Transboundary Diagnostic Analysis of the Eastern Kalahari-Karoo Basin Aquifer system

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

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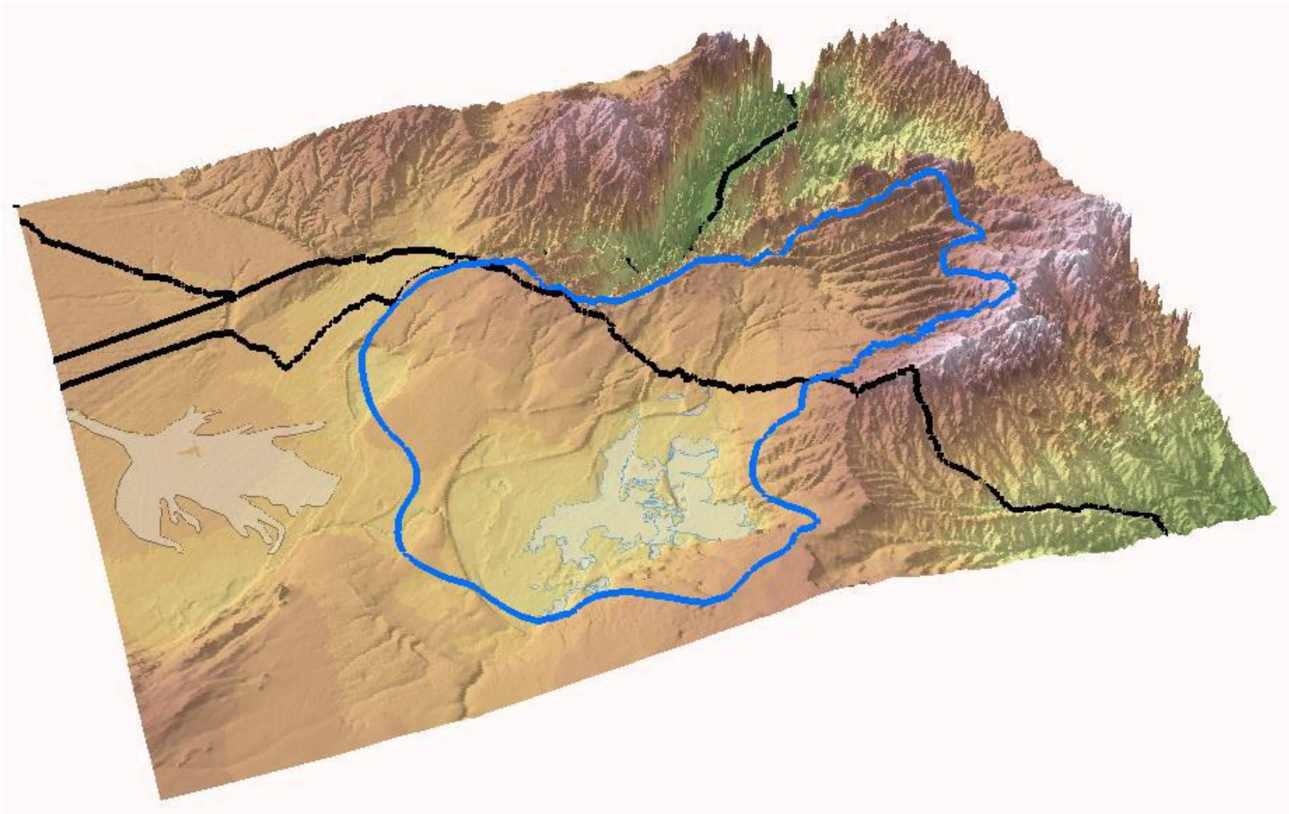

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EXECUTIVE SUMMARY

A Transboundary Diagