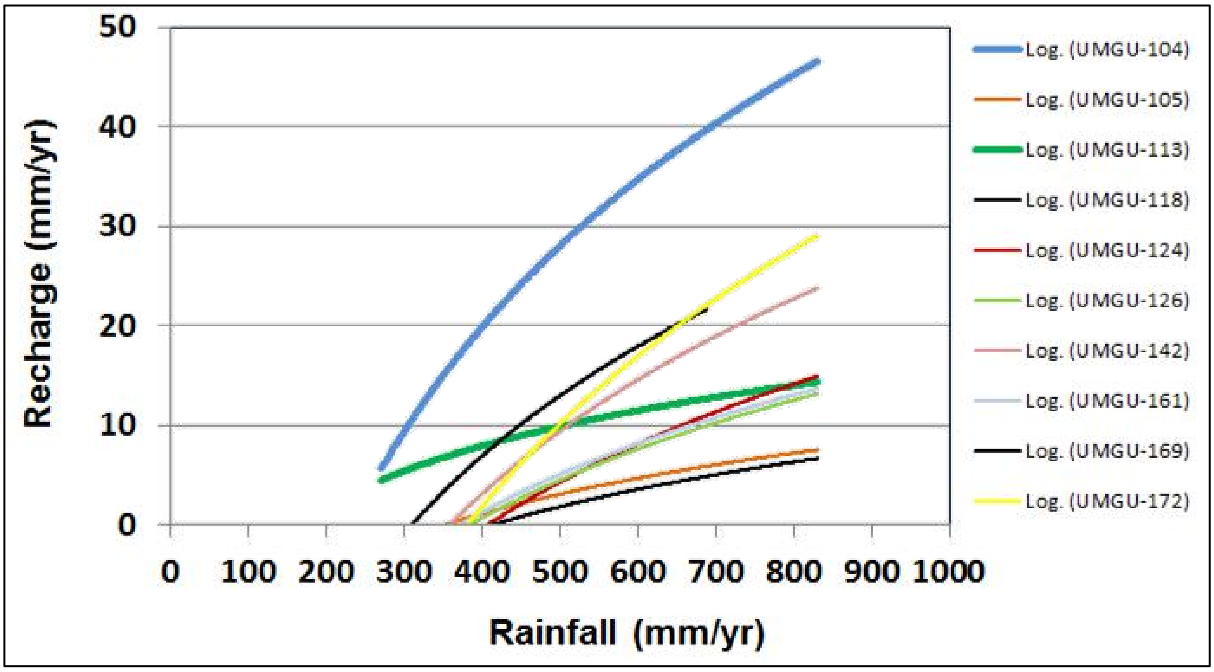


Figure 5.19: Rainfall versus recharge in the Nyamandlovu area

UMGU-104 represents a borehole name

Source: after Beekman and Sunguro (2015)

5.1.4.2.5. Hydraulic characteristics

The Forest Sandstone aquifer parameters were determined through numerous assessment studies including pumping tests from as early as 1973. In general, the transmissivity (T) values range from 1-100 m^2/d, the hydraulic conductivity (K) values from 0.1-1.7 m/d and the storage coefficient (S) from 1E-4 to 1E-3, Table 5.14 (Beekman and Sunguro, 2015). Transmissivity of the Batoka Basalt ranges between 1 and 300 m^2/d, specific capacities are in the range of 10-100 m^3/d/m and storativity values are averaging 10^{-5} (Interconsult, 1986). Note that the relatively high hydraulic conductivity of borehole 4-UMGU-80 (Exp 2) of 10.77 m/d likely represents the alluvium as the borehole is shallow and next to the Khami River. The transmissivity values of the Kalahari Group deposits range from 5-50 m^2/d.

Table 5.14: Hydraulic characteristics Forest Sandstone – Nyamandlovu area

Formation	Thickness (m)	Yield (m^3/d)	Water Strike (m bgl)	Transmissivity (m^2/d)	Hydraulic Conductivity (m/d)	Storage Coefficient
Kalahari Group and Alluvium	<10	<100	>20	5-50	<10.77	-
Batoka Basalt	10-50	10-250*	>20	1-300*	-	10^{-6}
Forest Sandstone	50-120	50-500	>20	1-100	0.1-1.7	$1x10^{-5}$-$8x10^{-3}$

*Higher values if the Batoka Basalt is fractured

Source: Beekman and Sunguro (2015)

5.2. Private owned and managed diamond mines wellfields

Most private owned and managed wellfields within the EKK-TBA are from the diamond mining industry (Orapa, Letlhalkane and Damtshaa Mines (OLDM) and the Karowe Diamond Mine (KDM)) and these by far abstract most of the groundwater for mining activities. The wellfields for diamond mining are to the south of the Makgadikgadi Pans, Figure 5.20.

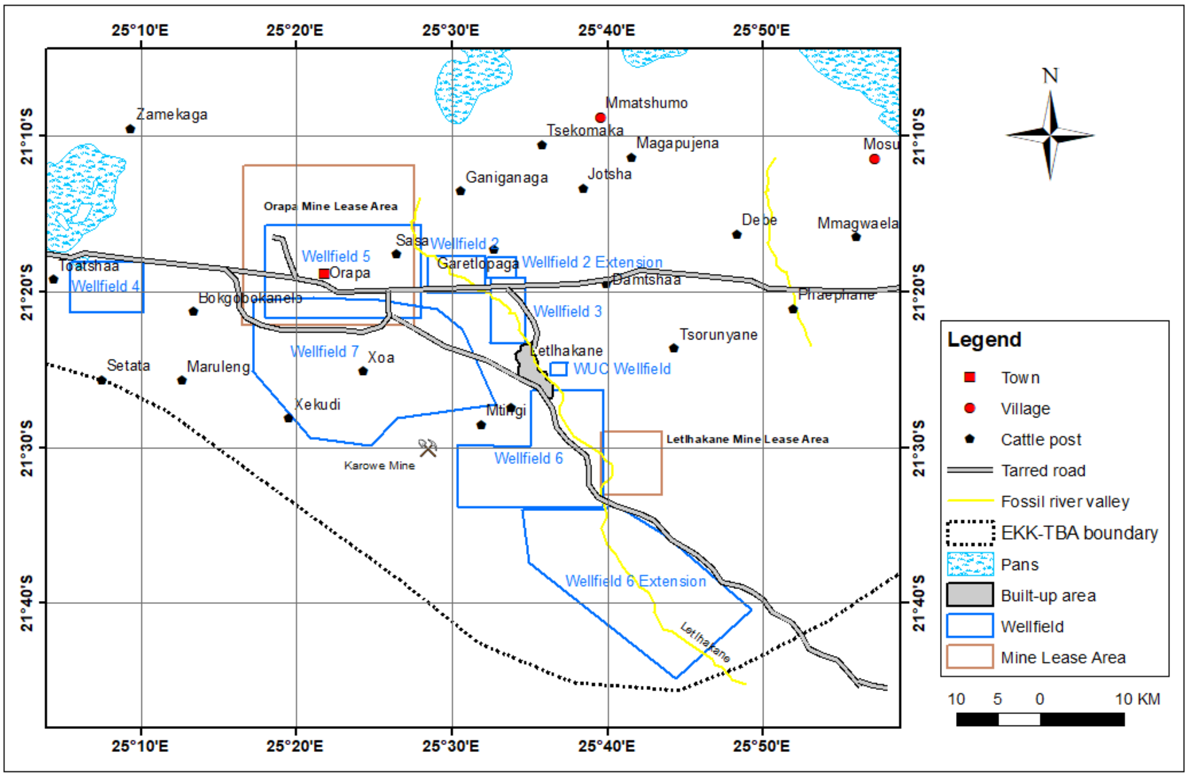


Figure 5.20: OLD mines and wellfields, Karowe mine and WUC Letlhakane Wellfield
Source: modified after Mogami (2013) and Debswana (2015)

Three Debswana diamond mines (OLDM) within the EKK-TBA came into operation in 1969 and initially relied on both surface water from the Mopipi dam and groundwater from wellfields, until 1984 when the dam dried up. Additional wellfields (Figure 5.20) had to be established to secure water supply to the mines, the latest being Wellfield 7 operationalised in 2014 with 29 production boreholes. Wellfield 8, to be developed to the east of Damtshaa mine, comprises 15 exploration boreholes. The Lucara Diamond Mine, known as Karowe Diamond Mine (KDM), also lies within the EKK-TBA and commenced operations in 2012. East of Letlhakane Village is the Water Utilities Corporation (WUC) wellfield (Letlhakane Wellfield, section 5.1.2) which supplies water to the village, Figure 5.20. Numerous hydrogeological and groundwater modelling studies were carried out to the establish the sustainable abstractions and these include the Water Surveys Botswana (WSB) modelling of regional groundwater flow in the Greater Orapa area from 2008 (WSB, 2008 in Mogami, 2013), which is updated regularly (Debswana, 2020).

5.2.1. Lithostratigraphy and structural geology

Figure 5.21 shows a litho-stratigraphic correlation between the Orapa, Karowe and Letlhakane mines which can be considered representative for the Greater Orapa area. Apart from thickness variations, the Kalahari-Karoo sequence for each of the mines is similar.

The stratigraphic units are from top to bottom:

- Kalahari Group (incl. calcrete)
- Stormberg Basalt
- Ntane sandstone
- Mosolotsane (red mudstone and sandstone)
- Tlhabala (mudstone)
- Tlapana (carbonaceous mudstone)
- Mea Arkose (siltstone and sandstone)
- Basement Complex (granite, weathered upper zone and unaltered)

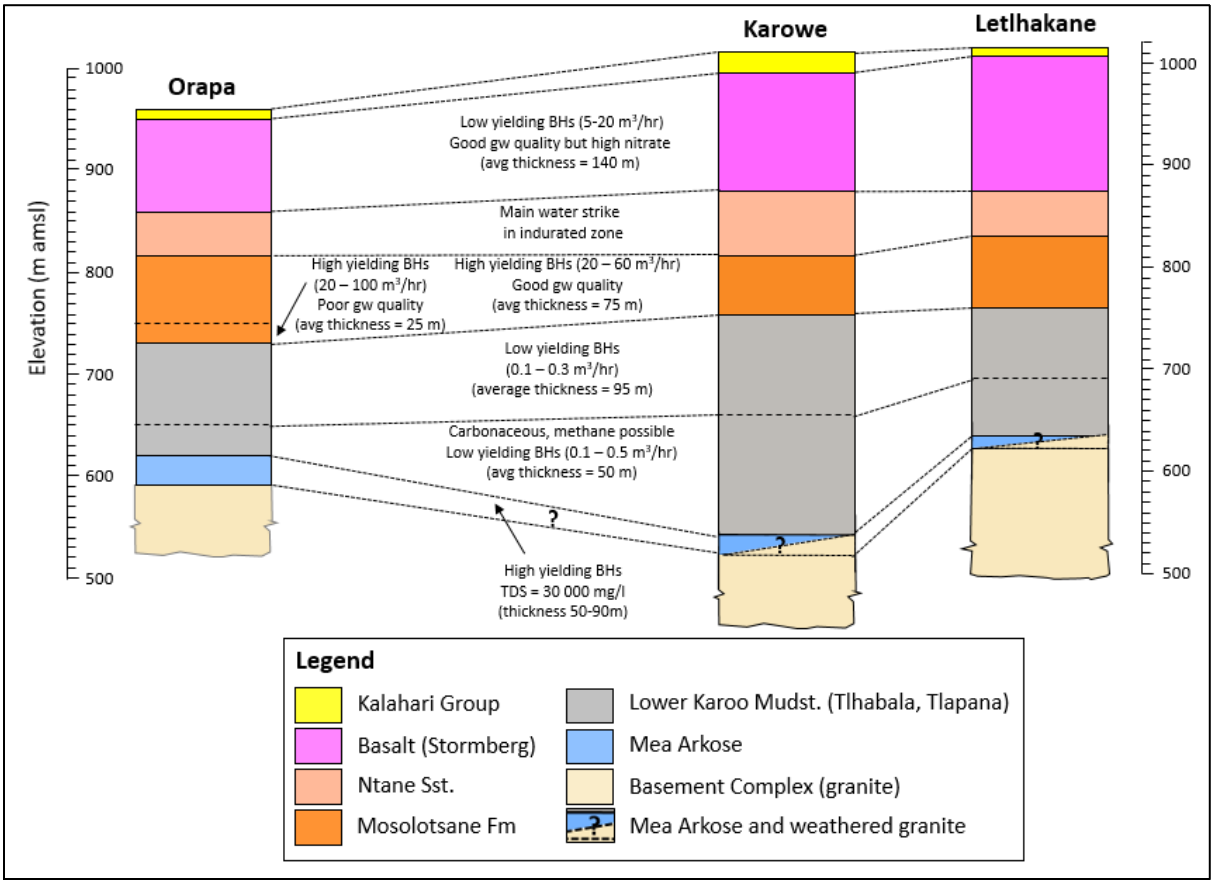


Figure 5.21: Lithostratigraphic correlation between Orapa, Karowe and Letlhakane mines
Source: modified after Royal HaskoningDHV (2017)

5.2.2. Hydrogeology

5.2.2.1. Hydrostratigraphy

The mines' wellfields penetrate three major sedimentary aquifers: the Ntane Sandstone, the Mosolotsane sandstone and mudstones, and the Mea Arkose Sandstone and weathered granite contact zone, Figure 5.21. The aquifers are compartmentalised by hydrogeological boundaries of SE-NW and SW to NE faults with a dominant WNW trend. Late to post Karoo dolerite dyke intrusions occur especially along the WNW trending faults. The influence of the faults and dykes on groundwater levels and flow direction in the OLDM area is considered limited (Debswana, 2020). The Ntane Sandstone Formation constitutes the main aquifer in the region (20-110m thickness) and underlies the Stormberg basalt (95-110m thickness) and the superficial Caenozoic to recent Kalahari Group deposits (less than 20m thickness). Yields of the Ntane Sandstone vary between 0.3 and 100 m^3/hr with a general trend of decreasing yield with increasing depth.

5.2.2.2. Groundwater levels and flow

Groundwater monitoring (abstractions, groundwater levels and water quality) and rainfall measurements take place at each of the mines and wellfields as it is mandatory by law and forms an integral part of sustainable water supply for mining operations. Debswana, the largest individual groundwater user in Botswana, currently manages and monitors its own wellfields that supply OLD mines and as well as Orapa Town (after treatment by reverse osmosis) via the WUC water distribution system. The monitoring also includes effects of dewatering, regional observation boreholes and selected private boreholes. Since consistent water supply is critical to mining operations, considerable human and financial resources have been put into the design, implementation and operation of comprehensive groundwater monitoring and management systems. Comprehensive annual monitoring reports are submitted to the Water Apportionment Board (WAB) as required under their Water Rights allocation (Farr, 2017). Long-term hydrographs from observation boreholes in all wellfields and regional boreholes generally show an average decline of groundwater levels of 0.33 m/yr. The water level decline differs from wellfield to wellfield with Wellfield 6 showing the largest average decline of 1.07 m/yr, Figure 5.22 (Debswana, 2015). The latest information on groundwater levels from observation boreholes was derived from Debswana (2020):

- Wellfields 2, 3 and 4 near Orapa and Damtshaa dewatering centres: groundwater levels decline only a few metres over a long time period of 30 years, from 1989 to 2019, Figure 5.22
- Wellfield 5 to the east of Orapa mine: groundwater levels show a mixed response over a long time period, from 1987 to 2019 of ± 5m
- Wellfield 6 to the west and southwest of Letlhakane mine: groundwater levels in most observation boreholes show a rapid decline of up to 35m from 1991 to 2008 with stabilization thereafter, Figure 5.22

- Wellfield 7 to the south of Orapa mine was operationalised only recently: groundwater levels declined up to 10m from 2016 to the end of 2019
- Wellfield 8 east of Damtshaa mine comprises exploration boreholes and abstraction in the area is from private boreholes: groundwater levels remained more or less the same over the period of 2013 to 2019
- Private boreholes in Wellfields 6 and 7 mostly abstract groundwater from the Stormberg Basalt: groundwater levels declined up to 20m over the period of 1991 to 2019.

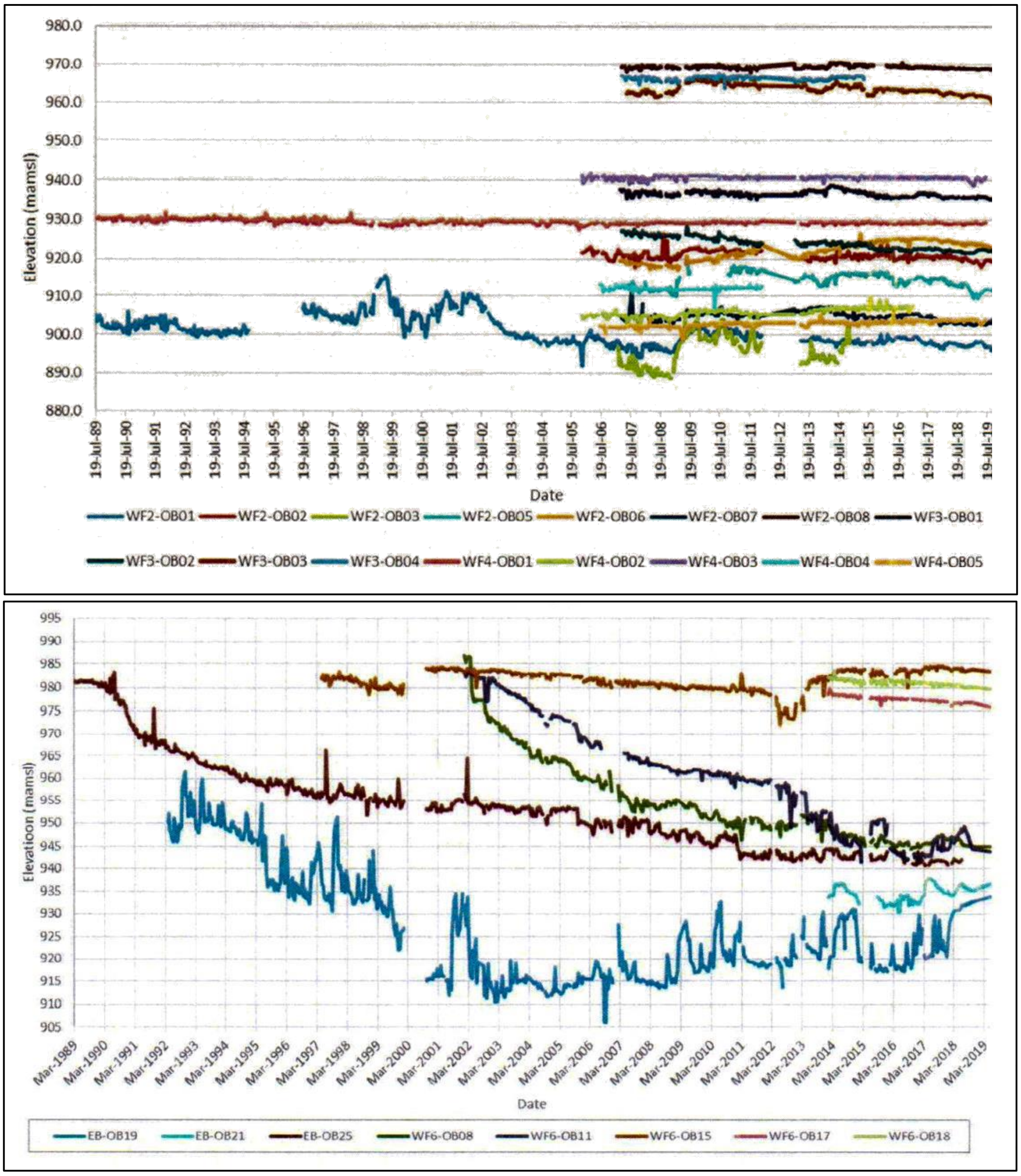


Figure 5.22: Groundwater hydrographs OLDM Wellfields

Top: Wellfield 2, 3 and 4 and Bottom: Wellfield 6

Source: Debswana (2020)

Figure 5.23 shows a cross-section through the Karowe Diamond Mine (KDM) with dewatering boreholes and piezometers for monitoring groundwater levels. Dewatering in the Greater Orapa area has been effective to about 500 m below ground level (m bgl) (Brook, 2009). Maximum inflow for the KDM open pit and underground mine is estimated at between 3.2 Mm^3/yr and 6.7 Mm^3/yr depending on rates of mining and how much water is extracted up-gradient. Minor seepage is expected from the waste rock dumps and slimes dams unless intercepted (Royal HaskoningDHV, 2017).

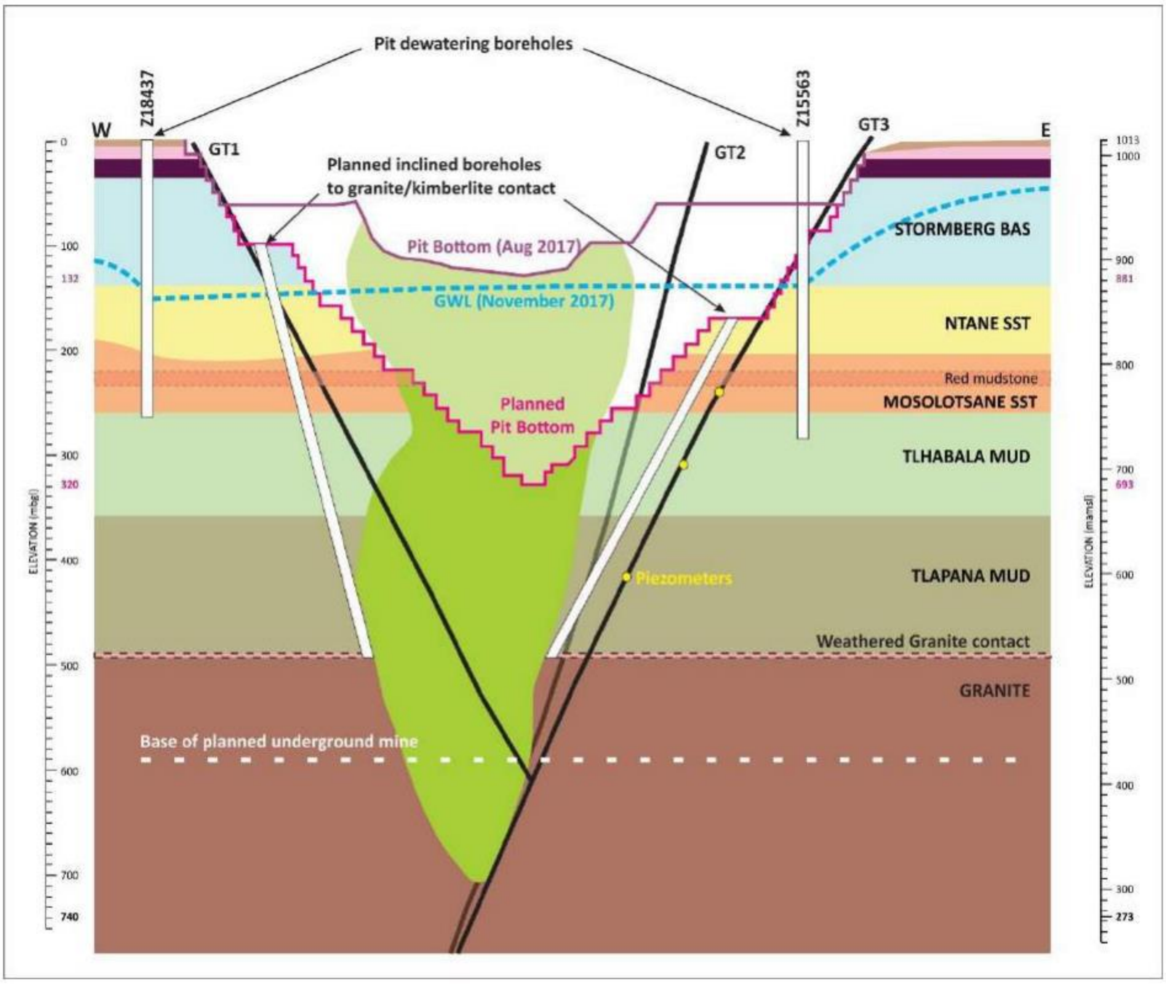


Figure 5.23: KDM with dewatering boreholes and piezometers
Source: Royal HaskoningDHV (2017)

Figure 5.24 shows monitored groundwater levels near the KDM and planned lowering of the water levels upon dewatering of the open pit in the course of time. Note that the deliberate lowering of groundwater levels has the effect of mobilizing saline water which may result in contamination of potable groundwater.

Regional groundwater flow in the Greater Orapa area is from the south and the east towards the Makgadikgadi Pans in the north, with a gradient of about 0.0001 to 0.0002 (Debswana, 2020), Figure 5.25. Locally, groundwater flows towards major pumping centres. Nevertheless, this does not mask the general regional groundwater flow.

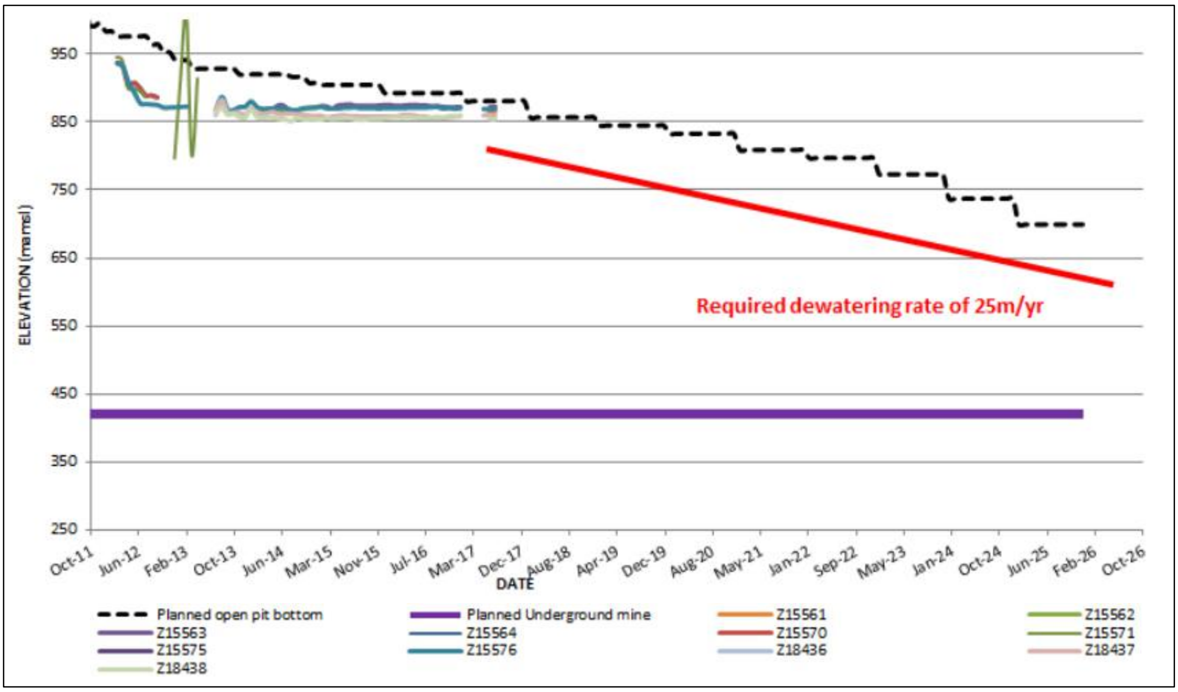


Figure 5.24: Groundwater levels and planned dewatering of the KDM

Source: Royal HaskoningDHV (2017)

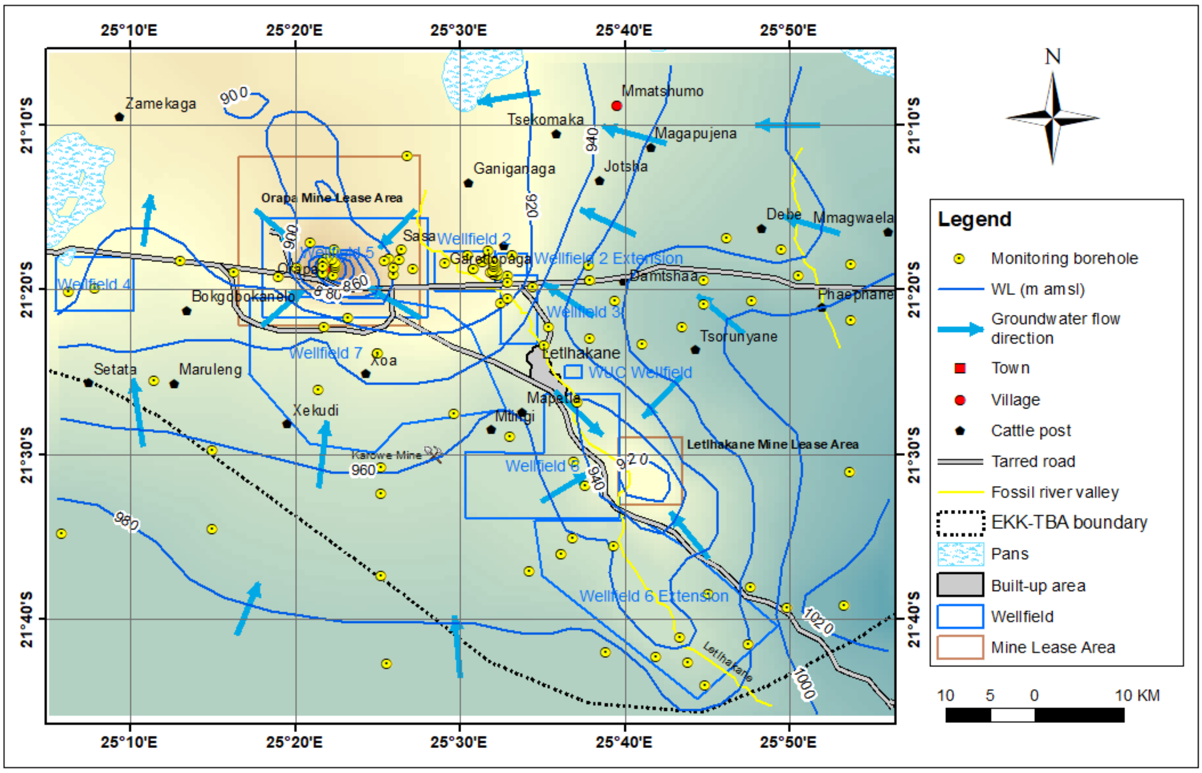


Figure 5.25: Regional groundwater flow in the OLDM area as at 2019

Source: modified after Debswana (2020)

The regional Orapa groundwater model was updated in 2013/14 to include Wellfield 7 and other wellfields and boreholes drilled since 2008. The model contains 384 pumping boreholes and groundwater level changes were simulated up to 2034. The model revealed that a total daily abstraction of 8 040 m^3 for Wellfield 7 would result in a lowering of the groundwater levels by up to 30 m by 2034 or 50% of available drawdown (Mogami, 2013). The model was developed for steady-state conditions and needs to be validated under transient-state conditions to verify the findings.

5.2.2.3. Groundwater chemistry

Groundwater salinity increases down-gradient, with increasing depth and away from recharge areas. The TDS of water samples from boreholes range from about 300 to 16 000 mg/l. Groundwater from Wellfield 6 is generally of a better quality than the other wellfields with a mean TDS value of 1 643 mg/l, which is slightly brackish (Debswana, 2015). High nitrate levels of up to 600 mg/l at the mines are partly attributed to nitrate based explosives used in the blasting operations. Most of the OLDM groundwater samples show a dominant Sodium Chloride (Na-Cl) water type with some samples having a significant proportion of bicarbonate (HCO_3) (Debswana, 2015; 2020). Travel and residence times of groundwater is usually long (hundreds of years), resulting in dissolution of minerals from the host rock hence making the groundwater brackish. Table 5.15 presents statistics of groundwater quality of all OLDM production boreholes sampled in 2014 (Debswana, 2015). No single groundwater sample from the wellfields and dewatering boreholes complied with the requirements of the BOS 32:2000 guidelines for drinking water (see Table 5.3).

Table 5.15: Water quality statistics of OLDM production boreholes

Parameter	Min	Max	Mean
Electrical Conductivity (µS/cm)	774	10800	3090
TDS (mg/l)	504	8636	1974
pH	7.3	10.1	7.9
Na (mg/l)	75	1622	530
K (mg/l)	2.3	20	8.1
Ca (mg/l)	0.91	894	103
Mg (mg/l)	0.13	348	56
Cl (mg/l)	86	3785	736
F (mg/l)	0.2	4	1.0
HCO_3 (mg/l)	104	856	458
CO_3 (mg/l)	0	73	1
NO_3 (mg/l)	0.3	239	53
SO_4 (mg/l)	17.7	1735	176

Source: Debswana (2015)

5.2.2.4. Groundwater recharge

Average annual rainfall at Letlhakane and Orapa is 392 and 375 mm/yr respectively (Debswana, 2020), hence direct (rainfall) recharge is expected to be very small and limited

(Beekman et al., 1996). Recharge mainly occurs via the outcropping Ntane Sandstone and is mostly indirect, e.g. such as localized recharge occurring along the Letlhakane fracture zone. Average annual recharge rates estimated by groundwater modelling varies from 0.3 to 1 mm/yr, whereas recharge rates estimated by the Chloride Mass Balance Method amounts to 2.7 mm/yr, or less than 1% of the average annual rainfall (WSB, 2013 in Mogami, 2013). The bulk of the groundwater may have been recharged during the last pluvial period some 5 000 – 10 000 years ago.

5.2.2.5. Hydraulic characteristics

Table 5.16 summarizes the hydraulic characteristics of the OLDM and Table 5.17 of the KDM

Table 5.16: Hydraulic characteristics of the OLDM

Unit	K (m/d)	Storage coeff.	Sy
Basalt	0.05	$1x10^{-5}$	$1x10^{-3}$
Ntane Sst	0.1 - 0.4	$5x10^{-5}$	$1x10^{-3}$
Mosolotsane	0.016	$1x10^{-5}$	$1x10^{-3}$
Tlhabala mudstone	<0.0001	$3x10^{-5}$	$1x10^{-3}$

Source: Royal HaskoningDHV (2017)

Table 5.17: Hydraulic characteristics of the KDM

Unit	Thickness (m)	Depth (m bgl)	Kh (m/d)	Kv (m/d)	Storage coeff.	Sy
Basalt	130	130	0.05	0.01	$2x10^{-6}$	$1x10^{-3}$
Ntane Sst	70	200	0.15	0.15	$3x10^{-5}$	$5x10^{-3}$ - $2x10^{-2}$
Upper Mosolotsane	40	240	0.024	0.024	$2x10^{-6}$	$5x10^{-3}$
Lower Mosolotsane	16	256	0.1	0.1	$2x10^{-6}$	$5x10^{-3}$
Tlhabala mudstone	90	346	0.0005	0.0005	$3x10^{-5}$	$1x10^{-3}$
Tlapana mudstone	45	391	0.0005	0.0005	$3x10^{-5}$	$1x10^{-3}$
Mea Arkose Sst	30					
Upper granite	100	491	0.05	0.05	$2x10^{-6}$	$1x10^{-3}$
NW-SE Dykes & NNW-SSE Faults	Width > 790 Range 50 - 500	>790	0.00001	0.01	-	-
High permeability structures	Range 20 - 100	>790	0.35 - 0.5	0.1	$3x10^{-5}$	$2x10^{-2}$

Source: Royal HaskoningDHV (2017)

6. REGIONAL HYDROGEOLOGICAL PERSPECTIVE

Information and data from the various wellfields, the Hwange National Park (HNP) and regional geology was used to build a regional hydrogeological perspective of the EKK-TBA.

6.1. Hydrostratigraphy

There is general hydrogeological data paucity within the EKK-TBA in both countries. The dearth of data and information are most pronounced for the Hwange National Park (Zimbabwe) which covers the larger section of the EKK-TBA in Zimbabwe and for aquifers underlying the basalt in both countries. A larger proportion of the basin is sparsely inhabited and hence there are no significant drivers for water demand, and this could explain the absence of data and information. The lack of data and information could also be attributed to poor record management since there is little information on the available boreholes within this area. Another compelling reason is that the deeper aquifers underlying the basalt are expensive to develop and hence, groundwater development is confined to the shallow Kalahari Group aquifer. Poor water quality could be another cogent reason why no groundwater development is taking place within the central areas of the basin particularly with regards the deep aquifers.

The main hydrogeological information on the Zimbabwean side is from the Nyamandlovu Wellfield (section 5.1.4), 45 km NW of the City of Bulawayo (the second largest city of Zimbabwe), and lies on the eastern fringes of the EKK-TBA where the 'aquiferous' unit of the Karoo sediments (Forest Sandstone) has been developed. On the Botswana side, the information is mostly from the Public (Dukwi, Chidumela, Letlhakane and Maitengwe) and Private (OLD and Karowe Diamond Mines) Wellfields (sections 5.1 and 5.2). The aquifers of the EKK-TBA are the Kalahari Group, Karoo Basalt and the Ntane/Forest Sandstone of the Upper Karoo) and Mea Arkose Sandstone/Wankie Sandstone Formation of the Lower Karoo. Basement rocks form the eastern and southern margins of the EKK-TBA and the contact zones with the basin sediments, particularly sandstone mostly serve as recharge areas. The sandstones (Ntane/Forest Sandstone and Mea Arkose/Wankie Sandstone) are also recharged directly from rainfall. Figure 6.1 is a simplified hydrogeological map covering the EKK-TBA which shows the outcropping sandstones in the southern and eastern fringes of the Basin.

6.1.1. Kalahari Group

The Kalahari Group is ubiquitous throughout the EKK-TBA and is generally unconsolidated sand and thus presents a primary porosity aquifer. The base of the sand, however, is indurated into a sandstone and is hollow in certain places due to decayed organic material. The hollow sandstone is referred to in Zimbabwe as the Pipe Sandstone (secondary porosity) and presents good groundwater potential. The thickness of the Kalahari Group varies from 0-

270m and is thickest in the central portions of the Basin which lies mostly in Botswana and with the Kalahari Group deposits thickening in an East–West azimuth which coincides with the central part of the EKK-TBA (see Figure 4.3). The thickest sections are inferred to occur some 50-80 km NW of Maitengwe Wellfield and about 160-210 km NNE of Letlhakane Wellfield (Figure 4.9 and Figure 4.10).

The Kalahari Group in Botswana is generally <50 m thick and thickens towards the central portions of the basin (Haddon, 2005). Within the central sections of Botswana's EKK-TBA, west of Makgadikgadi Pans, the Kalahari Group directly overlies Precambrian ultramafic to mafic rocks (Figure 4.8).

Most boreholes in the Kalahari Group formation of the EKK-TBA occur in the communal lands, commercial farming areas and wildlife/safari areas of Zimbabwe and around the northern sections of the Makgadikgadi Pans in Botswana.

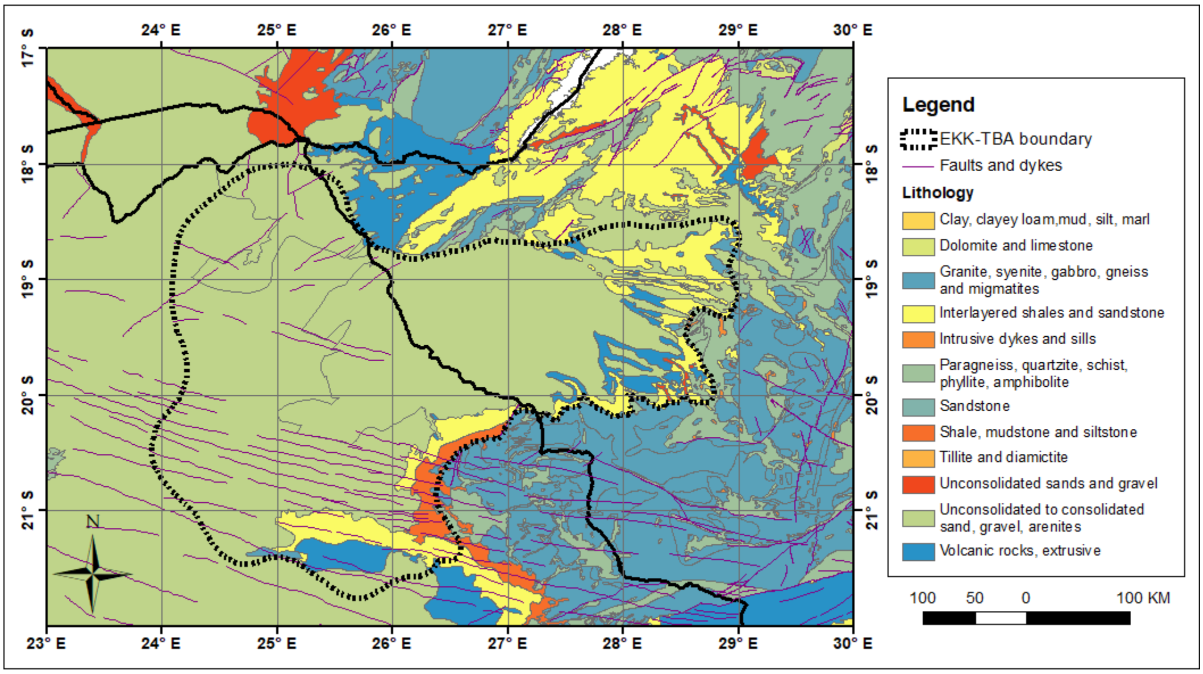


Figure 6.1: Simplified hydrogeological map of the EKK-TBA
Source: modified after SADC-HGM (2010)

Rural water supply boreholes tap the shallow Kalahari Group formation (Figure 6.2) since it would be very expensive to drill through the underlying basalt into the Ntane/Forest Sandstone and secondly as mentioned earlier, there is a high possibility of the groundwater being saline, particularly towards the centre of the Basin.

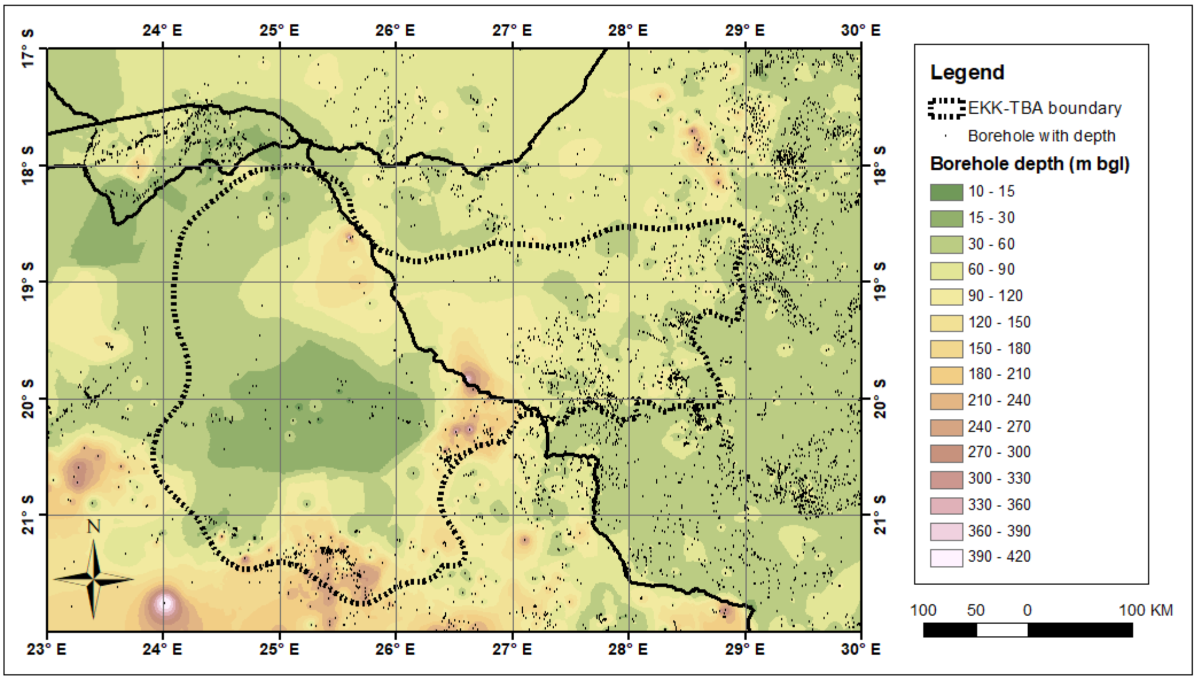


Figure 6.2: Borehole depth distribution

The aquifer characteristics of the Kalahari Group are quite varied. Within Botswana, the Kalahari Group does not constitute a major aquifer (DWA, 2002). In certain areas, where the Kalahari Group can be locally developed for groundwater, low permeability beds (clays, silts, etc.) tend to reduce the groundwater potential. Borehole yields range between 2 and 10 l/s (Jones, 2010).

In Zimbabwe, the Kalahari Group has been eroded away along major river channels, exposing the underlying basalt. The transmissivity values of the Kalahari Group range from 5-50 m^2/d, with the thickness varying from 0-70m and thickening particularly towards the deeper parts of the Basin (northwards and westwards), water levels (measured below ground level) are generally >20m and borehole yields generally lie between 100-1000 m^3/d (Interconsult, 1986). The Kalahari Group formation, covering approximately 80% of the Hwange National Park is the main source of groundwater for the National Park (wildlife and humans) (WWF, 2019). Within the Nyamandlovu area, the Kalahari Group does not form a significant aquifer due to its thinness and also that it cannot meet the abstraction volumes required for urban water supplies or intensive irrigation. The Kalahari Group can be developed for handpump equipped boreholes.

6.1.2. Basalt

The Basalt is by and large an aquitard that overlies the Karoo Supergroup formations. It is absent in the eastern and southern fringes of the Basin and mainly outcrops in the eastern and southern parts of the EKK-TBA. The basalt is overlain by the Kalahari Group in the greater part of the Basin and thickens from the east and southeast towards the west and southwest, fronting the central portions of the Basin where it reaches a thickness of about 300 m.

Within the fringes of the EKK-TBA in Zimbabwe, the basalt is absent and has been eroded away along the Umguza and Khami River channels, resulting in the Forest Sandstone forming the river bed. The basalt thickness within the Nyamandlovu area is usually less than 50m and thickens towards the north and north west (Beekman and Sunguro, 2015). Within Botswana's EKK-TBA, the basalt thickness ranges from around 35m to about 300m and has an average thickness of 110m. Precambrian interlayered metasedimentary rocks occur in the western sections of the Basin and Precambrian mafic to ultramafic extrusive rocks occurring to the west of the Makgadikgadi Pans and striking northeasterly, disrupt the continuity of the basalt (see Figure 4.6 and Figure 4.8).

The basalt only becomes an important 'aquifer' at a very local scale when it is 'adequately' fractured and/or faulted to provide domestic water to rural communities (DWA, 2002; Interconsult, 1986). In areas where the basalt is not fractured, it forms a bedrock (aquiclude) for the Kalahari Group and allows for groundwater accumulation within the Kalahari Group which can be exploited at local levels. Interconsult (1986) noted that yields in the basalt vary between 8-90 m^3/d, with borehole depths ranging from 30-70m and the transmissivity values ranging between 1 and 300 m^2/d, and specific capacities being in the range of 10-100 m^3/d/m and storativity values averaging 10^{-5}. Localised high yields >960 m^3/d have been reported (DWA, 2002). The United Nations (1989) noted that typical yields from the basalt are around 200 m^3/d. Where the basalt is fractured to the bottom, it has been reported that it acts as an aquitard instead of an aquiclude and allows water to infiltrate to the underlying formations thus providing groundwater recharge to the underlying sandstone formations (Sunguro, 1991; DWA, 2002).

6.1.3. Ntane and Forest Sandstone

The sandstone formation underlying the basalt is known as the Ntane Sandstone and Forest Sandstone in Botswana and Zimbabwe, respectively and forms the main aquifer within the EKK-TBA.

In Botswana, the sandstone (Ntane) outcrops in the southern and southeastern margins of the Basin, whereas in Zimbabwe, the sandstone (Forest) outcrops in the eastern margins of the Basin, Figure 6.1. The sandstone is overlain by basalt in the greater part of the Basin. The thickness of the Ntane/Forest Sandstone outside the wellfields is not known. Precambrian interlayered metasedimentary rocks occur in the western sections of the Basin and Precambrian mafic to ultramafic extrusive rocks occurring to the west of the Makgadikgadi Pans and striking northeasterly, similarly disrupt the continuity of the Ntane Sandstone (see Figure 4.6 and Figure 4.8).

It is uncertain whether the contact zones of these Precambrian rocks contribute to the recharge of the Sandstone. Note that it has been established elsewhere within the EKK-TBA that indirect recharge can occur through fracture and fault zones depending on the amount of rainfall and the thickness and hydraulic characteristics of the overlying Kalahari Group. It should however, be noted that even if groundwater recharge were to take place, the amount would be very small (Figure 6.5) and would hardly impact the refreshening of the aquifer since the groundwater within area is presumed to be very saline.

Within the Zimbabwean EKK-TBA, the sandstone dips and thickens towards the NW and W. It overlies the Basement Complex on the fringes of the Basin and the Lower Karoo sediments away from the margins of the Basin.

The Ntane/Forest Sandstone is heavily faulted and structurally controlled in certain areas of the Basin (see Figure 4.9 and Figure 5.2). Variations in elevation of the Ntane Sandstone and the depth to basement are all indicative of faulting and vertical displacement along the southern margin of the graben structure. The Ntane Sandstone has been uplifted through block faulting (normal faults) and outcrops in areas such as the Dukwi in the south eastern sections of the Basin (within Botswana) where it is controlled by the Red Beds Fault (Figure 5.2). The Ntane/Forest Sandstone exhibits unconfined to semi-confined dual porosity conditions and becomes confined when moving towards the central portions of the Basin.

The hydraulic characteristics of the Ntane/Forest Sandstone aquifer are very varied which is indicative of the heterogeneity of the system. The thickness ranges from 2-80 m and is inferred to be more than 100m in the central sections of the Basin. The transmissivity values range from 2-400 m^2/d and are mostly <30 m^2/d and the hydraulic conductivities range from 0.1-10 m/d and are generally <1 m/d. Borehole yields are very variable, ranging from 10 to 2 000 m^3/d m^3/d (Beekman and Sunguro, 2015; DWA, 2002; Martinelli and Hubert, 1996; Beasley, 1983).

6.1.4. Mudstones and Siltstones

Various formations (Botswana: Tlapana, Tlhabala and Mosolotsane Formations; Zimbabwe: Madumabisa Mudstones and Escarpment Grit) comprising mudstones and siltstones underlie the Ntane/Forest Sandstone Formations and can be regarded as a single unit. Their exposures to the surface are prognostic of the vertical faulting with up and down thrusts. In Zimbabwe, the mudstones and siltstones within the EKK-TBA are ill defined and cannot be considered as aquifers. The unit can broadly be regarded as an aquitard due to intercalations of sandstone, e.g. within Botswana's EKK-TBA, the Ngwasha Formation equivalent to the Mosolotsane Formation of the Karoo Supergroup comprises red mudstone with sandstone (DWA, 2002).

6.1.5. Mea Arkose Sandstone

The mudstones and siltstones unit discussed in section 6.1.4 is underlain by a sandstone formation that is represented by the Mea Formation in Botswana and its equivalent, the Lower Wankie Sandstone Formation, in Zimbabwe. These formations do not widely outcrop within the Basin. The Mea Arkose Formation outcrops in the southern section of the EKK-TBA, (in Botswana) within the Dukwi area and attains a thickness of around 180m and an average thickness of 58m (Legadiko, 2015) and forms the main aquifer in Dukwi. In this area, the Ntane Sandstone is not highly productive and where significant yields have been encountered, the groundwater has been established to have very high Total Dissolved Solids (TDS) which render the groundwater not suitable for human consumption *(ibid)*. The exposure of the Mea Arkose Formation to the surface is also indicative of vertical faulting within the Basin, particularly within the fringes of the EKK-TBA. It has been identified as a potential aquifer and in the Dukwi Wellfield, it yields around 400 m^3/d (DWA, 2002). The yield falls within the range of 100-500 m^3/d of its Zimbabwea equivalent, the Wankie Sandstone (Interconsult, 1986). The transmissivity of the Mea Arkose Sandstone within the Dukwi Wellfield ranges from 48 – 1618 m^2/d with K values of around 0.001 m/d. There is no information on the hydraulic characteristics of the Wankie Sandstone in Zimbabwe.

6.2. Regional groundwater levels and flow

There are no groundwater level data and information discretely classified into the various aquifers (Kalahari Group, Basalt, Ntane/Forest Sandstone and Mea Arkose Sandstone) for the whole EKK-TBA. Data and information were only available for specific wellfields discussed in Chapter 5 and which all occur on the southern and eastern margins of the EKK-TBA. A regional groundwater piezometry constructed from lumped static groundwater levels is shown in Figure 6.3.

Figure 6.3 shows the location of boreholes with only static water levels (SWLs) measured below ground level and then corrected for above mean sea level (amsl) using 30-m SRTM DEM data (30m resolution). The SWL data was obtained from the SADC-HGM (2010) database and is from an area bounded by longitude 22 and 30 degrees East and latitude 16 and 22 degrees South (WGS 84) covering portions of Botswana, Namibia, Zambia and Zimbabwe. Note that the static water levels are from different aquifers: Kalahari Group, Basalt (Stormberg Basalt in Botswana and Batoka Basalt in Zimbabwe) and Sandstone (Ntane Sandstone in Botswana and Forest Sandstone in Zimbabwe) and are over different time periods (the time when the boreholes were drilled), and hence, they provide a rough or crude idea of a regional piezometric surface and the potential groundwater flow directions at the larger scale. Ideally, piezometric surfaces for the discrete aquifers should be constructed from water level data of the same time period or space. Unfortunately, such piezometric surfaces could not be constructed at a regional level due to scarcity of data and information (see Chapter 1).

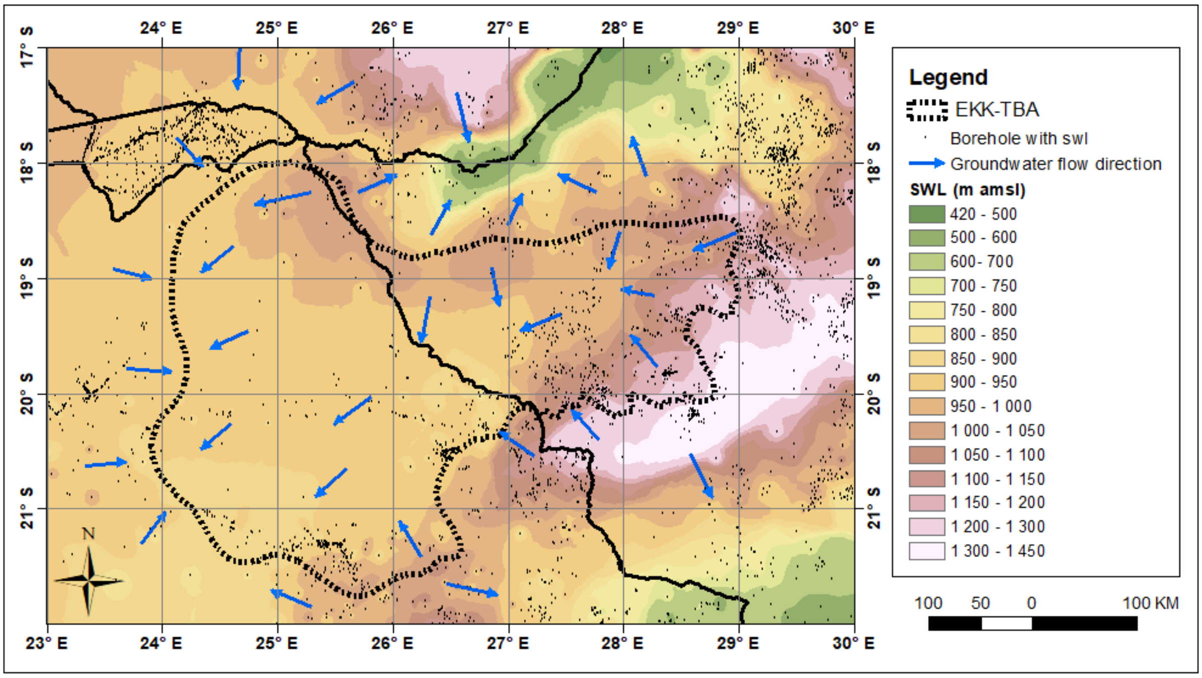


Figure 6.3: Regional piezometry and groundwater flow from boreholes with SWL

Under natural conditions and in the absence of 'artificial' groundwater abstraction, groundwater flow tends to mimic the surface topography albeit at a more subdued level (Khorrami et al., 2018; IAH, 2017). It is this concept that was loosely adopted to gain a broader understanding of the general groundwater flow dynamics. It should, however, be noted that most of the boreholes away from the fringes of the EKK-TBA were drilled into the Kalahari Group since the borehole locations coincide or fall within the shallow zones of the Kalahari Group (see Figure 6.2 and Figure 4.3). The piezometry represented in Figure 6.3 shows that groundwater flows from Zimbabwe towards the Makgadikgadi Pans in Botswana (from higher to lower swl) and the regional piezometry indeed mimics the surface topography. Similarly, groundwater flow from the western section of the EKK-TBA is also towards the Makgadikgadi Pans (Lekula et al., 2018; WCS, 2020; SADC-GMI, 2020).

The piezometric surfaces from the wellfields developed in the Ntane/Forest Sandstone and Mea Arkose Sandstone aquifers along the southern and southeastern margin of the EKK-TBA, (discussed in Chapter 5), show groundwater flow directions which conform to that of the regional groundwater flow pattern, Figure 6.4. Recent studies by WWF (2019) in the Hwange National Park in Zimbabwe, established that groundwater flow within the Kalahari Group is southwestwards towards the Makgadikgadi Pans in Botswana conforming to the regional groundwater flow pattern, Figure 6.4.

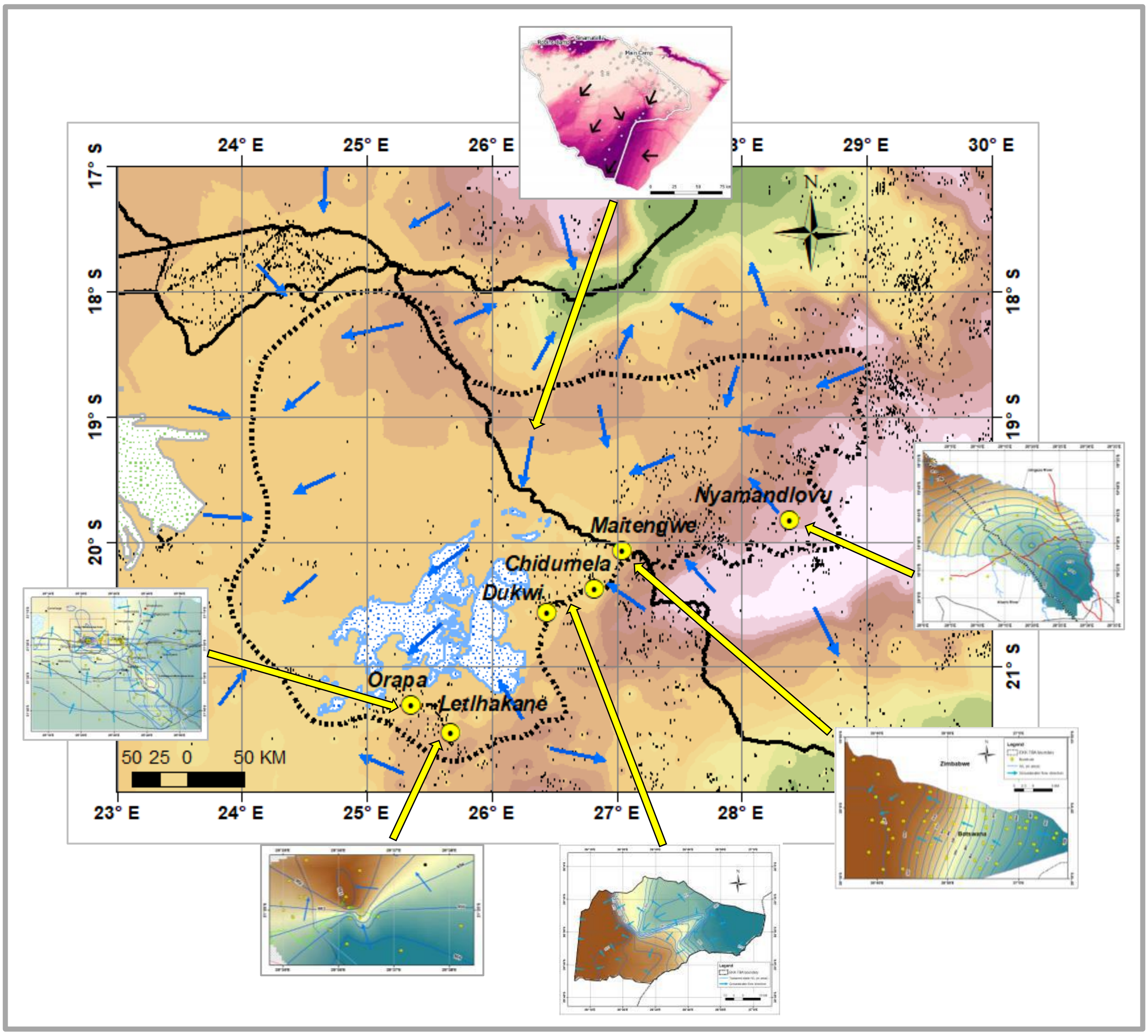


Figure 6.4: Regional and local piezometry of the EKK-TBA

6.3. Groundwater recharge and discharge

6.3.1. Groundwater recharge

Groundwater recharge can be defined as the portion of total precipitation falling onto a drainage basin that ultimately reaches the water table by percolation in an aquifer / and or the lateral migration of groundwater from adjacent aquifers (Freeze and Cherry, 1979). Groundwater recharge is the most critical component for determining sustainable abstraction from an aquifer.

6.3.1.1. Groundwater recharge in southern Africa

Numerous groundwater recharge studies were carried out in southern Africa using a multitude of recharge estimation techniques which included the Chloride Mass Balance (CMB), Water Table Fluctuation (WTF), Cumulative Rainfall Departure (CRD), Environmental Isotopes, Groundwater Modelling, etc. The results of these studies, mainly from Botswana

(Beekman et al. 1996), South Africa (Bredenkamp et al. 1995; Xu et al. 2007; Van Wyk et al. 2011), Namibia (JICA 2002; Stone and Edmunds 2011) and Zimbabwe (Houston 1988; Nyagwambo 2006; Shamboko-Mbale et al. 2012), indicate that with an average annual rainfall (which is almost all the precipitation in this semi-arid region) below 350 mm, hardly any recharge occurs, Figure 6.5 (Beekman et al., 1996; Xu and Beekman, 2019). The annual rainfall limits in the figure range from as low as 200 mm to 1 500 mm, whereas the annual recharge estimates range from as low as 0.20 mm to as high as about 1 000 mm. Since very few papers or reports are readily available from Zambia, limited data sets are drawn from isolated reports such as BGR reports and organisational reports, whose data are also plotted in Figure 6.5.

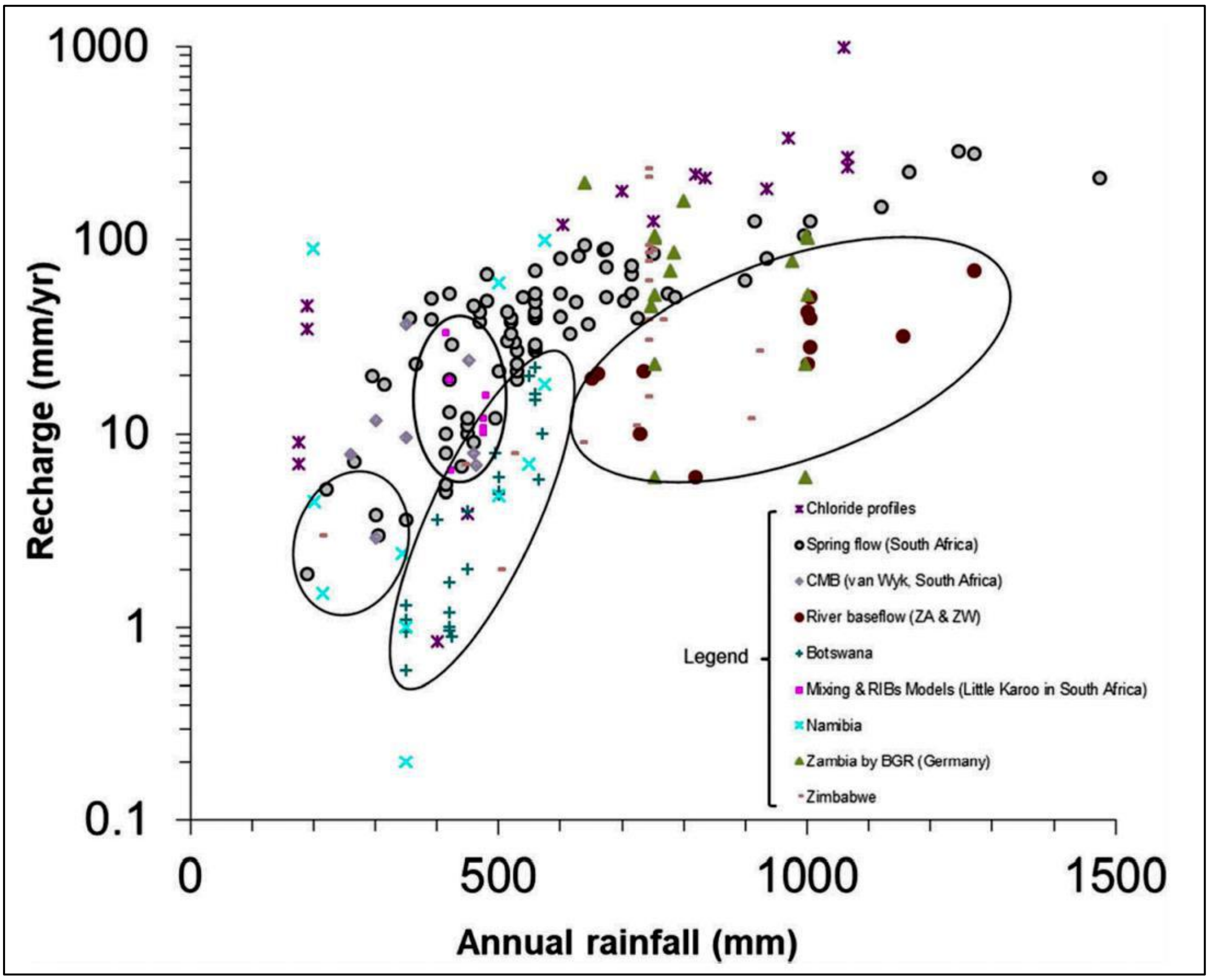


Figure 6.5: Recharge versus annual rainfall in southern Africa

Source: Xu and Beekman (2019)

Figure 6.5 also shows that there is a wide variation between recharge rates computed from the same amount of rainfall and is up to a factor difference of 100 and could be a result of preferential recharge along fault or fracture zones as opposed to diffuse recharge. The methods which have consistently been applied over the range of annual rainfall values illustrated are the CMB and the equal volume spring flow (EVSF) method (modified water balance) (Xu and Beekman, 2019). The results of other methods, such as the WTF and saturated volume fluctuation modelling, mostly fall within the same range of results. The ellipsoids in Figure 6.5 group results from some of the specific studies and similarities in rainfall are contrasted by huge variation in the recharge rates. For instance, results obtained in the Little Karoo in South Africa share resemblance with that of the Botswana with regards the amount of rainfall but recharge rates, which are higher than those of Botswana, evidently confirm that the recharge is enhanced by outcrops of fractured Table Mountain Group aquifers (preferential recharge). Zonation of the recharge rates within the high rainfall regions (700-1300 mm) shows three areas/zones, Figure 6.5. The first zone is represented by the CMB derived results with recharge rates varying between 100-1 000 mm, the second zone shows recharge rates obtained from spring flow and vary between 30-300 mm, and the third zone is represented by recharge rates obtained from baseflow studies and vary between 5-80 mm. The first zone represents chloride profiling in the unsaturated zone and seems to consistently overestimate recharge. One of the reasons is that the estimated amount of rainfall contributing to recharge may not fully reach the water table. On the other hand, the baseflow of a river represents recharge at a (sub)catchment scale and gives the lower limit of recharge due to possible water loss (e.g. through evapotranspiration) prior to discharge along rivers.

6.3.1.2. Groundwater recharge in the EKK-TBA

Within the EKK-TBA, recharge studies have been confined mostly to areas of large scale groundwater development, especially around wellfields in the southern and south-eastern fringe of the Basin. Recharge rates varied from 2-37 mm/yr in the Botswana wellfields and 2-62 mm/yr in the Nyamandlovu Wellfield in Zimbabwe. The lower values of recharge are indicative of direct recharge (from rainfall) whereas higher values are predominantly due to preferential recharge along river systems, faults and fractures and account for a small percentage of the total areal recharge within the EKK-TBA. Average annual recharge rates along the southern fringe of the Basin in Botswana are <1% of average annual rainfall and along the southeastern fringe of the Basin in Zimbabwe are <3%. Isotope recharge studies indicate that the main groundwater recharge occurred during the last pluvial period, about 5 000-10 000 years ago. There have not been groundwater recharge studies in the central, northern and western parts of the EKK-TBA.

Based on Figure 6.5, a linear best fit between annual recharge and annual rainfall is shown in Figure 6.6, and includes recharge rates from Botswana, Namibia, Zambia and Zimbabwe neighbouring the EKK-TBA. The figure shows ‘envelopes’ or bounds defined by ± 1 and ± ½ standard deviation (SD). Note that the range of recharge (plus and minus the one standard deviation) fully covers the recharge estimates obtained in Botswana, Namibia, Zambia and Zimbabwe, whereas most of the values are enveloped by the linear best fit ± ½ SD. The rainfall threshold of 350 mm/yr below which hardly any recharge occurs can be clearly observed from the figure. Recharge rates from the Botswana and Zimbabwe EKK-TBA wellfields (Dukwi, Letlhakane, Maitengwe, Nyamandlovu and Orapa-Wellfield 7) plot well within the envelope of linear best fit ± ½ SD, Figure 6.6.

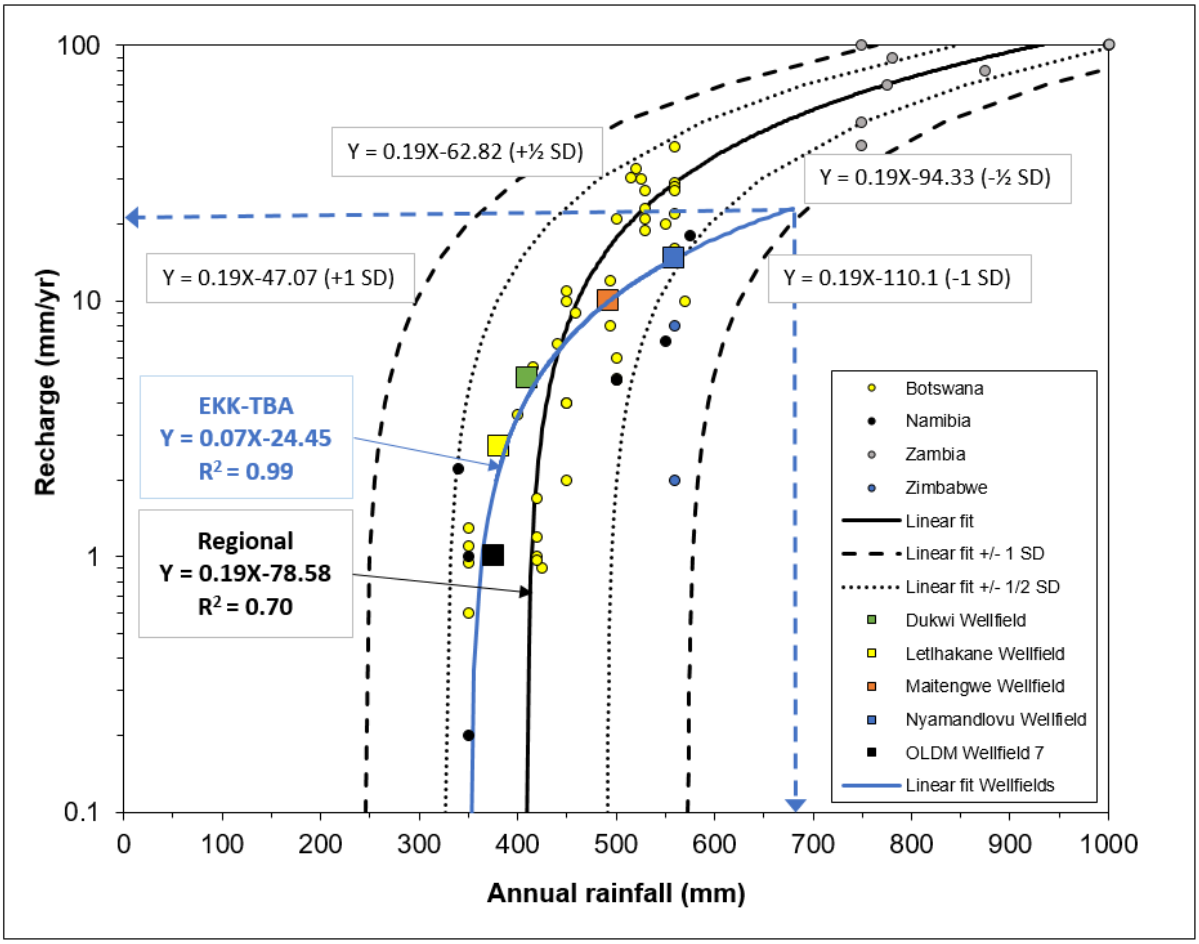


Figure 6.6: Correlation between recharge and rainfall of the EKK-TBA and surrounding

The average recharge rates of the five EKK-TBA wellfields appear to be related to average annual rainfall (between 378 and 560 mm/yr) according to the linear equation Y=0.07X-24.45 (with Y the recharge estimate (mm/yr) and X the average annual rainfall (mm/yr); R^2=0.99), albeit the few data points. This equation can be used in conjunction with the average annual rainfall map of the EKK-TBA, Figure 2.2, to construct a groundwater recharge potential map of the Basin, Figure 6.7. The map can be used for initial estimates of recharge in the absence of detailed (local) hydrogeological investigations which include recharge estimations. Note that for annual average rainfall above 560 mm/yr, in the north-eastern part of the EKK-TBA, recharge is likely to be underestimated up to a factor of two and hence the values can be considered as conservative estimates.

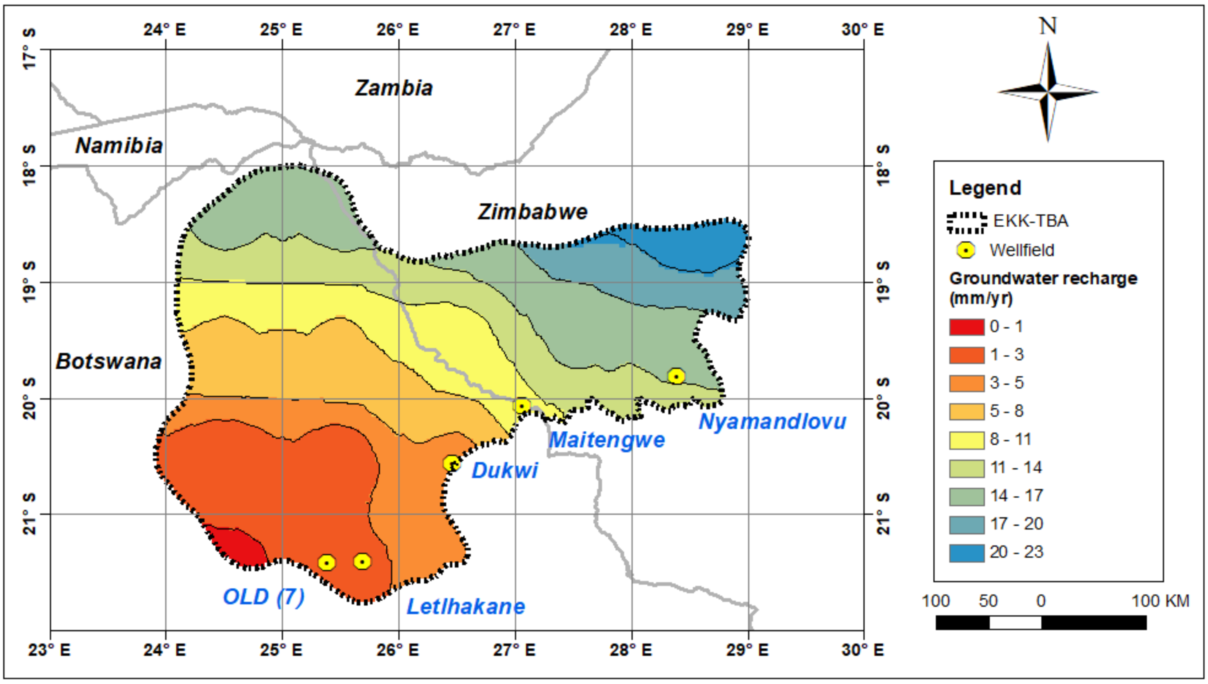


Figure 6.7: Groundwater recharge potential of the EKK-TBA

Groundwater recharge of the Kalahari Group, which covers most of the EKK-TBA, occurs through direct infiltration of rainfall. In the fringes of the Basin where the Mea Arkose Sandstone equiv. and the Ntane/Forest Sandstone are outcropping, replenishment is through both direct and indirect recharge. Groundwater recharge of the Ntane Sandstone could possibly occur through the contact zones with the Precambrian interlayered metasedimentary rocks in the western sections of the basin and Precambrian mafic to ultramafic extrusive rocks to the west of the Makgadikgadi Pans (see Figure 4.6 and Figure 4.8) if the rainfall and the hydraulic characteristics of the Kalahari Group are favourable. Hydrogeological investigations need to be carried out to validate this.

It must be cautioned that recharge does not occur everywhere as the map would seem to imply as recharge is limited to those areas where unconfined aquifer conditions occur. Also note that in a semi-arid climate setting such as the EKK-TBA, most recharge probably takes place through episodic events. Since average annual recharge is very low to negligible within the EKK-TBA, effective and robust groundwater management systems need to be instituted to ensure the sustainability of the groundwater resource.

6.3.2. Natural groundwater discharge

The piezometric surface shows that, on a regional scale (EKK-TBA scale), groundwater flows towards the Makgadikgadi Pans in the southern part of the EKK-TBA where it is discharged. Inasmuch as the groundwater flow within the Kalahari Group is towards the Makgadikgadi Pans, seepages and springs form another type of groundwater discharge, especially within the HNP. The seepages and springs are most likely a result of intercalations of impermeable layers, with limited areal extent and in the form of lenses, occurring within the Kalahari Group. These lenses can form perched aquifers which, when one end is close to the surface or outcrops, produces seepage or springs, depending on the height of the water level above the top of the impermeable layer. The impermeable layer can either be an aquitard or aquiclude.

Groundwater discharge has also been established to occur within the various rivers (Boteti and Gwayi Rivers), albeit not throughout the year. There are no known natural artesian groundwater discharges within the EKK-TBA. Wells constructed around Sawmills area on the Zimbabwean side of the EKK-TBA are artesian.

6.3.3. Groundwater chemistry

Data on the general groundwater quality, let alone comprehensive groundwater quality, is very scanty at the Basin scale (Chapter 1, Table 1.1). Water quality data, however, exists for the EKK-TBA wellfields (Chapter 5).

The groundwater quality in the Botswana wellfields (Dukwi-Chidumela, Letlhakane, Maitengwe, OLDM) ranges from potable to saline. It is generally 'fresh' in the recharge zones and deteriorates in quality with increasing depth and movement away from the recharge zones. The groundwater quality of the Nyamandlovu Wellfield in Zimbabwe is potable.

The position of the aquifer relative to the basement rocks outcropping at the fringes of the EKK-TBA also has a direct impact on the quality of the groundwater. For instance, within the Dukwi Wellfield, the Ntane Sandstone has been established to have very little groundwater potential and where significant yields have been encountered, the groundwater has very high Total Dissolved Solids (TDS) that make it unsuitable for human consumption (Legadiko, 2015). On the other hand, the Mea Arkose Sandstone which abuts the basement rocks from where recharge takes place, has fresh groundwater, whereas the Ntane Sandstone which is separated from the basement rocks by the Tlapana Formation (comprising non-carbonaceous mudstones, siltstones and carbonaceous mudstones) does not get recharge from the basement rock contact zones, Figure 5.2.

The recharge zones in Botswana generally have TDS values <1 000 mg/l. The TDS increases to >70 000 mg/l with increasing depth and distance away from the recharge zones (DWA, 2002; Kefentse, 2004; Geoflux, 2005; Legadiko, 2015). High nitrate values have been recorded in some of the Water Utilities Corporation (WUC) owned and managed wellfields and are attributed to leaching of the nitrate from cattle pens and posts along fracture and/or fault zones mostly during seasons of high rainfall (Kefentse, 2004). The groundwater quality of the Nyamandlovu Wellfield in Zimbabwe which is located in the recharge area of the Nyamandlovu (Forest Sandstone) Aquifer is good with TDS <1 000 mg/l (Interconsult, 1986) and is compliant with the Zimbabwe guideline for drinking water (Table 5.13).

Further away from the main recharge zones in Botswana, for example in the case of the diamond mining wellfields, no single groundwater sample complies with the requirements of the BOS 32:2000 guidelines for drinking water (Table 5.3). High nitrate levels within the diamond wellfields of up to 600 mg/l are partly attributed to nitrate based explosives used in the blasting operations (Debswana, 2015).

Increased groundwater abstractions risk a rapid deterioration of the groundwater quality through inducing upconing or intrusion of saline water. Proper aquifer and wellfield management systems are needed to prevent deterioration of the groundwater quality which would render it unsuitable for human consumption, agricultural purposes and other needs requiring potable water.

6.4. Hydraulic characteristics

Table 6.1 summarises the hydraulic characteristics of the Kalahari Group, Ntane/Forest Sandstone and Mea Arkose Sandstone equivalent aquifers and the basalt aquitard at the EKK-TBA wellfields (Chapter 5).

There is a lack of comprehensive data and information on the Kalahari Group deposits in the fringes of the EKK-TBA as they are relatively thin (<10m) and hence unproductive. This also applies to the other parts of the Basin. WWF (2019) postulates that the Kalahari Group deposits within the HNP is highly productive, however, this needs to be validated through detailed hydrogeological investigations. Lekula et al. (2018) used hydraulic conductivity values of the Kalahari Group ranging from 0.1 to 15 m/d and BH yields ranging from 4 to 40 m^3/hr for their conceptual hydrogeological model of the Central Kalahari Basin.

Although the basalt, by and large, constitutes an aquitard, locally, high yields are obtained due to fracturing and faulting. The fracturing and faulting may also provide hydraulic continuity between overlying and underlying aquifers. Hydraulic characteristics of basement contact and dykes and faults are presented in Table 6.2 and these features are important in enhancing indirect groundwater recharge.

The Ntane/Forest Sandstone aquifer within the southern and southeastern fringes of the EKK-TBA is generally productive, save for the Dukwi area where the TDS values are so high to render the groundwater unsuitable for human consumption. Note that the salinity of the groundwater of the aquifer drastically increases within a relatively short distance from the recharge area. Borehole yields are varied and average 30 m^3/hr. Hydraulic conductivity varies between 0.1 and 10 m/d and the storage coefficient lies between 10^{-6} and $8x10^{-3}$.

The Mea Arkose Sandstone aquifer (and its equivalent), although thinner than the Ntane/Forest Sandstone aquifer, has borehole yields of 100 m^3/hr, and in the Dukwi area, hydraulic conductivity of 10 m/d and storage coefficients between 10^{-4} - $8x10^{-2}$ were determined.

Table 6.1: Hydraulic characteristics of aquifers and aquitards at EKK-TBA wellfields

	Aquifer/Aquitard	Thickness (m)	BH yield* (m^3/hr)	T (m^2/d)	K (m/d)	Storage coefficient
Dukwi	Kalahari Group	<10				
	Basalt	<30				
	Ntane/Forest Sst.	10				$2x10^{-3}$
	Mea Equiv.	58	30	1.5-1760: 572	10	10^{-4}- $8x10^{-2}$: $7x10^{-3}$
Letlhakane	Kalahari Group	8-23: 15	7-8			
	Basalt	35-124: 80	<45			
	Ntane/Forest Sst.	48-140: 100	30	10-60	0.1-1	
	Mea Equiv.	-				
Maitengwe	Kalahari Group	23				
	Basalt	108	8-40**			
	Ntane/Forest Sst.	60	1-20	2-400	0.1-10	10^{-6} - $5x10^{-3}$: $2x10^{-4}$
	Mea Equiv.	-				
Nyamandlovu	Kalahari Group	<10				
	Basalt	10-50: 40	0.5-4: <1	1-300		10^{-6}
	Ntane/Forest Sst.	50-120: 100	2-20	1-100	0.1-1.7	$1x10^{-5}$-$8x10^{-3}$
	Mea Equiv.	-				
OLDM	Kalahari Group	<10		1-150	0.1-15	$2x10^{-3}$ - 0.16***
	Basalt	100	5-20	5	0.05	$1x10^{-5}$
	Ntane/Forest Sst.	40	20-60	4-16	0.1 - 0.4	$5x10^{-5}$
	Mea equiv.	30	20-100			
KDM	Kalahari Group	<10				
	Basalt	130	5-20	6.5	0.05	$2x10^{-6}$
	Ntane/Forest Sst.	70	20-60	10.5	0.15	$3x10^{-5}$
	Mea equiv.	30	20-100			

Note "8-23: 15" = "range: average"; *The sustainable yield of the aquifer (section 7.2) determines the maximum number of BHs; **Local value; *** Specific yield

Sources: see Chapter 5.1 and 5.2

Table 6.2: Hydraulic characteristics of basement contact, dykes and faults

Unit	Width (m)	Kh (m/d)	Kv (m/d)	Storage coefficient	Specific yield
Basement contact	-	0.001	-	0.002	
NW-SE Dykes & NNW-SSE Faults	50 - 500	10^{-5} - 0.5	0.01-0.1	$3x10^{-5}$ - $8x10^{-3}$	$2x10^{-2}$

Source: Royal HaskoningDHV (2017)

6.5. Conceptual hydrogeological model of the EKK-TBA

Figure 6.8 presents a 3D conceptual hydrogeological model of the multi-layered EKK-TBA system.

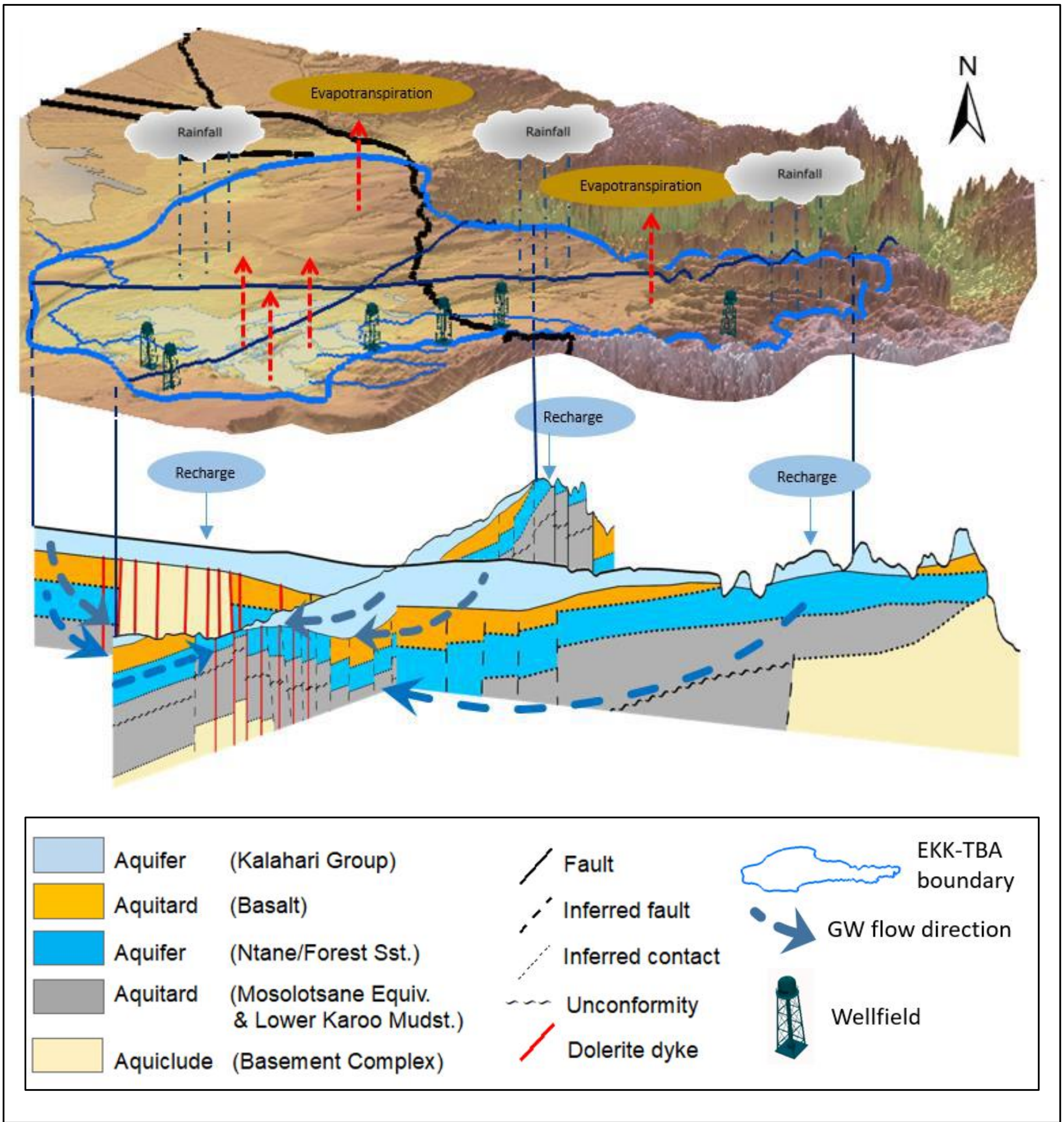


Figure 6.8: Conceptual hydrogeological model of the EKK-TBA

The shallow aquifer system (Kalahari Group) covers most of the EKK-TBA and is thickest in the central part of the Basin. Groundwater flow from the shallow aquifer is towards the Makgadikgadi Pans which forms a discharge area. Aquifer conditions of the Kalahari Group are unconfined to semi-confined. Because of the relatively low gradients of groundwater heads, salinity increases in the direction of flow.

Faulting and fracturing has resulted in compartmentalization of the deeper aquifers (Ntane/Forest Sandstone and Mea Arkose Sandstone). Groundwater from the deeper aquifers also flows towards the Makgadikgadi Pans and discharges via faults. Aquifer conditions are unconfined where the formations outcrop and recharge takes place and confined (overlain by the basalt and other Upper Karoo sediments) away from the recharge areas. The Ntane/Forest Sandstone aquifer is separated from the overlying Kalahari Group aquifer by basalt which forms an aquitard and where fractured and faulted, it hydraulically connects the Kalahari Group and Ntane/Forest Sandstone aquifers. The Mea Arkose Sandstone aquifer is separated from the Ntane/Forest Sandstone aquifer by Mosolotsane and Lower Karoo mudstones. The Basement Complex acts as an aquiclude of the EKK-TBA system. Note that recharge also takes place along contact zones between the Basement Complex and the aquifers.

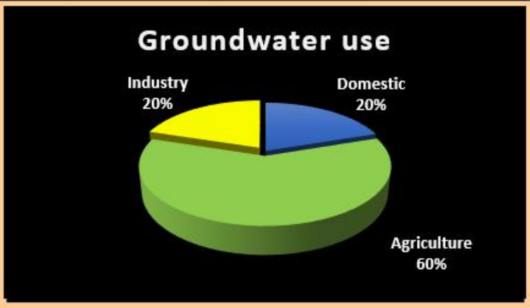
Most groundwater abstractions take place in the southern and southeastern fringes of the EKK-TBA from the Ntane/Forest Sandstone aquifer (Upper Karoo) and only in one area, Dukwi, from the Mea Arkose Sandstone aquifer (Lower Karoo). The aquifers become deeper away from the recharge areas in the direction of flow and over a short distance, groundwater salinity and groundwater age increase drastically.

7. GROUNDWATER USE, DEVELOPMENT AND MANAGEMENT

This chapter discusses water use, development and management in the context of domestic water supply, agriculture (crop water use) and mining. For Botswana as a whole, about 64% of the water use is from groundwater whereas for Zimbabwe, it is about 10% (Figure 7.1). In both countries, the agriculture sector, percentagewise, consumes most of the groundwater. The EKK-TBA is a semi-arid area with hardly any (perennial) surface water, except for a few rivers in the Gwayi Catchment in Zimbabwe. Thus, it can be safely assumed that the vast majority of water use in the area is from groundwater.

Botswana

Sectoral water use	Water use (million m^3/year)	GW contribution
Domestic (Urban and Rural)	37	41.0%
Agriculture	60	76.4%
Industry (Incl. Mining)	23	66.7%
Total	119	63.9%



Zimbabwe

Sectoral water use	Water use (million m^3/year)	GW contribution
Domestic (Urban and Rural)	410	9.8%
Agriculture	3 500	10.0%
Industry (Incl. Mining)	20	-
Total	3 930	9.9%

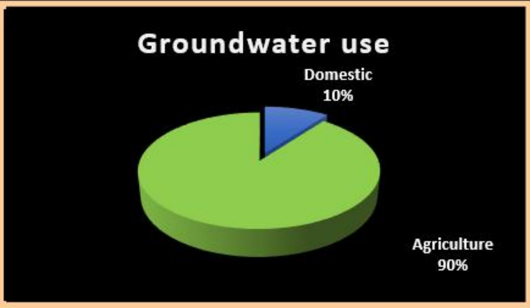


Figure 7.1: Groundwater use in Botswana and Zimbabwe
Source: Beekman (2010) and Pietersen and Beekman (2016)

7.1. Groundwater use

The current water use within the EKK-TBA can broadly be classified based on the land use and it can be seen that agriculture, domestic, mining and biodiversity constitute the main groundwater users/consumers, Figure 7.2.

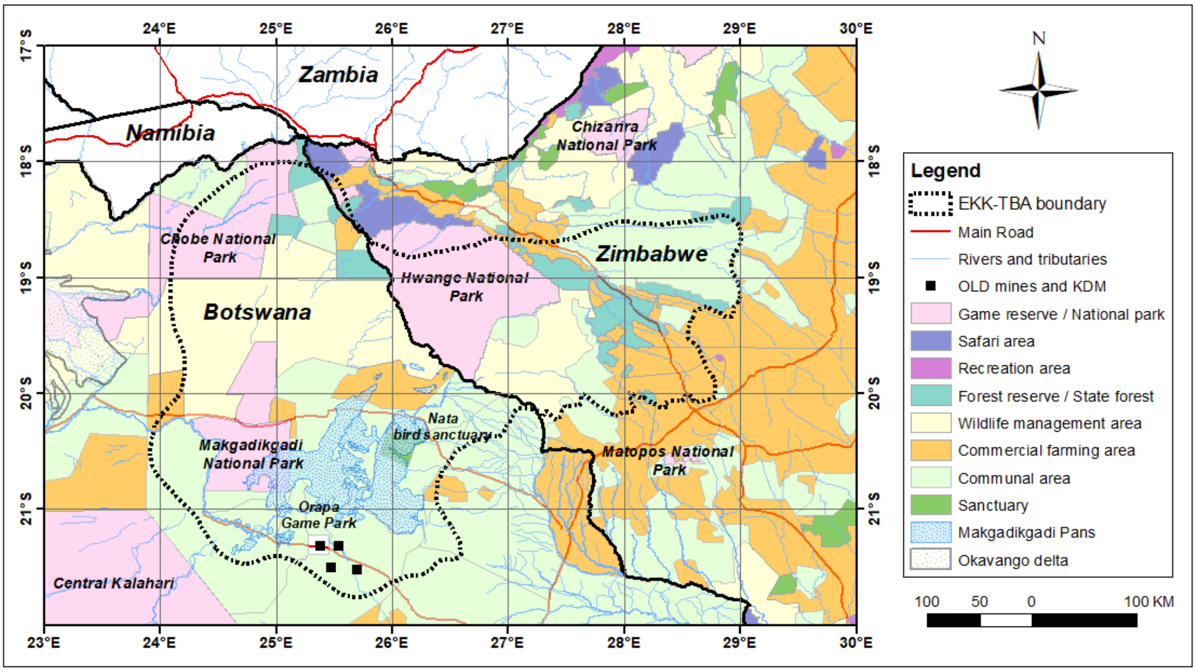


Figure 7.2: EKK-TBA land use map

Groundwater availability in the EKK-TBA is determined by the nature of the aquifer, its location, groundwater development costs and water quality, among other factors. The main source of groundwater for the domestic and mining sectors comes from the Ntane Sandstone and Mea Arkose Sandstone Aquifers in Botswana and for the domestic and agricultural sector in Zimbabwe, it comes from the Forest Sandstone Aquifer (which is equivalent to the Ntane Sandstone in Botswana). The main source of groundwater for biodiversity (environment, ecosystems, game parks and reserves) comes from the shallow Kalahari Group Aquifer.

The positioning of the Karoo Supergroup sandstone aquifers within the Basin has a direct bearing on the aquifer yields. Yields are much higher at the peripheries of the Basin within the sandstone aquifers. Groundwater quality poses a great constraint on the groundwater availability since saline groundwater is predominant particularly on the Botswana side of the EKK-TBA. Unmanaged abstractions can result in the mobilisation of the saline groundwater which will contaminate the potable groundwater and thus rendering it unusable and hence unavailable. In the Botswana wellfields, borehole yields average 20 m^3/hr and in the Nyamandlovu Wellfield (Zimbabwe), yields range from 2-20 m^3/hr.

Yields towards the central portions of the Basin are not known due to lack of data. Drilling deeper into the underlying sandstone aquifers (Ntane/Forest Sandstone, Mea/Wankie Sandstone) is expensive since the drilling has to go through unconsolidated Kalahari Group and the indurated basalt and into the 'collapsible' sandstones, a process that calls for costly and specialised borehole drilling and development procedures since each lithological unit requires its own unique drilling approach, and this makes the groundwater inaccessible and unavailable. Moreover, as mentioned earlier, the groundwater in the central portions of the

Basin is saline (inferring from data from the wellfields) and would not be suitable for human and agricultural purposes without prior treatment, which at this stage, would be uneconomical.

Sectoral groundwater use from the Ntane/Forest Sandstone and Mea Arkose Sandstone Aquifers within the EKK-TBA, based on current abstractions (sections 7.1.1, 7.1.2 and 7.1.3), excluding groundwater use for the environment and biodiversity, is estimated at 22% for the domestic sector, 15% for the agricultural sector and 63% for the industrial (mining) sector. Clearly, at 63%, the mining sector is by far the largest groundwater user in the EKK-TBA, Figure 7.3.

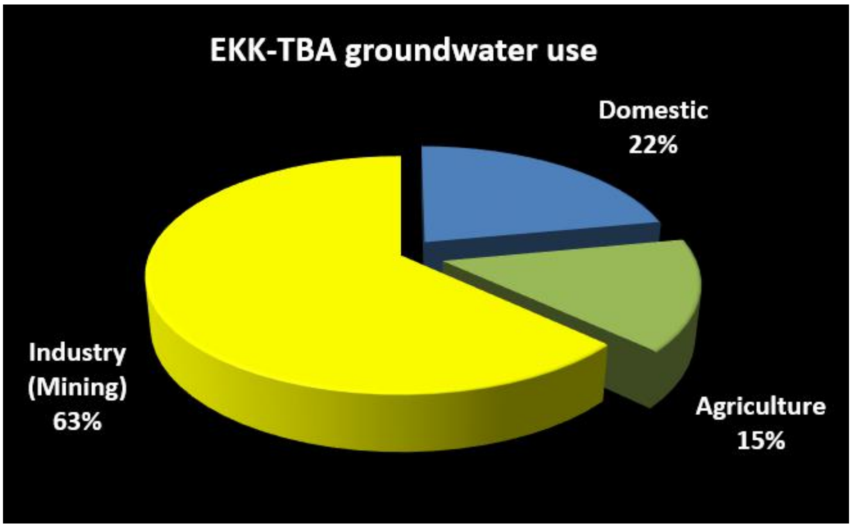


Figure 7.3: EKK-TBA sectoral groundwater use

7.1.1. Domestic water use

Water Utilities Corporation (WUC) is responsible for the supply of potable water for domestic use in Botswana, including the Botswana part of the EKK-TBA. It also provides wastewater management services such as operation and maintenance of the sewerage infrastructure in serviced areas. In Zimbabwe, ZINWA is responsible for operating and maintaining water works in order to provide water in bulk to local authorities and reticulated water to consumers on behalf of local authorities who lack the capacity to provide this service. Most of the water supply for rural and urban areas in the EKK-TBA is from groundwater from public owned and managed wellfields or mostly from handpump equipped boreholes in the case of rural parts of the Zimbabwean side of the EKK-TBA.

The present total (sustainable) groundwater abstraction from the major wellfields within the EKK-TBA for domestic water supply is estimated at 9.7 Mm^3/yr (Dukwi: 1.46 Mm^3/yr; Letlhakane: 0.55 Mm^3/yr; Maitengwe: 1.20 Mm^3/yr and Nyamandlovu: 1.48 Mm^3/yr).

7.1.1.1. Dukwi Regional Wellfield

The Dukwi Wellfield Phase II supplies an average of 30 m^3/hr per borehole to Sowa Town, Soda Ash Botswana Mine, Nata and Dukwi villages as well as the Dukwi Refugee camp and Quarantine Camp (Legadiko, 2015). Abstractions have been increasing over the years due to increased water demand as a result of increasing population, Figure 7.4. The water demand stands at more than 6 000 m^3/day against a supply of about 4 000 m^3/day *(ibid)*.

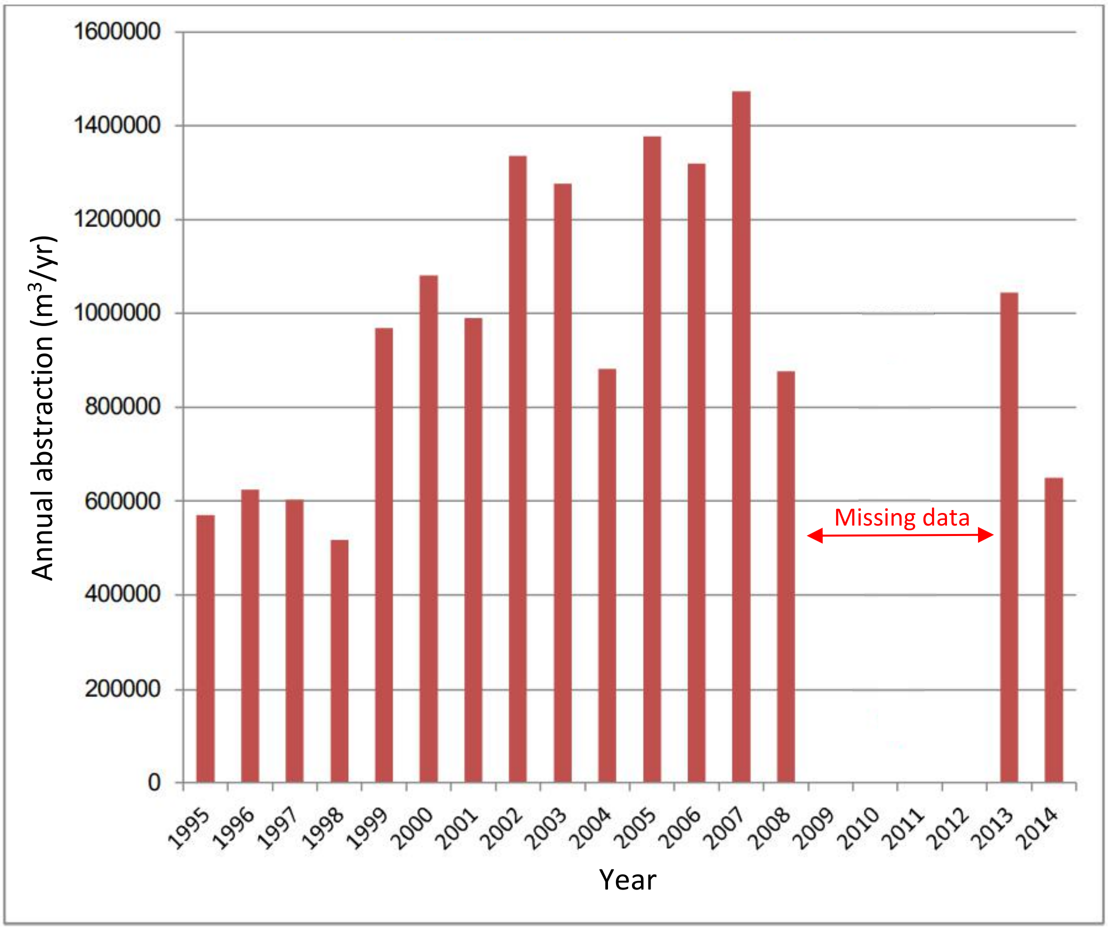


Figure 7.4: Dukwi Wellfield annual abstractions
Source: Legadiko (2015)

The water demand currently exceeds the supply and innovative water demand management strategies need to be put in place to optimize water resource utilisation given the diminishing supply, which is compounded by reduced rainfall as a result of climate variability and change and an increasing Basin population (SADC-GMI, 2020).

7.1.1.2. Letlhakane Wellfield

Groundwater abstraction from the Letlhakane Wellfield has been rising steadily since 1992 in response to a growing population (from 14 962 in 2001 to a projected figure of 24 822 in 2020), Figure 7.5.

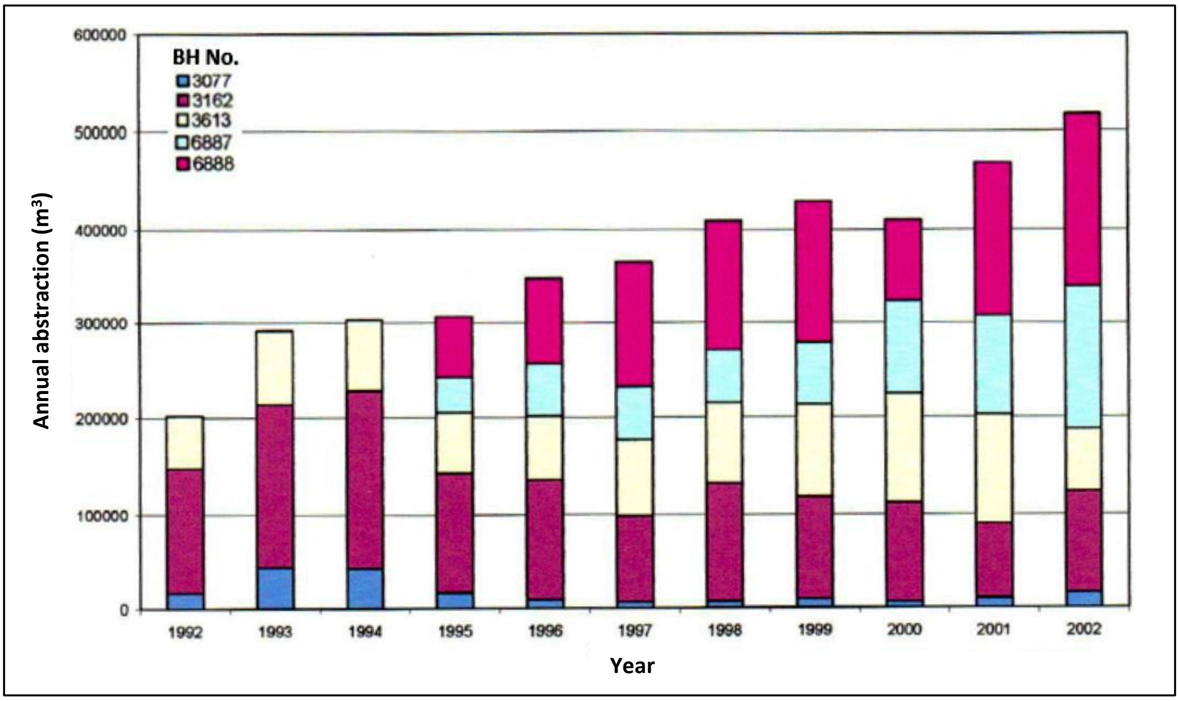


Figure 7.5: Letlhakane Wellfield annual abstractions
Source: Geoflux (2005)

Five new boreholes were drilled and developed in 2005 to give a combined yield of 274 m^3/hr and yet there is still a water supply deficit. Figure 7.6 shows an increasing deficit in potable water supply from 2004 up to 2020. It appears that the groundwater supply was developed to its maximum in 2004, which was less than the water demand from the onset. Further groundwater development or increase in abstraction would be unsustainable.

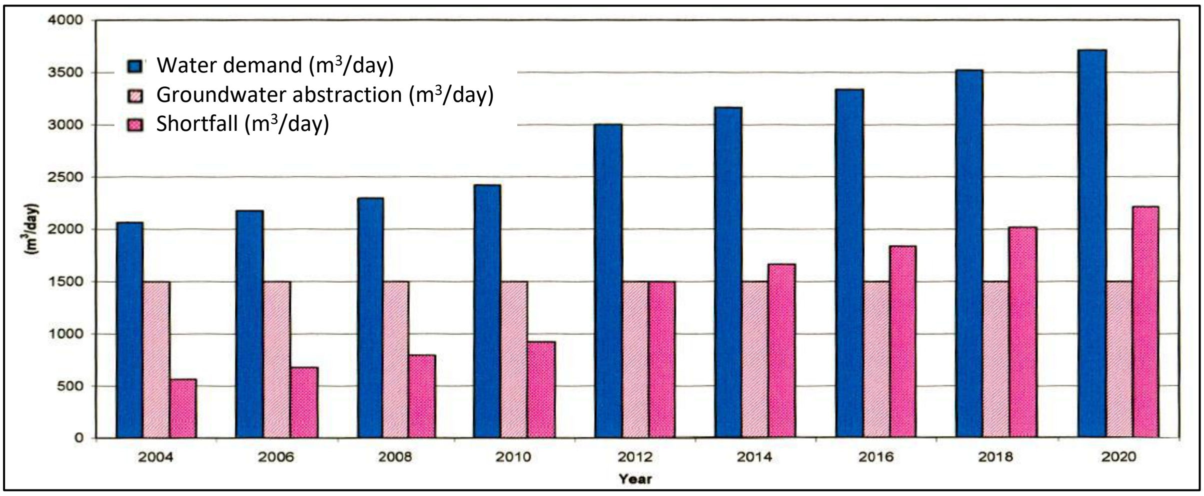


Figure 7.6: Letlhakane Wellfield - Water demand vs water supply
Source: Geoflux (2005)

7.1.1.3. Maitengwe Wellfield

The Maitengwe Wellfield comprises fifteen boreholes of which eight are production boreholes with the other seven being standby production boreholes. The standby boreholes are in the east, close to the edge of the Ntane Sandstone Aquifer. Given their close proximity to the edge of the aquifer and their limited available drawdown, these boreholes should only be pumped during drought periods to supplement supply. They are not recommended for pumping for extended periods whilst the eight production boreholes can be pumped on a managed schedule. The maximum wellfield output (from the main aquifer, Ntane Sandstone) should be maintained at the sustainable yield of 3 288m^3/day (DWA, 2002).

The water demand in the Northeastern District in Botswana which is supplied by the Maitengwe Wellfield was estimated at around 9 680 m^3/day by 2025 against a sustainable groundwater abstraction of around 3 300 m^3/day (DWA, 2002). Water supply from the Ntimbale Dam, which was commissioned in 2008, and existing crystalline boreholes, has relieved the pressure on the wellfield by reducing the abstractions, thus providing an opportunity to transfer excess groundwater (up to the sustainable yield) to other areas, such as Dukwi. Note that the Ntimbale Dam water supply and Maitengwe Wellfield constitute a good example of a sustainable conjunctive water supply scheme and in addition a potential water transfer scheme.

7.1.1.4. Nyamandlovu Wellfield

Figure 7.7 shows monthly abstractions from the Nyamandlovu Wellfield for the City of Bulawayo over the period of March 1993 to July 1999 and January 2012 to September 2020. From 1996 to 1999, the average daily abstraction was ~ 3 800 m^3/day. Note that the graph shows a prolonged period of missing data from (July 1999 to December 2011). The absence of abstraction data will have a critical impact on predictive (transient state) groundwater modelling which is a prerequisite for sustainable management of the aquifer.

A safe yield of 15 000 m^3/day or about 456 600 m^3/month was calculated for the whole aquifer system through detailed groundwater resource assessment and modelling (Beekman and Sunguro, 2015). The City of Bulawayo's water demand outstrips the current total supply inclusive of the Nyamandlovu Wellfield supply, implying that additional water supply sources need to be developed coupled with instituting innovative water demand management strategies that include efficient water utilisation techniques, particularly for agriculture, to meet the ever-increasing potable water demand.

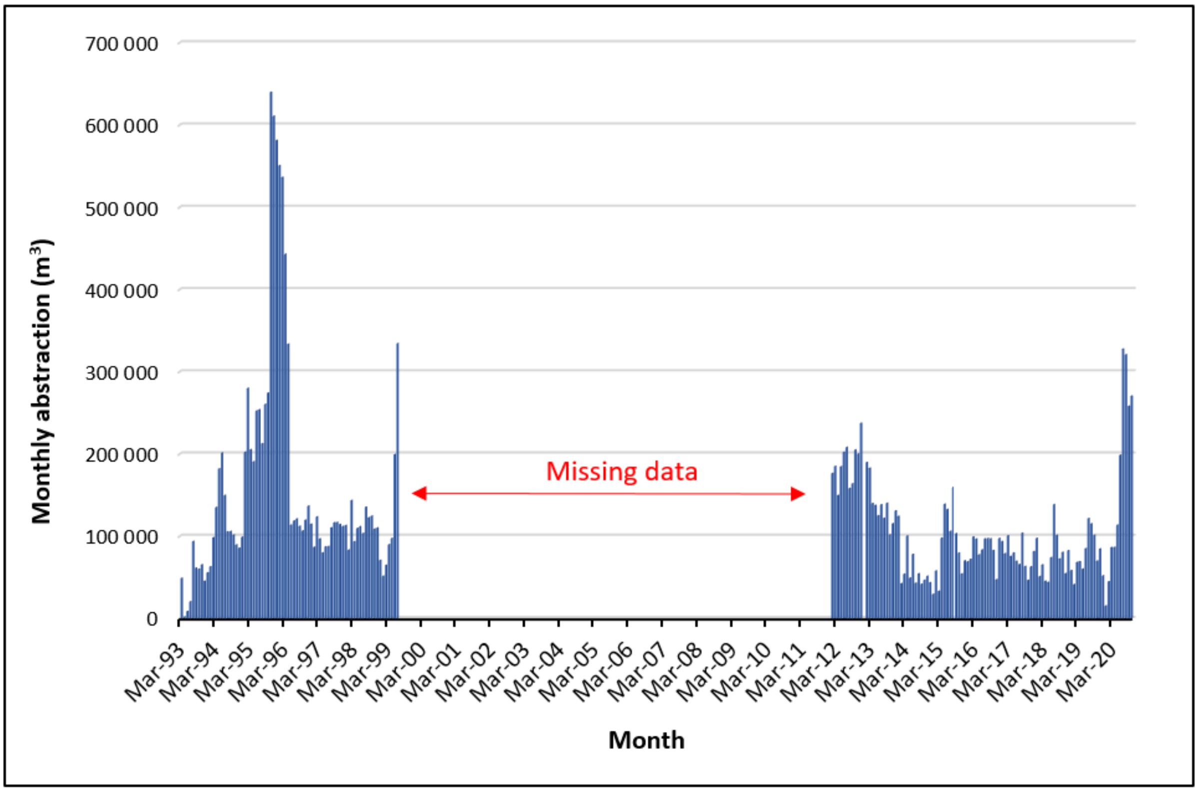


Figure 7.7: Nyamandlovu Wellfield monthly abstractions

Source: Beekman and Sunguro (2015); 2012-2020 data provided by ZINWA

7.1.2. Agricultural water use

Livestock and subsistence farming make up the most important part of people's livelihoods in the EKK-TBA. In communal areas, production of field crops is almost exclusively through rainfed arable agriculture.

There are two distinct areas within the EKK-TBA where commercial farming (cropping) is being practised: Pandamatenga in Botswana and Nyamandlovu-Umguza in Zimbabwe.

Pandamatenga is considered suitable for rainfed arable farming due to its characteristic fertile black cotton soils and favourable rainfall conditions averaging 600mm annually. Pandamatenga farms constitute the grain basket of Botswana and are reported to be responsible for 92% of all cereal production in Botswana. In 1984, the Government of Botswana commissioned the Pandamatenga Farming Project with the aim of increasing the country's cereal production and boosting its food security. The project involved the allocation of 25 000 hectares of virgin land to pioneering commercial farmers (SADC-GMI, 2020).

Commercial agricultural activities (including cropping) in Zimbabwe mainly occur in the Nyamandlovu and Umguza areas and rely on both rainfall and groundwater. These areas provide fresh produce to the City of Bulawayo and surrounding areas. The acreage of irrigated cropping between the Khami and Umguza Rivers amounts to ~1 200 ha (Beekman and Sunguro, 2015).

Crop water use was estimated for the Nyamandlovu area based on the general irrigation design criterion used by ZINWA of 1 litre/sec per hectare, 6 hrs per day, 4 days of irrigation per week, for 3 types of crops and for each type of crop for a growing period of 90 days (horticulture) and this amounts to 3 332.6 m^3/yr/ha or 9.1 m^3/day/ha. Agricultural groundwater use for the Nyamandlovu area between the Khami and Umguza Rivers is estimated at 1 200 x 3 332.6 = 4 Mm^3/yr. If the crop growing period exceeds 90 days, coupled with groundwater abstraction for the CoB, the overall groundwater abstraction increases and would inevitably result in over-exploitation of the aquifer.

7.1.3. Mining water use

Within the EKK-TBA, mining takes place predominantly on the Botswana part of the EKK-TBA (where diamonds and soda ash are mainly mined) and the mining operations require significant volumes of water. The mining sector in Botswana accounts for 10-15% of the total water use (DWA, 2014)[6] and within the EKK-TBA, the source of water is almost exclusively groundwater abstracted from private owned and managed wellfields. Other sources of water for mines include pit water and some storm water. Figure 7.8 shows the water use in the mining sector of Botswana. Diamond mining accounts for about 70% of the sector's water use.

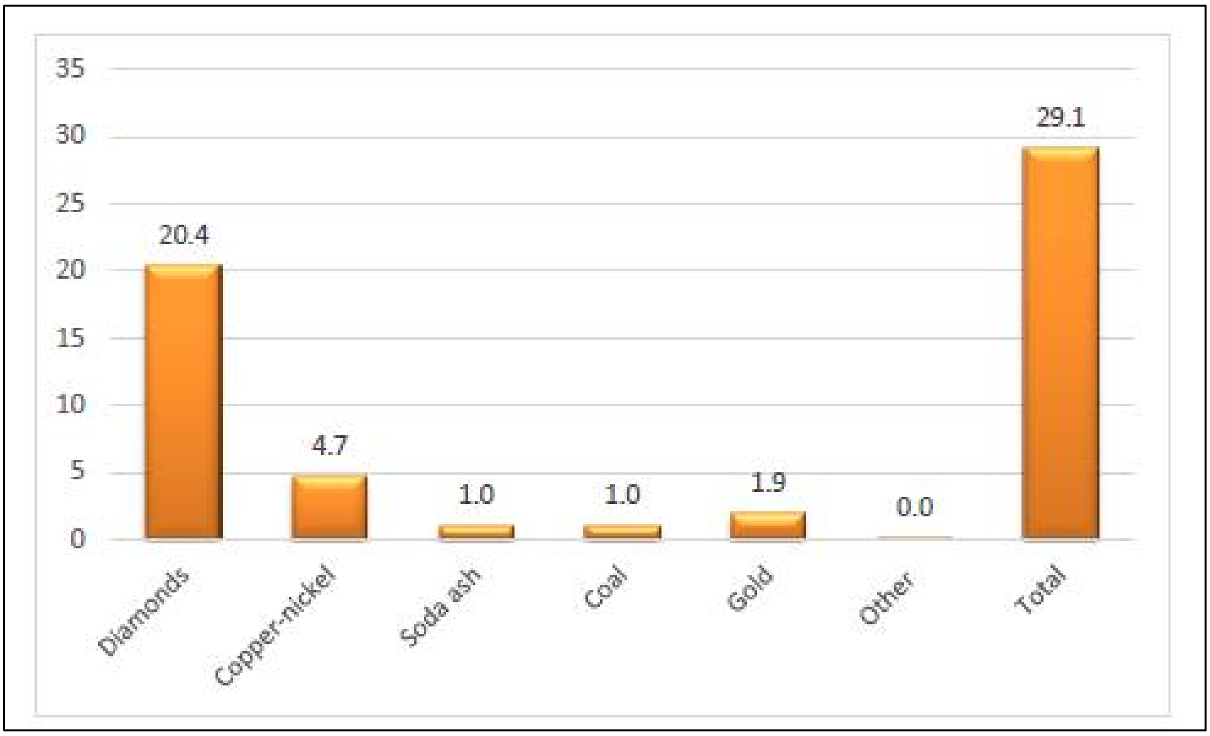


Figure 7.8: Water use in the Botswana mining sector (Mm^3/year)
Source: DWS (2018)

[6] https://www.car.org.bw/wp-content/uploads/2016/05/Botswana-Policy-Brief-mining-water.pdf

The present groundwater abstraction from the diamond mining wellfields within the EKK-TBA is estimated at 16.5 Mm^3/yr (OLDM: ~14 Mm^3/yr, including wellfield abstractions and dewatering boreholes, and KDM: ~2.5 Mm^3/yr).

7.1.3.1. OLDM Wellfields

The Orapa, Letlhakane and Damtshaa diamond mines (OLDM) from Debswana have been supplied with groundwater for nearly 40 years. A time-series of annual groundwater abstractions from all OLDM operations from 1991 to the end of 2019 is shown in Figure 7.9 (Debswana, 2020).

The annual abstractions range from 4 to 12 Mm^3/yr and have always been within the limits (less than 62%) of the allocated water rights. Wellfields contribute about 75% of the total groundwater abstracted by the mines, with dewatering providing the remainder. Wellfield 6 located between Karowe Mine and Letlhakane Mine Lease Area currently contributes most of the groundwater supply at about 34% of the total groundwater abstracted.

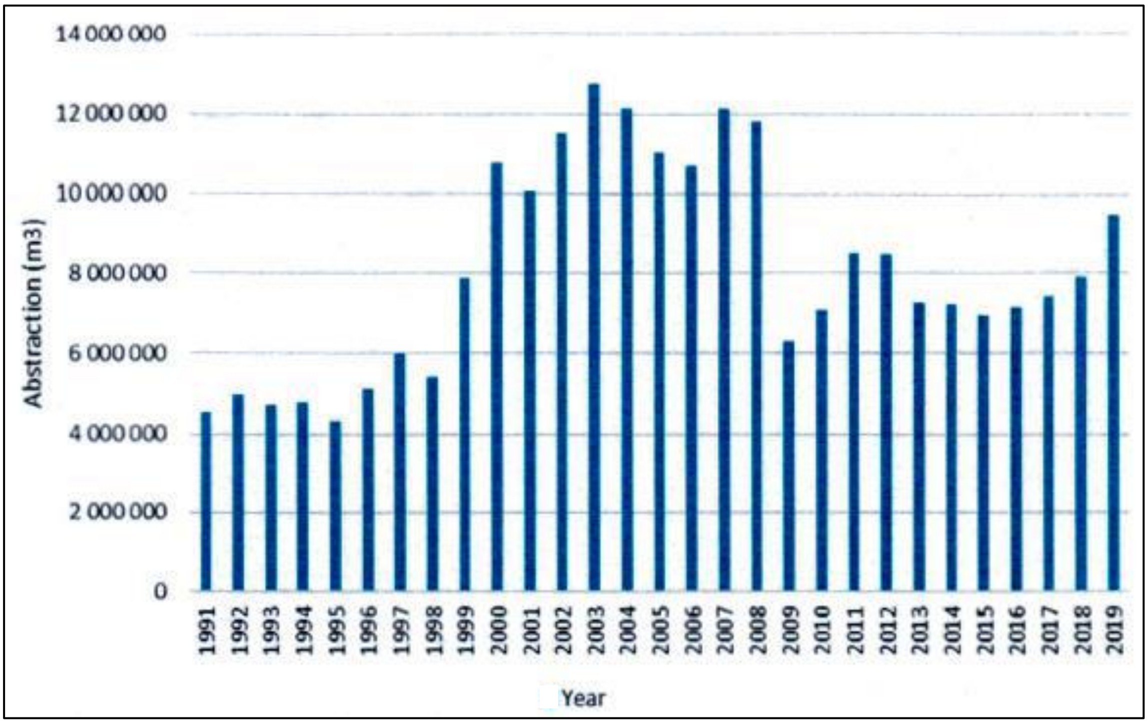


Figure 7.9: Total annual abstraction from OLDM's production boreholes
Source: Debswana (2020)

Figure 7.10 shows the water supply vs demand projections of OLDM operations up to 2050 (Debswana, 2015). The water supply is demand driven and this tends to negate the sustainability of supply as the thrust would be geared towards meeting the demand rather than ensuring the sustainability of the supply. This approach needs to be critically revaluated in a water stressed country such as Botswana as the sustainability of supply should be a key driving factor.

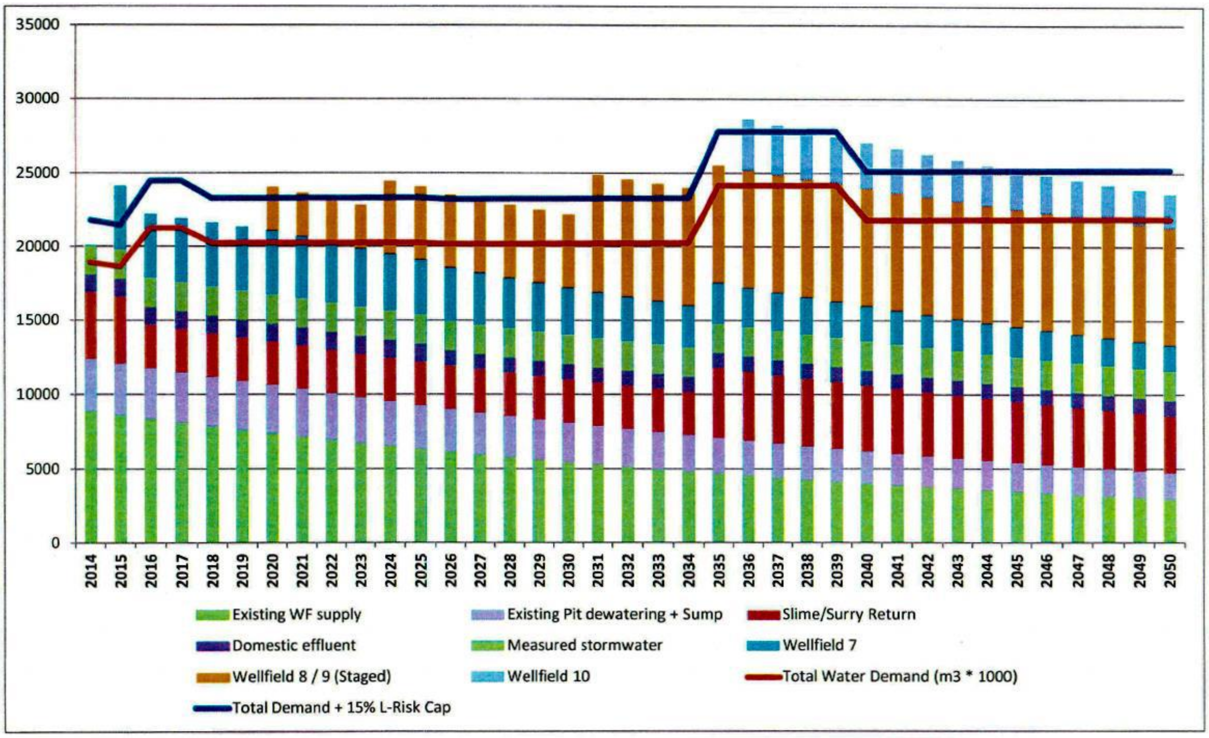


Figure 7.10: OLDM water demand and supply projections (m^3 * 1000)
Source: Debswana (2015)

Groundwater abstractions from Wellfields 2, 3, 5 and 6 are planned to decrease in the course of time due to declining groundwater levels; Wellfield 7 commenced abstraction in 2014; and new Wellfields 8, 9 and 10 will be established and operationalised in the near future.

Alternative sources of groundwater have been studied and blending of hyper-saline groundwater (ref. saline wellfield northwest of Orapa) and fresh groundwater was found to be the best option (Debswana, 2015). Rainwater harvesting e.g. storm water control and water re-use are being practised and should be upscaled.

7.1.3.2. KDM Wellfield

The Karowe Diamond Mine (KDM), owned by Lucara Diamond Corporation, has an abstraction permit for 8 Mm^3/yr and the average annual abstraction over the past 5 years has been around 2.5 Mm^3, implying that the permit volumes are highly inflated. Approximately 20% of water needs are met from water recovered from the slimes dam, whereas no water is discharged from mining sites into the environment as reported by Royal HaskoningDHV (2017) and this needs to be independently established.

7.2. Groundwater development

Sustainable groundwater development is concerned with meeting both current and future beneficial purposes without causing unacceptable consequences to the groundwater source or aquifer or compromising its ability to meet present and/or future needs.. It is therefore, very critical to conduct detailed hydrogeological investigations within the groundwater developed areas of the EKK-TBA in order to establish parameters for sustainable groundwater development. Similarly, new undeveloped areas would require detailed hydrogeological investigations to establish the aquifers, sustainable yields and vulnerability to pollution, among other parameters.

7.2.1. Sustainable groundwater abstraction

As a rule of thumb, where little or no information is available on groundwater recharge, sustainable groundwater abstraction is usually taken to be about 40% of the average annual recharge (Ponce, 2007). Figure 7.11 shows the daily sustainable groundwater abstraction (in 10^{-6} m/day) derived from the recharge potential map (Figure 6.7) and based on the 40% rule. To obtain the daily sustainable abstraction rate in m^3/day, one has to multiply the value of the daily sustainable abstraction representative of the specific recharge area read from the map, Figure 7.11, by the size of the specific recharge area (in km^2), see examples below.

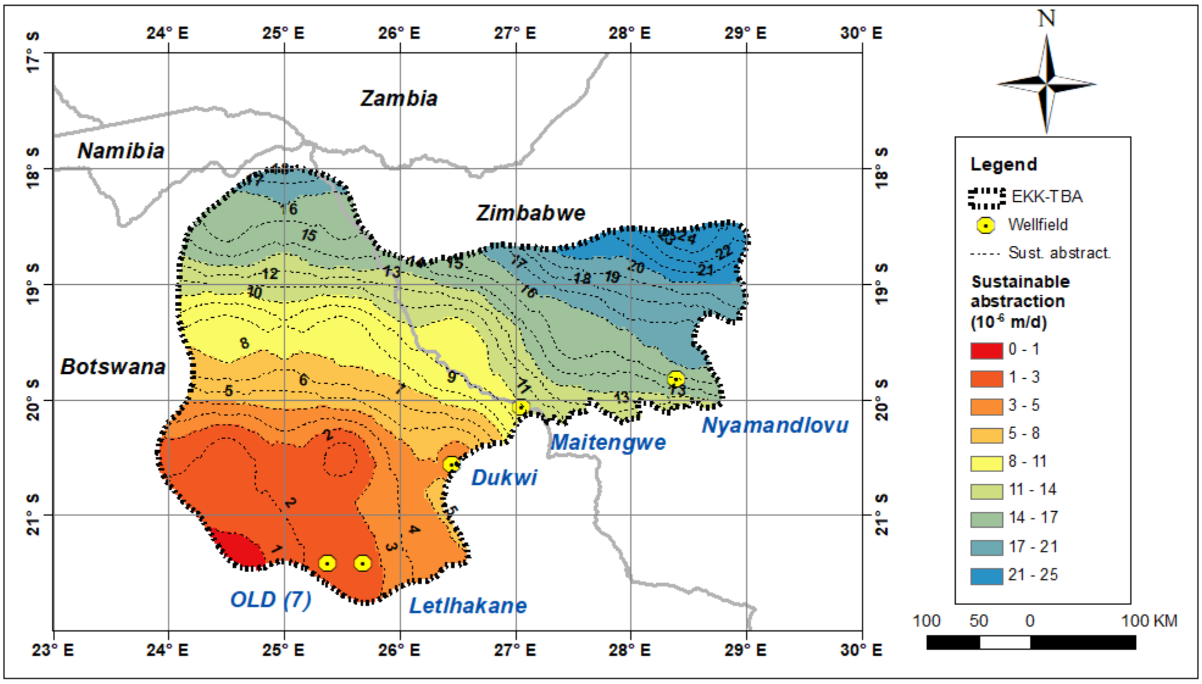


Figure 7.11: Sustainable abstraction in the EKK-TBA (10^{-6} m/day)

Example 1: Nyamandlovu Area

The recharge area of the Forest Sandstone Aquifer = 960 km^2 (Beekman and Sunguro, 2015). The sustainable abstraction over this area read from Figure 7.11 = 15. Then the daily sustainable abstraction = 15 x 960 = 14 400 m^3/day.

Note that this figure is close to the recommended sustainable abstraction of 15 000 m^3/day as determined through a steady-state groundwater model of the area *(ibid)*. From 1996 to 1999 the average groundwater abstraction for the CoB was ~3 800 m^3/day and for agricultural activities in the Nyamandlovu area it was ~10 960 m^3/day prior to the steady-state groundwater conditions in (September) 1999.

Groundwater levels from 2013 to 2015 (Figure 5.17) and average wellfield abstractions over the period of 2012 to 2019 (Figure 7.7) are similar to groundwater levels and abstractions over the period of 1996 to 1999 and this suggests that from 2013 to 2015, abstractions for the CoB and for agricultural activities in the Nyamandlovu area were sustainable. Note that abstraction data for the period of July 1999 to December 2011 are missing. Rainfall data, groundwater levels and abstraction data for agricultural activities are needed for the period from 2015 to present to determine if the aquifer is still being sustainably abstracted.

Following successive periods of low rainfall, groundwater abstractions for the CoB have drastically increased from about 100 000 to 300 000 m^3/month and if prolonged, may compromise the sustainability of the groundwater resource. Note that reduced rainfall amounts in the preceding seasons resulted in low inflows into the City's dams. The City has since decommissioned 3 of its water supply dams due to low water levels.

Communal tap in Empompini in Cowdray Park, Bulawayo, August 3, 2019
Source: Cynthia R Matonhodze / Bloomberg

Small patch of water at a dam - prolonged drought near Bulawayo, January 18, 2020
Source: REUTERS / Philimon Bulawayo

Example 2: Dukwi Regional Wellfield (Phase II)
The recharge area of the Mea Arkose Sandstone Aquifer = 105 km^2.
The sustainable abstraction over this area read from Figure 7.11 = 4.5. Then the daily sustainable abstraction = 4.5 x 105 ~ 470 m^3/day. This figure is close to the sustainable yield of the Mea Arkose Sandstone Aquifer, which was calculated at 400 m^3/day by DWA in 2000 but may not have taken into account indirect recharge.

Note that groundwater abstractions since 1995 were above 600 000 m^3/yr or 1 650 m^3/day, Figure 7.4, and are well above the calculated daily sustainable abstraction of 470 m^3/day. This is confirmed by declining groundwater levels as observed in BH 7547, Figure 5.4. Discontinuity in monitoring or missing data between 2009 and 2013, Figure 7.4, should be addressed.

Clearly, the need for continued groundwater monitoring, including data collection, processing, analysis and reporting, and predictive groundwater modelling for proper groundwater management for the EKK-TBA cannot be overemphasized. The following minimum data and information are critically needed for a groundwater management plan:

- A hydrocensus of all boreholes in the Basin:
  - BH-number and location coordinates
  - State and use of the borehole
  - Depth of the borehole
  - Lithologies intersected, where data exist
  - Groundwater level
  - Abstraction rate
  - Hydrochemistry
- Daily rainfall and temperature data from climate stations
- Daily streamflow data, particularly for perennial rivers such as the Umguza and Khami Rivers
- From each individual Basin wellfield production borehole:
  - Monthly: groundwater level
  - Monthly: abstraction
  - Bi-annual: groundwater chemistry
- From each groundwater monitoring borehole:
  - Monthly: groundwater level
  - Monthly: abstraction (if the monitoring borehole is also a production borehole)
  - Bi-annual: groundwater chemistry
- Assessment of groundwater use for agricultural activities:
  - Cropping area
  - Type of crops and crop water requirements
  - Duration and amount of irrigation

The data and information should be used in improving and periodically updating the Basin groundwater model in order to sustainably manage the groundwater resources.

7.2.2. Potential for future groundwater development

It is evident from the above that groundwater development in most of the identified aquifers on Botswana's EKK-TBA has reached its limits and new groundwater sources need to be established.

On the Zimbabwean side of the EKK-TBA, groundwater abstraction is currently taking place in the Nyamandlovu Wellfield. A safe aquifer yield of 15 000 m^3/d was calculated for the aquifer system (Beekman and Sunguro, 2015) and current abstractions are above the safe yield (assuming that groundwater abstraction for irrigation has not changed since 1999). It should also be noted that the current total suppressed daily water demand for the City of Bulawayo is around 160 x 10^6 m^3/d (unsuppressed daily demand = 180 x 10^6 m^3/d) and the combined supply from all the water sources (including surface water and the Nyamandlovu Wellfield) is at the moment less than the demand. This implies that additional water sources need to be identified and developed.

Rehabilitation Nyamandlovu Wellfield – 2015

Additional groundwater development within the EKK-TBA could possibly take place in the northeastern part of the basin, particularlys on the fringes of the basin especially where sandstone formations outcrop, and the Kalahari Group (where it is thickest and possessing good hydraulic characteristics). Zimbabwe also has the opportunity to develop groundwater within the Epping Forest area, northwest of the current Nyamandlovu Wellfield, Figure 7.12.

Hwange National Park has a surface water deficit for the greater part of the year (Chamaillé-Jammes et al., 2007; Msiteli-Shumba et al., 2018). Due to the water deficit, 67 boreholes were installed at some natural waterholes and wetlands in the Kalahari Group which covers approximately 80% of the Park, to ensure water availability throughout the year (Msiteli-Shumba et al., 2018). Due to the heavy reliance of the HNP on groundwater, there is need for detailed hydrogeological studies to quantify and evaluate the sustainable development of the resource.

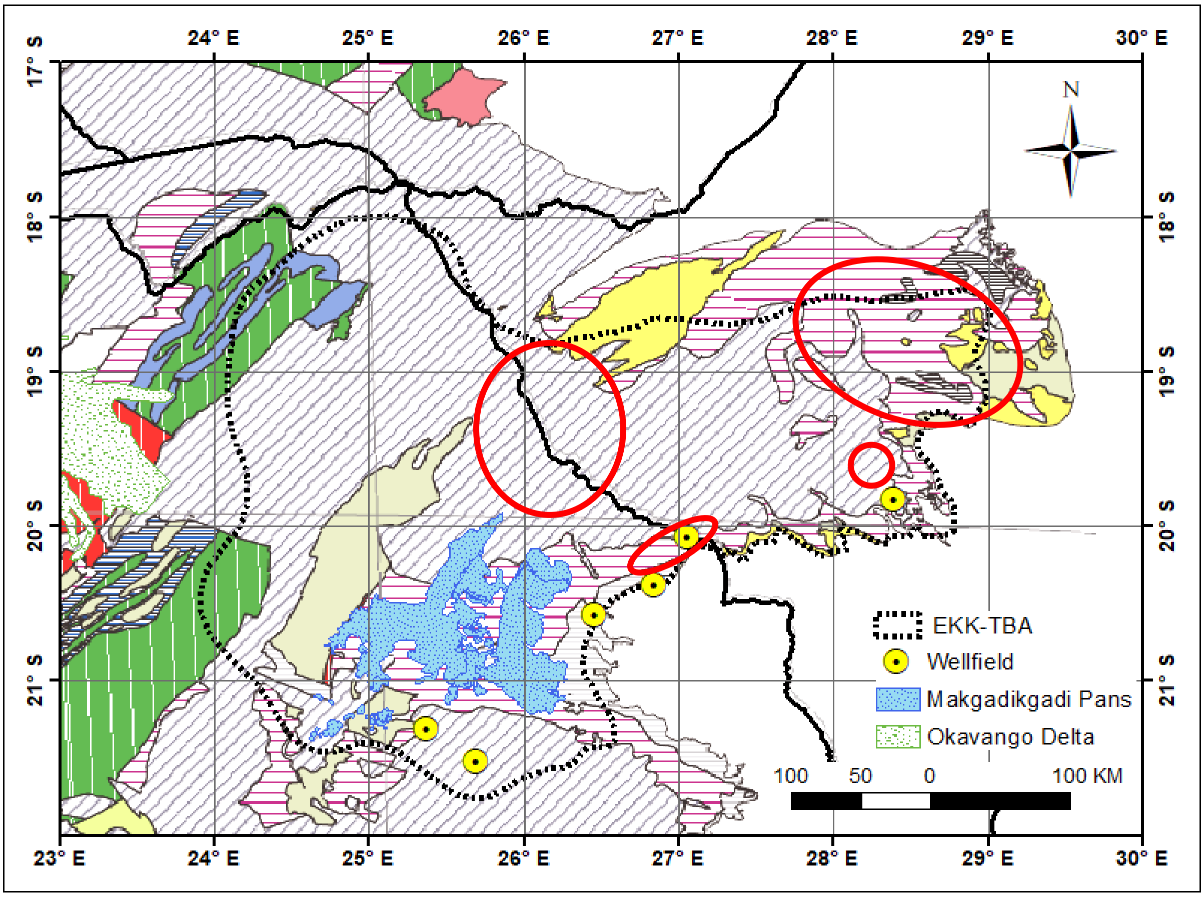


Figure 7.12: Potential areas for future groundwater development

As the potential for future groundwater development in the EKK-TBA is limited, groundwater management measures including water conservation and demand management remain critical in ensuring sustainability of water supply.

Complementary to the abovementioned groundwater management measures, and being cognisant of the semi-arid climate in the EKK-TBA, Managed Aquifer Recharge (MAR) could be implemented at the local scale to enhance the groundwater potential, e.g. in the Maitengwe area and using flows from the Nata River system. This, however, requires thorough hydrogeological investigations and detailed cost benefit analysis. A raft of water demand management and water conservation strategies, inter alia, introduction of innovative modern irrigation methods, change in cropping patterns, water recycling in 'urban' centres, timely fixing of burst pipes and leaky taps, blending of saline and fresh groundwater, etc., assist in ensuring sustainability of the resources and accessibility to potable water by consumers.

7.3. EKK-TBA Groundwater Management Unit

Neither of the two river basin organisations (OKACOM and ZAMCOM), under whose jurisdiction the EKK-TBA falls, are currently involved in groundwater management. Groundwater management within the EKK-TBA is localized and is carried out by both public (DWS and WUC in Botswana and ZINWA in Zimbabwe) and private sector (Debswana, Lucara, Botash, etc.) and is in-coherent (SADC-GMI, 2020).

The SADC water institutional framework as given in Figure 7.13 allows for the establishment of bi-lateral or multi-lateral water institutions to support specific purposes (SADC-GMI, 2019).

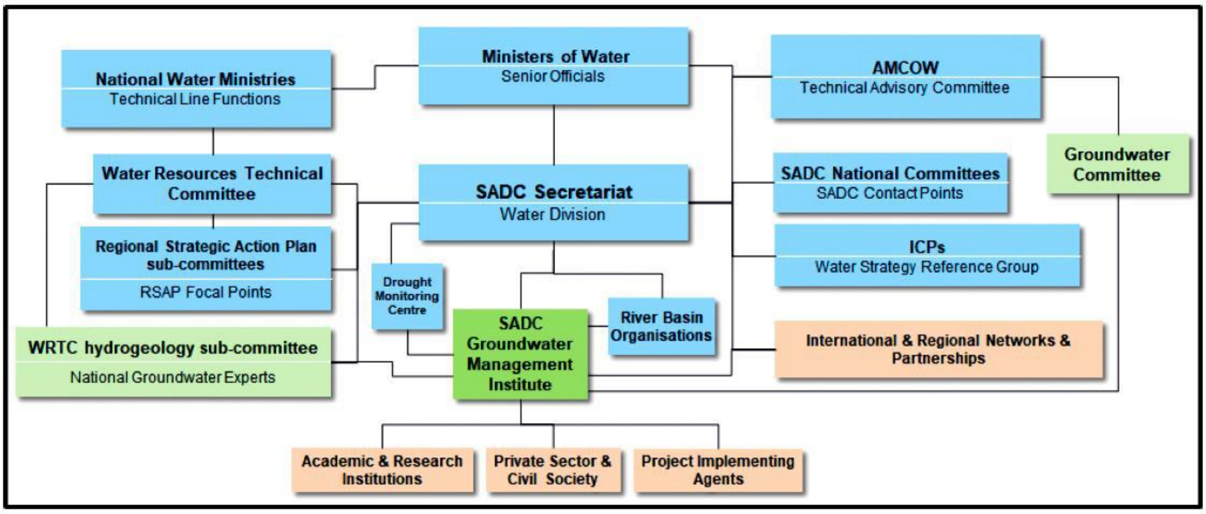


Figure 7.13: SADC water sector institutional framework

Note that the SADC Contact Points are known as National Focal Point Persons

Source: SADC-GMI (2019)

Hence, groundwater management (including monitoring, data and information exchange) of the EKK-TBA may be formalised through the establishment and nesting of a groundwater management committee or unit or any such outfit within the structures of OKACOM and ZAMCOM.

8. GROUNDWATER MONITORING

In this chapter, the current state of groundwater monitoring in Botswana and Zimbabwe is analysed and discussed, and a pragmatic approach to designing a groundwater monitoring network is presented.

8.1. Introduction

Groundwater monitoring and groundwater data acquisition are pre-requisites for any effective management of groundwater resources in terms of both, the groundwater quality and the quantity. Data such as groundwater levels, water quality and abstraction rates must be collected at predetermined intervals to detect potential changes or trends in groundwater flow and water quality. Constant groundwater monitoring provides the necessary data input for the decision-making process concerning spatial planning, development and management of groundwater resources. The monitoring data also provide an input into climate change adaptation. Groundwater monitoring is achieved through the establishment of a groundwater monitoring network and can be expensive to set up but is worth it given the dire consequences that would otherwise arise from not carrying out the monitoring. A monitoring network can comprise a series of observation wells coupled with a selection of abstraction wells, and meteorological data measurements (rainfall and temperature) with the aim of:

- Understanding groundwater dynamics (including flow direction)
- Assessing the potability of groundwater
- Assessing aquifer recharge and discharge
- Assessing the interaction between groundwater and surface water
- Detecting changes in groundwater storage, flow and quality and impact on groundwater availability
- Determining the impact of climate variability and change on groundwater levels, shedding light into future groundwater availability
- Assessing specific risks to the aquifer such as contamination, type and source of contamination and remedial measures to be taken
- Assessing saline water intrusion and upconing from deeper aquifers
- Establishing early warning systems (for overexploitation, salinization, pollution)
- Understanding the long term sustainability of aquifers
- Formulating appropriate groundwater management policies to ensure sustainability of groundwater use and supply

8.2. Analysis of current monitoring

8.2.1. Status quo

Groundwater monitoring within Botswana and Zimbabwe is conducted by both government institutions and by private mining companies. Figure 8.1 shows the locations where monitoring within the EKK-TBA is taking place and is very limited and localised.

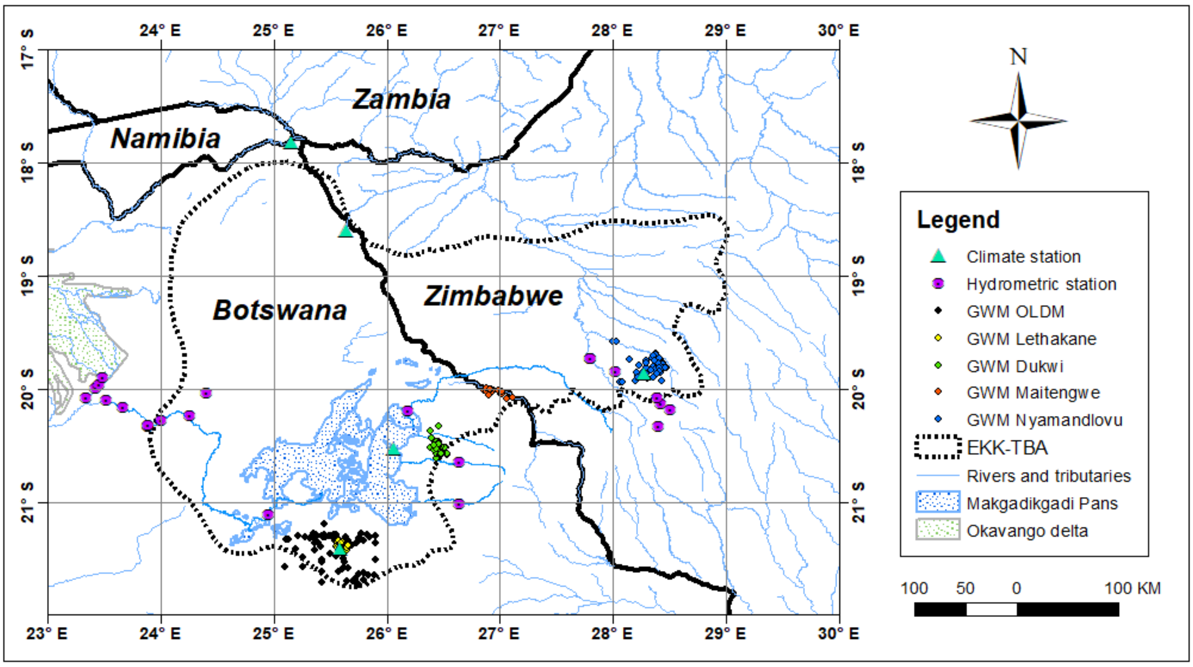


Figure 8.1: Monitoring within the EKK-TBA

8.2.1.1. Botswana

In Botswana, the continuous monitoring of water resources together with information management and dissemination are catered for in the National Water Policy (MoMEWR, 2012). The Water Utilities Corporation (WUC) and the Department of Water and Sanitation (DWS) are the two primary stakeholders for monitoring of water resources. The WUC is both a water supplier and a water resource operator. The institution would require data and information to enable it to operate its groundwater sources efficiently and cost effectively. This would ensure continuity of least-cost supply to its customers in a sustainable manner with respect to the source capacity and resource longevity, and within the limits set by their Water Rights. This requirement essentially focusses on issues of individual source depletion and over pumping, degradation and possible rehabilitation, pump installation depth and dynamic water levels, overall wellfield performance, and water quality. The DWS on the other hand, is both a water resources 'manager' and water use regulator and needs data and information to enable it to fulfil its mandate as the 'manager' and regulator of Botswana's groundwater resources to ensure equitable and sustainable use for optimum national development for both, current and future demands. This requirement focuses on data used in the numerical modelling of these resources both in major wellfields and in a broader national context. The use of such predictive models aids in realistic planning and drought mitigation, and the regulation of the exploitation of the resource via the Water Apportionment Board (WAB).

DWS

Groundwater monitoring commenced in the late 1970's – early 1980's under the auspices of the then Department of Geological Survey (DGS). The DWS monitors non-WUC 'observation' boreholes in and around the major wellfields as well as a network of boreholes scattered around its various regions through its regional offices. Most groundwater monitoring by DWS is done manually using dippers, although other wellfields have data loggers installed in some of the monitoring boreholes (Farr, 2017). There appears to be no continuation of the historic 'national' dispersed, aquifer-based monitoring network as originally inherited from DGS *(ibid)*.

WUC

WUC monitors all its production boreholes in both the major wellfields and in more dispersed Rural Supply Schemes (RSS). As at May 2017, the WUC had a total of 732 boreholes from which 487 (~67%) and 76 (~10%) were monitored for abstraction and groundwater levels respectively. The groundwater levels are all measured manually (Farr, 2017).

Mining companies

Private sector groundwater monitoring is largely undertaken by the mining companies who operate their own water sources for mine supply. Principal amongst these is Debswana who manage and monitor wellfields (8 No.) at Orapa and Jwaneng (1 No.), plus Soda Ash at Sowa Pan, Kheomacau Copper at Toteng, BPC at Morupule, and several other mining entities (Farr, 2017). Mining companies (particularly Debswana) have invested adequate resources into groundwater monitoring and this has resulted in consistency in monitoring and submission of comprehensive Annual Monitoring Reports to the WAB as required under their Water Rights allocation. However, no data is required to be submitted alongside these reports which presents a major flaw since the data is critical for groundwater modeling. Botswana Power Corporation (BPC) does likewise. Companies should be obligated to submit both the reports and comprehensive data and information.

Data Flow and Storage

DWS

Monitoring data is collected in both manual format and in digital format as output from borehole data loggers. Manual data collected on data collection forms is compiled by the Regional Offices into spreadsheets and both these and the digital data is submitted to DWS HQ. Onward transmission of data to DWS HQ appears to be irregular and somewhat dependent on the level and inclination of the regional staff. The DWS uses WELLMON as the monitoring database. However, the WELLMON database at both the DWS and Regional Offices is essentially non-functional and there appears to be little management incentive or initiative to improve this data flow (Farr, 2017). The DWS also has HydroGeoAnalyst (HGA) software from which a database is meant to be developed, and is yet to be fully utilised. It is suspected that digital data files are likely to be scattered across various computers at both DWS HQ and in the Regional Offices *(ibid)*.

WUC

Monitoring data gathered in the WUC wellfields is all manually collected in notebooks or on data sheets in each Management Centre. The data is then re-compiled into spreadsheets for storage and onward transmission to WUC HQ.

8.2.1.2. Zimbabwe

In Zimbabwe, the Zimbabwe National Water Authority (ZINWA) is the only institution mandated with national groundwater monitoring and is doing so infrequently and inconsistently due to lack of resources.

ZINWA

The Zimbabwe National Water Authority (ZINWA), a parastatal under the Ministry of Lands, Agriculture, Water and Rural Resettlement (MLAWRR), took over the responsibility from the then Department of Water Development in 2001 for monitoring groundwater. ZINWA, through the Groundwater Department, only monitors groundwater levels monthly in three main aquifers which include the Nyamandlovu Sandstone Aquifer, Save Alluvial Aquifer and Lomagundi Dolomite Aquifer. A few data loggers were installed in some boreholes within the Nyamandlovu Aquifer in 1999 but these were vandalised. There is no continuous monitoring of the groundwater levels and there is no groundwater chemistry monitoring and coherent daily groundwater abstraction monitoring for the Nyamandlovu Wellfield boreholes.

Hwange National Park

It is believed that HNP monitors groundwater levels within the park. However, the data is not easily accessible.

Data Flow and Storage

ZINWA

Monitoring data is virtually collected manually and is captured into Excel Spreadsheets for incorporation into HydroGeoAnalyst (HGA), a database software used by ZINWA.

8.2.2. Limitations to groundwater monitoring

There are several limitations that hamper effective and efficient groundwater monitoring:

DWS

- Shortage of suitably trained monitoring personnel at some Regional Offices
- Limited monitoring equipment
- No specific monitoring budgets

- Unclear division of roles and responsibilities between DWS and WUC with regards to wellfield monitoring
- Relatively small 'core team' of limited experience and poorly incentivised management staff at DWS HQ
- Poor cooperative working relationship with WUC on monitoring

WUC

- Lack of measuring access on boreholes – no dipper access tubes (removed/discarded or were never installed)
- Lack of manpower and equipment – shortage of personnel, GPS and dedicated transport, and dippers
- Lack of training of monitoring staff – pump operators not trained in monitoring; technicians not trained in data QA/QC, evaluation or storage
- No/incomplete database for boreholes under WUC, reporting structure regarding groundwater management at Management Centres not well defined
- Limited office space
- Frequent faulty telemetry
- Inadequate supervision of borehole operation and monitoring processes at Management Centres
- Inadequate appreciation of monitoring requirements and importance – lack of knowledge at Manager/ Technician level at Management Centres; lack of management and sensitisation from WUC HQ; lack of staff/personnel incentivisation
- Unclear linkages between WUC and related departments like DWS, Land Board, etc.
- Poor enforcement of recommended borehole pumping regimes and implementation of recommendations from groundwater monitoring reports; lines of authority for ensuring such implementation not well defined

ZINWA

- Lack of logistical support – shortage of dedicated transport and budgetary support
- Lack of dedicated staff to carry out the monitoring
- Lack of telemetry
- Inadequate appreciation of monitoring requirements and importance

Data quality

DWS

- There is generally lack of data quality control at both the Regional Offices and DWS HQ

WUC

- There is minimal quality control at the various levels

- Data is nominally quality controlled by inadequately trained Groundwater Technicians in the Management Centres
- There is lack of oversight by senior management

ZINWA

- There is limited data quality control with only irregular checks by the Groundwater Department Head Office
- Irregular checks are conducted several weeks or months from the date of measurement and which takes long to effect any remedial action, resulting in poor quality data and in data gaps

Data Flow and Storage

DWS

- The database software is not user friendly
- Lack of financial resources to subscribe for later versions of the software and support services
- Lack of staff training
- Lack of management of the database system
- Lack of human resources

WUC

- There is no central monitoring data storage system at WUC HQ, nor is there any decentralised database system in the Management Centres
- The existing data flow and storage may be adequate at a local wellfield scale, but to gain a basin wide perspective, the data also needs to flow to and stored at the national level

ZINWA

- There is severe staff shortage within the Groundwater Department resulting in the HydroGeoAnalyst software not being used
- There are huge monitoring gaps as a result of lack of capacity
- The database software requires a high level of computer literacy and database management among the staff and this is lacking
- Lack of financial resources to subscribe for later versions of the software and support services

Mining companies in Botswana

- The non-submission of data creates a gap when the basin or national groundwater resources are to be looked at in totality

8.3. Designing a groundwater monitoring network

Inasmuch as the setting up of a basin wide groundwater monitoring network within the EKK-TBA is considered paramount, its adoption, prioritisation and implementation need to be effected through the EKK-TBA Strategic Action Plan (SAP) which looks at all the Basin key issues. The EKK-TBA SAP prioritises the various key issues that need to be actioned on and implemented in order to answer to pressing Basin needs. In this section, we limit ourselves to describing the requirements for establishing an EKK-TBA groundwater monitoring network.

Advocacy for inclusion of monitoring of meteorological data in a groundwater monitoring network has been necessitated by the challenges that water management authorities face in acquiring such data from the relevant institutions and the fact that the meteorological stations might be absent or inadequate within the groundwater basin. Note that for assessing groundwater-surface water interactions also streamflow monitoring needs to take place.

8.3.1. Considerations for designing an EKK-TBA monitoring network

The setting up of an EKK-TBA basin wide monitoring network requires a comprehensive understanding of the situation obtaining on the ground within Botswana and Zimbabwe. This would entail visits to the countries and field visits to the EKK-TBA. The designing of a groundwater monitoring network should be guided by specific and clear objectives and the type of data required to fulfil the objectives and should all be based on a good hydrogeological conceptual model of the basin. The following considerations are required when setting up a groundwater monitoring network, and being mindful of issues discussed under section 8.2.

Existing groundwater monitoring networks
There are several groundwater monitoring networks within the EKK-TBA which are more aligned to answering local wellfield needs (localised monitoring networks). Some boreholes from these monitoring networks can be incorporated into a basin wide monitoring network.

A basin wide transboundary monitoring network should consider the institutional set-up of both countries. Farr (2017) advocates for the formulation of a National Water Resources Monitoring Strategy for Botswana to ensure reliable monitoring data collection by the DWS and WUC which should encompass both surface and groundwater monitoring. This should be accompanied by a National Monitoring Framework that sets out the roles and responsibilities, and addresses the data needs and operational modalities, of all stakeholders, and determines the data storage, sharing and usage priorities to enable the stakeholders to fulfil their water sector mandates. Figure 8.2 shows the proposed National Groundwater Monitoring Framework to address limitations to groundwater monitoring in Botswana *(ibid)*.

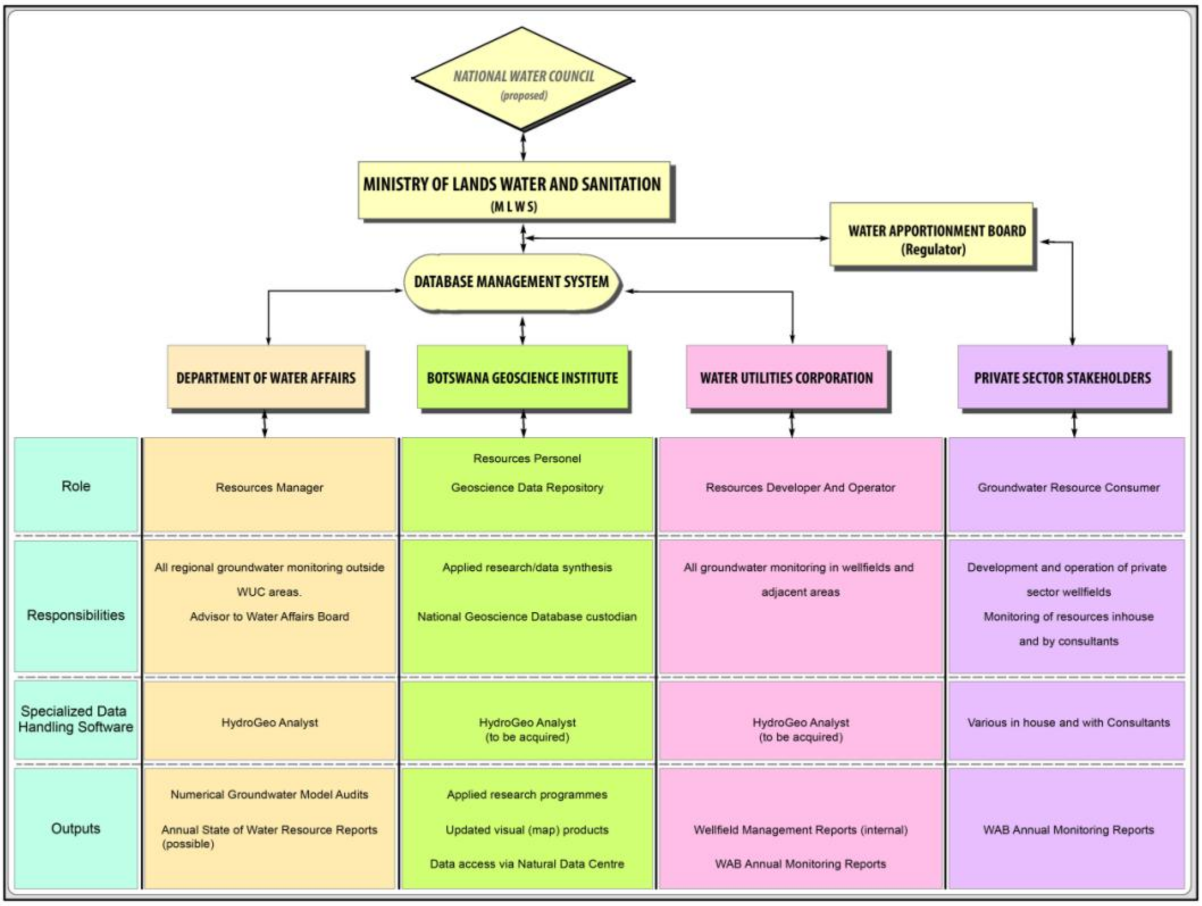


Figure 8.2: Proposed National Groundwater Monitoring Framework for Botswana
Source: Farr (2017)

Leaning on the proposed monitoring framework for Botswana, the existing monitoring frameworks in both countries, and experiences from other transboundary monitoring frameworks, a transboundary institutional framework for the EKK-TBA can be developed.

Site selection
The selected sites should be based on the defined monitoring objectives and should provide comprehensive information that is representative of the aquifers being monitored. Some of the monitoring sites could be installed within the wellfields. Sites selected in the unmonitored sections of the Basin should answer to the monitoring objectives.

Existing boreholes
Existing boreholes can be incorporated into the monitoring network when adequate information on intersected lithologies, construction details and construction material, condition, possibility of use as a monitoring well, etc are well known. Most of such information has been established to be lacking and where information and data are available, some of it has been found to have quality issues (see Chapter 1).

Parameters to be monitored
It is essential to identify the parameters to be monitored and from which boreholes they are to be monitored. For example, monitoring for groundwater chemistry would ordinarily require boreholes that accommodate a purging pump whereas groundwater level monitoring would only need a borehole that accommodates a probe. As this might be the case, issues of borehole rehabilitation need to be taken into account since narrow/small diameter boreholes would be difficult to rehabilitate with an ordinary borehole drilling machine.

Parameters to be monitored and not necessarily from the same boreholes and at every station are:

- Groundwater quality
- Groundwater levels
- Abstraction rates
- Meteorological (rainfall and temperatures)

Frequency of monitoring
Frequency of measurements is one of the most important components of a groundwater monitoring programme. Groundwater systems are dynamic and continuously adjust to groundwater abstraction, climate, and land use activities. Inasmuch as economic consideration plays a huge role, the benefits of a monitoring programme must be weighed against economic issues. Anticipated data variability and the extent of detail needed to fully understand the aquifer systems should be the lead factors in determining the frequency of monitoring. It is worth noting that some of the field data can be acquired remotely through telemetric systems.

Data quality assurance
Good data quality assurance practises are essential in maintaining the accuracy and precision of measurements and yield data that can be relied upon in policy decision making processes or for any intended use. Field and office procedures that ensure the acquisition and maintenance of high quality data need to be established and employed to the letter. These include sampling and sample transportation protocols, accurate field records, expeditious electronic archiving, data quality protocols, etc. Appropriate databases are a requisite to the proper archival and processing of the data.

Data collection, analysis and reporting
It is important to establish institution(s) that will be responsible for data collection, analysis and reporting. Key management decisions should be informed by the collected data and as such, the monitoring network should take this on board. Regular data reporting is essential as it motivates those who carry out the monitoring and instils confidence in the financing institutions as they will see the product of their budgetary support and will influence policy makers to push for sustained financial support of the monitoring programme. Use of electronic reporting cannot be overemphasised.

Data acquisition instrumentation

Various data acquisition instrumentation exist. The monitoring network design should consider the type of instrumentation that will be used for the data acquisition. Currently, the majority of the groundwater data is acquired manually within the EKK-TBA. Manual acquisition comes with logistical issues for field data measurements which in most cases results in data not being measured consistently. Consideration should be given to telemetric data acquisition and should thus be incorporated in the designing of the monitoring network. Nevertheless, there still should be room for manual measurements in some of the boreholes to validate the remotely acquired data.

The setting up of an EKK-TBA monitoring network system should be alive to the current limitations and challenges institutions in the two countries are facing and should therefore develop mitigation measures to prevent the EKK-TBA from suffering the same fate. Data quality control shortcomings could be partly overcome by immediately plotting data after measuring and recognising anomalies which could be instantly resolved.

8.3.2. Setting up a groundwater monitoring network

It should be recognised that monitoring system design is not a once-off activity but is a task that requires regular updating and refinement of the monitoring system to ensure that the data collection procedures are still valid and are providing valuable information to meet the monitoring objectives (Figure 8.3). The data collection and capture of information systems must be followed by a phase of data analysis and interpretation. During this assessment phase, data gaps should be identified and the successes as well as shortcomings highlighted for feedback into the next cycle of the monitoring system design and the process is repeated.

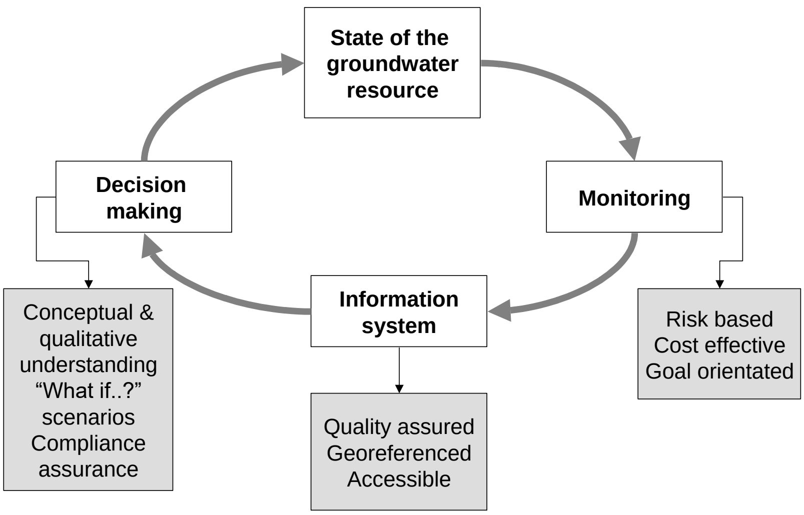


Figure 8.3: Monitoring and decision making cycle

Source: Cavé et al., 2002 (in Beekman, 2005)

8.3.2.1. Overcoming resource limitations

Limitations will always creep up and these need to be effectively attended to. The monitoring strategies should aim to make the best use of available resources. This requires proactive efforts to:

- Prioritise monitoring activities which provide the most critical data and information
- Promote cooperation and coordination with other monitoring activities e.g. surface water, meteorology (or else setup on monitoring stations where there are no existing met. stations)
- Incorporate and refine existing monitoring programmes to avoid unnecessary effort or duplication of effort
- Streamline monitoring procedures to reduce man-hours and travel times wherever possible
- Make the best use of existing infrastructure, especially existing boreholes if construction details and condition are known
- Make use of local water users for financial and/or logistical support (requires stakeholder engagement and involvement)
- Make use of modern data acquisition technologies
- Conduct cost-benefit analyses for the monitoring network design
- Mainstream the monitoring programme into the national budget

8.3.2.2. Designing a Groundwater Monitoring System

There are various approaches that can be employed in designing a groundwater monitoring network or system. A typical step-wise approach (8 step approach) in designing a monitoring programme is provided below. The 8-step approach was effectively employed in Eritrea (Cavé et al., 2002 in Beekman, 2005) and Zimbabwe (Beekman and Sunguro, 2015).

Note that the development of a conceptual EKK-TBA hydrogeological model is an essential prerequisite for the design of a groundwater monitoring network. Without some conceptual understanding of how the system works (e.g. where groundwater is recharged, in which direction it flows, relative rates of flow, etc.), the monitoring network is bound to be haphazard and will not answer some of the objectives. The conceptual model forms part of Step 4 where the network is designed. The 8-step approach comprises:

STEP 1: Set monitoring goals
STEP 2: Establish monitoring status quo
STEP 3: Coordinate with other monitoring initiatives
STEP 4: Design monitoring programme
STEP 5: Address support services and training requirements

STEP 6: Set up quality assurance/quality control procedures
STEP 7: Draw up planning document
STEP 8: Implement and update groundwater monitoring programme, Figure 8.4

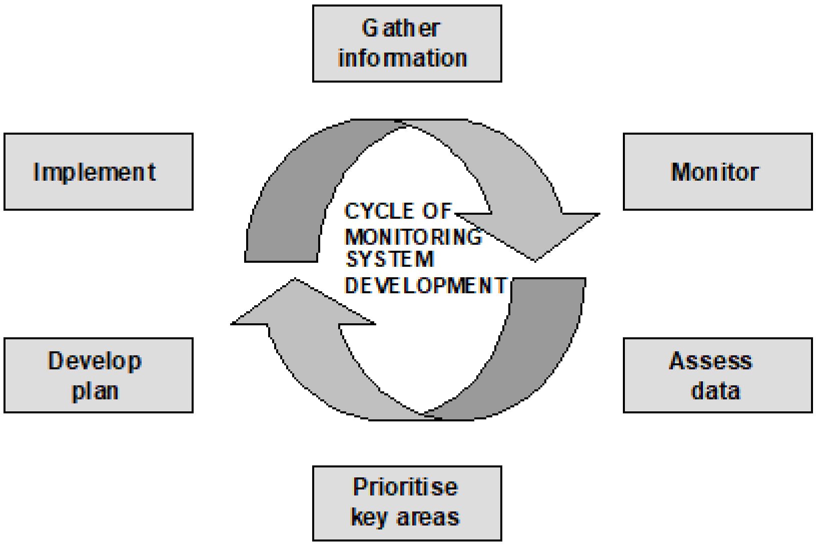


Figure 8.4: Cycle of monitoring system development
Source: Cavé et al., 2002 (in Beekman, 2005)

Detailed information on the designing of a groundwater monitoring network is given in Appendix I.

9. FINDINGS AND WAY FORWARD

9.1. Findings

The study has established the following findings:

- Groundwater constitutes the main source of water in the EKK-TBA. Most rivers within the EKK-TBA are ephemeral, save for the Gwayi River system in the eastern part of the Basin. Surface – groundwater interactions are limited and localized, hence limiting opportunities for conjunctive water use
- Climate analysis of rainfall data (30+ years) did not reveal any statistically significant trend whereas for temperature data (30+ years), an increasing trend was observed
- The EKK-TBA constitutes a multi-layered aquifer system comprising of a shallow unconfined to semi-confined aquifer (Kalahari Group deposits) which covers most of the Basin, and deeper confined (Ntane/Forest Sandstone and Mea Arkose/Wankie Sandstone) aquifers. The principal aquifer on a basin wide scale is the Ntane/Forest Sandstone. In the Botswana part of the Basin, the Ntane and Mea Arkose Sandstone aquifers are structurally controlled by NNW-SSE trending Faults and intersected by a NW-SE dyke swarm. Conceptual geological and hydrogeological models constructed for the EKK-TBA based on inferences from peer reviewed (hydro)geological publications and (hydro)geological maps at the basin scale and based on detailed hydrogeological data and information from public and private wellfields in the southern and southeastern fringes of the EKK-TBA show the extent of the aquifers and aquitards and structural control
- Groundwater development: within the EKK-TBA, groundwater development is generally localized and is mostly confined to public and private wellfields in the southern and south-eastern fringes of the EKK-TBA
    - Water demand for domestic use currently exceeds water supply in both Botswana and Zimbabwe
    - Water supply for the mines in Botswana is demand driven and this negates the sustainability of supply. Groundwater modelling has shown that the abstraction rates required for pit dewatering and abstraction rates of the wellfields to meet the long-term water demand will lower regional water levels and this will inevitably affect local farmers who rely on the groundwater for agriculture
- Groundwater recharge and sustainable abstraction: except for wellfield areas, there is limited knowledge of groundwater recharge of the EKK-TBA. To overcome this knowledge gap, a groundwater recharge potential map was derived for the EKK-TBA based on rainfall-recharge relationships from four decades of groundwater recharge studies in the region and local recharge studies (mainly around the wellfields) within the EKK-TBA. Average annual recharge was estimated to be generally less than 3% of

the average annual rainfall within the EKK-TBA, which is expected for such a semi-arid environment. The shallow Kalahari Group aquifer is mainly replenished by direct or diffuse (rainfall) recharge, whereas replenishment of the (deeper) Ntane/Forest and Mea Arkose/Wankie Sandstone aquifers is from both direct and indirect (through faults, river beds, etc.) recharge. The groundwater recharge potential map was converted into a sustainable abstraction map using a general rule of thumb that on the average, 40% of average annual recharge can be abstracted sustainably. Multiplying the size of the recharge area (in km^2) with the average sustainable abstraction figure of the map for the specific aquifer provides a sustainable abstraction rate in m^3/day. Note that the recharge area needs to be appropriately and accurately delineated.

- Groundwater quality: a critical issue to consider is the potential upconing of saline groundwater and intrusion into shallower and lower salinity aquifers which would render the shallower aquifers unsuitable for domestic and agricultural purposes. Away from the recharge areas in the southern and southeastern fringes of the EKK-TBA in the direction of groundwater flow, the salinity rapidly increases over a short distance and towards the Makgadikgadi Pans, reaching salinities in excess of 190 000 mg/l
- Groundwater monitoring:
    - There is inadequate (integrated and automated) monitoring in both countries to allow for a thorough understanding of the groundwater dynamics and groundwater management for the EKK-TBA as a whole
    - Neither the DWS nor the WUC have an effective and efficient groundwater monitoring system in operation in Botswana. Monitoring is done over too short time periods, infrequently, and in most cases, for very few parameters. The collected data is neither comprehensive nor consistent, and the data is stored in formats that are not readily useable (Farr, 2017). DWS monitors all non-production boreholes within and around WUC wellfields and supply schemes as well as a network of boreholes scattered around various regions, but comprehensive information is lacking, e.g. only a very low percentage of boreholes have groundwater levels being monitored (*ibid*). Groundwater monitoring in Zimbabwe is carried out by the Groundwater Department of ZINWA and the institution faces similar challenges as those in Botswana. Lack of resources (human resources, material and financial) are militating against consistent data collection
    - Debswana, the largest individual groundwater user in Botswana, manages and monitors its own wellfields that supply OLD Mines and as well as Orapa Town (after treatment by reverse osmosis). The monitoring includes abstractions, groundwater levels, water quality and rainfall, as well as effects of dewatering, regional observation boreholes and selected private boreholes. Comprehensive annual monitoring reports (without the data) are submitted to the Water Apportionment Board (WAB) as required under their Water Rights allocation (Farr, 2017) but access to these reports and the data is difficult

    - Unsustainable abstractions in some of Botswana's wellfields within the EKK-TBA have resulted in the decommissioning of the wellfields. Increased abstractions for the City of Bulawayo and by the local Nyamandlovu farmers in Zimbabwe may be unsustainable if no proper groundwater monitoring and management is carried out
- Groundwater management institutions: the institutions in both countries are bedevilled by several challenges. The institutions lack adequate resources to carry out effective and efficient groundwater monitoring and management

9.2. Way forward

The following way forward is proposed to ensure the sustainable development and management of the EKK-TBA groundwater resources:

- There is need to setup an EKK-TBA groundwater management institution with specific roles and responsibilities. This could be nested on the existing structures. This could take the shape of a unit with representatives from both river basins. It might be prudent to include representatives from data acquisition institutions into the unit to ensure ease of access to their organisational data and information
- There is an urgent need for capacitating groundwater institutions (human resources and infrastructure) in both countries with particular focus on groundwater management and monitoring (ref. SADC-GMI, 2020)
- A comprehensive EKK-TBA monitoring programme (groundwater levels, abstractions, water quality and rainfall) needs to be set up to ensure the sustainable development of groundwater resources within the EKK-TBA. The density and frequency of monitoring at both local and regional scales will be determined by the objective(s) of the monitoring
- Data and information management:
    - The quality of all the existing data and information needs to be thoroughly interrogated and proper data quality control protocols (QC and QA) implemented and this should be prioritized.
    - Data storage needs to be done electronically and in harmonised user-friendly databases. Acquisition of appropriate computers and software and personnel training would be required. Consideration for purchase of such should also be extended to data acquisition institutions such as the meteorological offices so that they feel that they are part of the programme and not only sources of data. It should be noted that such institutions are not commercial and rely on the national fiscus for budgetary support which is usually inadequate to cover their needs
    - Data acquisition protocols need to be established to ensure that all the requisite data and information are accurately collected
    - Alternative data collection techniques need to be explored to address data gaps and improve on data quality, e.g. use of GRACE satellite data (SADC-GMI, 2020)

    - Data and information sharing between the two countries also helps in improving personnel skills
    - There is need to develop synergies with other institutions such as data collection agencies, e.g. meteorological offices and research institutions, e.g. universities as well as synergies with the private sector to ensure that data is easily accessed and analysed and interpreted and informs decision making
- Groundwater management:
    - It is critical to carryout studies to determine the actual EKK-TBA potable water requirements and how best they can be met
    - Groundwater and surface resources should be used conjunctively where possible to ensure sustainability of supply to consumers (ref. Maitengwe wellfield and Ntimbale Dam)
    - Managed Aquifer Recharge schemes should be implemented where possible to improve on the availability of potable groundwater resources. This requires detailed hydrogeological investigations and a cost benefit analysis prior to their development
    - Water supply for mining operations is currently demand driven and this should be critically reviewed by the Water Apportionment Board in terms of setting timely, realistic and sustainable abstraction rates and volumes. Related to this is the mines' projected increasing abstractions from the wellfields and dewatering boreholes which have the potential to derail the objective of sustainable management of groundwater resources
    - Groundwater blending of saline and fresh groundwater may be an alternative to lessen the pressure on fresh groundwater resources
    - Groundwater conservation measures including water demand management need to be instituted to safeguard sustainable utilization of the limited groundwater resources
- When additional data and information (especially from deeper aquifer systems) become available, the EKK-TBA boundary might require further refinement, particularly the western and northern boundaries
- An EKK-TBA groundwater recharge study needs to be carried out to enhance the understanding of the nature and occurrence of recharge which will assist in the delineation of recharge areas and protection zones as well as refining the sustainable abstraction map, Figure 7.11.
- It is highly recommended to start building a numerical groundwater model to evaluate the groundwater dynamics and sustainable development quantitatively at the transboundary basin scale. Such a model also provides guidance for the designing, implementation and optimization of a basin-wide monitoring network.

REFERENCES

Beasley, A.J. (1983). The Hydrogeology of the Area around Nyamandhlovu, Zimbabwe. PhD Thesis.

Beekman, H.E. (2005). Groundwater monitoring in the Alla Valley – Eritrea. Establishing the primary monitoring network. GTZ.

Beekman, H.E. (2010). Compilation of groundwater data and statistics of the SADC Region: Executive summary, explanatory notes for updating SADC country sheets and printing fact sheets, and SADC and country fact sheets, SADC-UNOPS.

Beekman, H.E., Gieske, A. and E.T. Selaolo (1996). GRES: Groundwater Recharge Studies in Botswana 1987-1996. Botswana Journal of Earth Sciences, Vol. III, 1-17.

Beekman, H.E. and Sunguro, S. (2015). Groundwater management of the Nyamandlovu Aquifer System with special emphasis on the Nyamandlovu wellfield: Nyamandlovu Groundwater Model – Steady State, pp. 40.

Botswana Bureau of Standards (BOS) (2000). Water Quality – Drinking Water – Specification, BOS 32:2000.

Bredenkamp, D.B., Botha, L.J., Van Tonder, G.J. and Van Rensburg, H.J. (1995). Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity. WRC Report TT 73/95, Pretoria, pp 407.

Carney, J.N., Aldis, D.T., Lock, N.P. (1994). The Geology of Botswana. Bulletin 37, Geological Survey Department, Botswana, 37, 113pp.

Catuneanu, O., Wopfner, H., Ereiksson, P.G., Cairncross, B., Rubidge, B.S, Smith, R.M.H. and Hancox, P.J. (2005). The Karoo basins of south-central Africa. J. Afr. Earth Sc., 43, 211-253.

Chamaillé-Jammes, S., Fritz, H. and Holdo, R.M. (2007). Spatial relationship between elephant and sodium concentration of water disappears as density increases in Hwange National Park, Zimbabwe. Journal of tropical ecology, 725-728.

Cooke, H.J. (1979). The origin of the Makgadikgadi Pans. Botswana Notes and Records, vol. 11, pp.37-42.

Cooke, H.J. (1980). Landform evolution in the context of climatic change and neo-tectonism in the Middle Kalahari of north-central Botswana. Transactions of the Institute of British Geographers, pp.80-99.

Council for Geoscience (2009). Geological Map of the Southern African Development Community (SADC) Countries. Scale 1:2 500 00. Compiled by F.J. Hartzer.

Debswana (2015). Debswana Orapa, Letlhakane and Damtshaa Mines groundwater monitoring report 2014 (Anderson, M.), No 43, Final Report, pp. 129.

Debswana (2020). Debswana Orapa, Letlhakane and Damtshaa Mines groundwater monitoring report 2019 (Anderson, M.), No 48, Final Report, pp. 89.

Department of Environmental Affairs and Centre for Applied Research (2010). The Makgadikgadi Framework Management Plan. Government of Botswana, Gaborone.

Department of Surveys and Mapping (2000). Botswana Atlas.

DGS (1973). The Geology of the Area around Dukwe and Tlalamabele, Central District, Botswana. Author: G. Stansfield. Geological Survey District Memoir 1.

DWA (1993). Protection Zones and Guidelines for Major Wellfields, Aquifers and Dams in Botswana. Vol. 9. Letlhakane Village Wellfield. Water Surveys Botswana (Pty) Ltd.

DWA (1995). Dukwi Wellfield Extension and Resource Evaluation. Main Report by Water Surveys Botswana.

DWA (2000a). Groundwater Monitoring – Final Report, Volume 3, Chidumela Wellfield, 2000.

DWA (2000b). Groundwater Monitoring – Final Report, Volume 4, Dukwi Wellfield, 2000.

DWA (2000c). Groundwater Monitoring - Final Report, Volume 9, Letlhakane Wellfield, 2000.

DWA (2002). Maitengwe Wellfield Development and Resource Evaluation, TB10/3/21/2000-2001 (WSB).

DWA (2006). National Water Master Plan Review: Volume3-Water Resources.

DWA (2014). Mining and water resources in Botswana. Policy Brief Sept 2014, Prepared by Department of Water Affairs & the Centre for Applied Research. https://www.car.org.bw/wp-content/uploads/2016/05/Botswana-Policy-Brief-mining-water.pdf [accessed17 June 2020]

DWS (2018). Water Accounting Report-2016-17.

Ebrahim, G.Y., Villholth, K.G. and Boulos, M. (2019). Integrated hydrogeological modelling of hard-rock semi-arid terrain: supporting sustainable agricultural groundwater use in Hout catchment, Limpopo Province, South Africa. Hydrogeology Journal, 27(3), pp.965-981.

Eckardt, F.D., Bryant, R.G., McCulloch, G., Spiro, B. and Wood, W.W. (2008). The hydrochemistry of a semi-arid pan basin case study: Sua Pan, Makgadikgadi, Botswana. Applied Geochemistry, 23, 1563-1580.

Farr, J.L. (2017). Groundwater Monitoring Assessment Study Botswana World Bank GFDRR Final Report.

Freeze, R.A. and Cherry, J.A. (1979). Groundwater. Englewood Cliffs, NJ: Prentice-Hall.

Geoflux (Pty) Ltd. (2005). Letlhakane Village Emergency Water Supply, Groundwater Investigations. Final Report, June 2005.

Haddon, I.G. (2005). The sub-kalahari geology and tectonic evolution of the kalahari basin, southern africa. Thesis submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy. Johannesburg, 2005, pp 340.

Haddon, I.G. and McCarthy, T.S. (2005). The Mesozoic–Cenozoic interior sag basins of Central Africa: the late-cretaceous–Cenozoic Kalahari and Okavango basins. Journal of African Earth Sciences, 43(1-3), pp.316-333.

Harris, I., Osborn, T.J. and Jones, P. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci Data 7, 109 (2020). https://doi.org/10.1038/s41597-020-0453-3

Houston, J. (1988). Rainfall-runoff-recharge relationships in the basement rocks of Zimbabwe. In: Simmers I (ed) Estimation of Natural Groundwater Recharge. NATO ASI series C222, Reidel, Dordrecht, 349-366.

IAH (2017). Characterizing regional groundwater flow systems: Insight from practical applications and theoretical development Symposium Agenda and Abstracts. Regional Groundwater Flow Commission of International Association of Hydrogeologists, 26–28 June 2017, Calgary, Alberta, Canada.

Interconsult A/S. (1986). National Master Plan for Rural Water Supply and Sanitation. Ministry of Energy and Water Resources Development, Republic of Zimbabwe.

JICA (2002). The Study of Groundwater Potential Evaluation and Management Plan in the Southeast Kalahari (Stampriet) Artesian Basin in the Republic of Namibia-Final Report. JICA Report, Pacific Consultants International Co., LTD, Tokyo.

Johnson, M.R., van Vuuren C.J., Visser, J.N.J., Cole, D.I., Wickens, H. de V., Roberts, D.L., Brandl, D. (2006). Sedimentary Rocks of the Karoo Supergroup. In: M.R. Johnson, C.R. Anhaeusser, R.J. Thomas (Editors). The Geology of South Africa. Geological Society of South Africa, 461-499.

Johnson, M.R., van Vuuren, C.J., Hegenberger, W.F., Key, R., and Show, U. (1996). Stratigraphy of the Karoo Supergroup in southern Africa: An Overview. Journal of African Earth Sciences Vol. 23, Issue 1, July 1996, pp3-15.

Jones, M J. (2010). The Groundwater Hydrology of the Okavango Basin. Internal Report prepared by M J Jones (Consultant) for FAO; Okavango River Basin Transboundary Diagnostic Analysis Technical Report, Biophysical Series; EPSMO.

Kefentse, K. (2004). Environment Hydrogeology of Letlhakane, Central District, Republic of Botswana, DGS and BGR.

Key, R.M., Tidi, J., Mc George, I., Aitken, G., Cadman, A. and Anscombe, J. (1998). The lower Karoo Supergroup geology of the southwestern part of the Gemsbok Sub-basin of the Kalahari Basin, Botswana. South African Journal of Geology, 101, 225-236.

Khorrami, B., Roostaei, S. and Kamran, K.V. (2018). Assessment of Groundwater-Level Susceptibility to Degradation Based on Analytical Network Process (ANP). International Journal of Environment and Geoinformatics (IJEGEO) 5(3): 314-324. DOI: 10.30897/ijegeo.

Larsen, F., Owen, R., Dahlin, T., Mangeya, P. and Barmen, G. (2002). A preliminary analysis of the groundwater recharge to the Karoo formations, mid-Zambezi basin, Zimbabwe. Physics and Chemistry of the Earth, Parts A/B/C, 27 (11-22), 765-772.

Le Gall, B., Tshoso, G., Dyment, J., Kampunzu, A.B., Jourdan, F., Féraud, G., Bertrand, H., Aubourg, C. and Vétel, W. (2005). The Okavango giant mafic dyke swarm (NE Botswana): its structural significance within the Karoo Large Igneous Province. Journal of Structural Geology, 27(12), pp.2234-2255.

Legadiko, O.D. (2015). Characterisation and Groundwater Flow Remodeling, Dukwi Wellfield Phase II, North-Eastern Sub-District, Botswana. Unpublished MSc Thesis.

Lekula, M., Lubczynski, M.W., and Shemang, E.M. (2018). Hydrogeological conceptual model of large and complex sedimentary aquifer systems–Central Kalahari Basin. Physics and Chemistry of the Earth, Parts A/B/C, 106, 47-62.

Martinelli, G.L. and Hubert, G.L. (1986). Consultancy Services for Geophysical and Hydrogeological Investigations, Aquifer Modelling and Monitoring of the Nyamandhlovu Aquifer, Bulawayo, Zimbabwe. Main Investigation Phase, Final Report. Royal Danish Embassy, Harare.

Mekonnen, T.K. (2005). Interpretation & Geodatabase of Dykes Using Aeromagnetic Data of Zimbabwe and Mozambique. Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation, applied geophysics, Enschede, the Netherlands, pp72.

Mitiku, A. (2019). Integrated Hydrological Modelling of River-Groundwater Interactions in The Boteti River Area, Botswana.

MLWS and MLIT (2018). Ministry of Land Management, Water and Sanitation Services (MLWS)-Botswana and Ministry of Infrastructure and Transport (MLIT)-Republic of Korea (2018). The National Water Master Plan Update Based on Smart Water Management-Final Report.

Modie, B.N. (2000). The Karoo Supergroup on the Kalahari Basin: Report on a filed visit to exposures in the Kalahari Basin of Botswana. University of Botswana, pp57.

Mogami, K. (2013). Impact of Pumping on Groundwater Resources. An Assessment through steady state modelling: Orapa Wellfield 7, Central Botswana. MSc. Thesis in IWRM. University of Zimbabwe, Dept. of Civil Engineering, pp. 61.

MoMEWR (2012). Botswana National Water Policy. Gaborone, Botswana.

Msiteli-Shumba, S., Kativu, S., Utete, B., Makuwe, E. and Hulot, F.D. (2018). Driving factors of temporary and permanent shallow lakes in and around Hwange National Park, Zimbabwe. Water SA, 44(2), 269-282.

Murwira, A., Masocha, M., Magadza, C.H.D., Owen, R., Nhiwatiwa, T., Barson, M. and Makurira, H. (2014). Zimbabwe-Strategy for Managing Water Quality and Protecting Water Sources-Final Report: Phase 1: Rapid Assessment – Identification and Characterization of Hotspots of Water Pollution and Source Degradation-Prepared for the Ministry of Environment, Climate and Water, Zimbabwe.

Nathan, R.J. and McMahon, T.A. (1990). Evaluation of automated techniques for base flow and recession analyses. Water resources research, 26(7), 1465-1473.

Nielsen, T.S. (2000). Assessment of the infiltration in semi-arid regions with the use of isotope chemistry – Carbon-14 ages and flow rates of water in the Karoo Sandstone, Nyamandhlovu aquifer, MSc thesis Technical University Denmark, pp. 97.

Nxumalo, V. (2011). Stratigraphy and basin modelling of the Gemsbok Sub-Basin (Karoo Supergroup) of Botswana and Namibia (Doctoral dissertation).

Nyagwambo, N.L. (2006). Groundwater Recharge Estimation and Water Resources Assessment in a Tropical Crystalline Basement Aquifer. PhD thesis, Delft University of Technology.

Pietersen, K. and Beekman, H.E. (2016). Position paper. Groundwater Management in the Southern African Development Community. Southern Development Community Groundwater Management Institute, Bloemfontein, South Africa.

Ponce, V.M. (2007). Sustainable yield of groundwater. California Department of Water Resources. http://groundwater.sdsu.edu/gra_0809251330.html.

Royal HaskoningDHV (2017). NI 43-101 Technical Report on the Preliminary Economic Assessment of the Karowe Diamond Mine Underground Project, pp. 206. https://www.miningdataonline.com/reports/Karowe%20Expansion_2017-11-27-PEA_Technical_Report.pdf

SADC (2000). Revised Protocol on Shared Watercourses in the Southern African Development Community. Gaborone, Botswana.

SADC-GMI (2019). Policy, Legal and Institutional Development for Groundwater Management in the SADC Member States: Regional Gap Analysis and Action Plan Report. Bloemfontein, SA.

SADC-GMI (2020). Transboundary Diagnostic Analysis of the Eastern Kalahari-Karoo Basin Aquifer system. SADC-GMI report: Bloemfontein, South Africa.

SADC-HGM (2010). Hydrogeological Map & Atlas. Sweco International, Water Geosciences Consulting, Council for Geoscience and Water Resources Consultants - SADC Hydrogeological Mapping Project.

Schlüter, T. (2008). Geological Atlas of Africa: With Notes on Stratigraphy, Tectonics, Economic Geology, Geohazards and Geosites of Each Country (2nd ed.). Springer. pp. 26–28. ISBN 9783540763734.

Shamboko-Mbale, B., Siwale, C., Baumle, R. and Kreleler, T. (2012). Development of a groundwater information & management program for the Lusaka groundwater system. Report No 7: Water balance estimates for sub-catchments of the Chongwe and Mwembeshi Rivers in the Lusaka Region (BGR report), 2012, Lusaka.

Sibanda, T. and Nonner, J.C. (2009). Comparison of groundwater recharge estimation methods for the semi-arid Nyamandhlovu area, Zimbabwe. Hydrogeology Journal, 17, 14287-1441.

Smith, R.A. (1984). The lithostratigraphy of the Karoo Supergroup in Botswana. Bulletin 26. Geological Survey Department, Botswana, 26, 239pp.

Stagman, J.G. (1978). An Outline of the Geology of Zimbabwe, Zimbabwe Geological Survey, Bulletin No. 80

Statistics Botswana (2016). National Literacy Survey 2014. Gaborone: Statistics Botswana. http://www.statsbots.org.bw/sites/default/files/Literacy%20Survey%202014%20%202.pdf

Stone, A.E.C. and Edmunds, W.M. (2011). Sand, salt and water in the Stampriet Basin, Namibia: Calculating unsaturated zone (Kalahari dunefield) recharge using the chloride mass balance approach. Water SA, 38(3), pp 367–380.

Sunguro, S. (1991). A Chemical and Isotopic Study of Groundwater in the Lomagundi Dolomite Aquifer and Nyamandhlovu Sandstone Aquifer Systems.

Unganai, L.S. and Kogan, F.N. (1998). Drought monitoring and corn yield estimation in Southern Africa from AVHRR data. Remote Sens. Environ., 63 (1998), pp. 219-232.

United Nations (1989). Groundwater in Eastern, Central and Southern Africa: Botswana. United Nations Department of Technical Cooperation for Development. Natural Resources / Water Series No. 19, ST/TCD/6.

Van Wyk, E., Van Tonder, G.J. and Vermeulen, D. (2011). Characteristics of local groundwater recharge cycles in South African semi-arid hard rock terrains – rainwater input. Water SA 37(2):147–154.

Visser, J.N.J. (1995). Post-glacial Permian stratigraphy and geography of southern and central Africa: boundary conditions for climatic modelling. Palaeogeography, Palaeoclimatology, Palaeoecology, 118, 213-243.

WCS (2020). Final Khoemacau annual groundwater monitoring report 2019, pp. 48.

WHO (1984). Guidelines for drinking-water quality. WHO chronicle.

Wilson, J.F., Jones, D.L. and Kramers, J.D. (1987). Mafic dyke swarms in Zimbabwe: in Mafic dyke swarm, Editors: Halls, H.C. and Fahrig, W.F., Geological Association of Canada Special Paper 34, p. 433-444.

WSB (2008). Orapa Numerical Groundwater Model Final Report. Debswana OLDM, Botswana.

WSB (2013). Wellfield 7 EIA Modeling Report. Debswana OLDM Company. Botswana.

WWF (2019). HSBC – Hwange Sanyati Biodiversity Corridor Project. Groundwater Component, ZIVA.

Xu, Y., Wu, Y., and Duah, A. (2007). Groundwater recharge estimation of Table Mountain Group Aquifer systems with case studies, WRC Report 1329/1/07, Pretoria.

Xu, Y. and Beekman, H.E. (2019). Review: Groundwater recharge estimation in arid and semi-arid southern Africa. Hydrogeol J 27: 929–943.

APPENDIX I: 8-STEP APPROACH TO DESIGNING A GROUNDWATER MONITORING NETWORK

STEP 1: SET MONITORING GOALS

Who	Groundwater coordinator, monitoring task team
What	Decide on monitoring objectives
How	❖ Establish current and potential groundwater use in the catchment ❖ Establish areas and requirements for non-point source pollution monitoring
Outputs	Statement of monitoring goals

STEP 2: ESTABLISH MONITORING *STATUS QUO*

Who	Groundwater coordinator, monitoring team
What	Collect information on existing systems including hydrocensus and available financial/human resources
How	❖ Collect information from all responsible institutions Consider: ❖ What data is currently collected? ❖ Will this be continued? ❖ What infrastructure is in place and in what condition? ❖ What historical data is available? A detailed hydrocensus to determine the current groundwater abstractions, water levels and water quality (baseline information) need to be conducted ❖ What are the available resources and capabilities in terms of manpower, vehicles, analytical facilities, etc. ❖ Where can additional resources be obtained?
Outputs	Status of existing monitoring efforts in the catchment

STEP 3: COORDINATE WITH OTHER MONITORING INITIATIVES

Who	Groundwater coordinator, monitoring team, other agencies involved in monitoring
What	Adopt a multi-media approach, taking into account monitoring of all natural resources in the catchment
How	❖ Consult surface water & water quality managers in the catchment e.g. government institutions, local authorities, meteorological offices, etc. ❖ Find out who is involved in monitoring resources in the catchment e.g. surface water, wetlands, meteorology, soil/sediments, waste/effluent discharge, etc. ❖ Resource optimisation: look for areas of overlap, possible cooperation and sharing of resources / manpower / travel costs (don't send, say 3 different people to the same place in 3 different vehicles) ❖ Try to coordinate sampling sites for different media to maximise data value e.g. soil, groundwater and surface water quality at a particular site. ❖ Develop data sharing agreements with other organisations where complementary data may lead to better understanding of the system
Outputs	Partnerships, Data sharing agreements

STEP 4: DESIGN MONITORING PROGRAMME

Who	Groundwater coordinator, monitoring team
What	Develop a groundwater conceptual model Decide on network requirements and sampling and data collection protocols to achieve monitoring goals
How	❖ Design network taking into account aquifer geometry and flow characteristics ❖ Design network around resource classification or land-use/cover type ❖ Decide on number and location of monitoring points, type of installation, the use of new, dedicated sites or existing boreholes ❖ Decide on sampling frequency ❖ Select type & frequency of measurements to be made ❖ Develop standardised protocols for sampling, data capture, retrieval, and analysis for consistency across the catchment management area (use government regulated guidance if this exists)
Outputs	Record of decisions on monitoring network and sampling requirements

STEP 5: ADDRESS SUPPORT SERVICES AND TRAINING REQUIREMENTS

Who	Groundwater coordinator, IWRM manager
What	Establish opportunities and gaps in support for monitoring programme implementation
How	Identify analytical service requirements: ❖ what analyses are needed? ❖ what facilities are available for analysing these ❖ can they be done in-house or contracted out? Identify information support requirements: ❖ who will handle data capture, database maintenance, data retrieval? ❖ how will this be structured? Identify staff and training requirements: ❖ do field staff & data management staff have the necessary skills? ❖ can experienced personnel be appointed / technical staff be trained to undertake new monitoring functions? Organise training sessions to meet skills requirements: ❖ where possible, train staff to take a variety of samples e.g. groundwater, biological, weather measurements for collaborative monitoring efforts
Outputs	Network of supporting services for the monitoring programme

STEP 6: SET UP QUALITY ASSURANCE/QUALITY CONTROL PROCEDURES

Who	Groundwater coordinator, monitoring team
What	Put procedures in place to ensure high quality data
How	❖ Ensure that staff collecting samples are trained to take good quality, representative samples. ❖ Ensure that sub-contractors are qualified and experienced, laboratories are accredited, and both have adequate quality control procedures in place. ❖ Design quality control measures into the monitoring programme, e.g. use of duplicate samples, blanks, certified standards, etc. ❖ Design data checking routines into data capture procedures.
Outputs	Quality Assurance (QA)/Quality Control (QC) guidelines and procedures for various aspects of monitoring

STEP 7: DRAW UP PLANNING DOCUMENT

Who	Groundwater coordinator, monitoring team
What	Draw up a detailed planning document covering all monitoring activities
How	Include: ❖ Appropriate information from steps 1 - 6 ❖ Framework of time and place for activities ❖ Role-players and responsibilities ❖ Opportunities for linking/support with other individuals and organisations ❖ Budget (allowing contingencies) ❖ Guidelines for subcontractors or support staff tasked with specific activities
Outputs	Groundwater monitoring strategy document for the catchment management area

STEP 8: IMPLEMENT & UPDATE GROUNDWATER MONITORING PROGRAMME

Who	Groundwater coordinator, monitoring team, field & data management staff
What	Commence monitoring and review success; carryout groundwater modelling
How	❖ Commence planned activities once network and supporting structures are in place ❖ Refine the strategy by conducting regular updates as more information becomes available e.g. work on a five-year cycle of information-gathering, plan development, implementation of monitoring, assessment of data, prioritisation of key areas
Outputs	Catchment groundwater monitoring programme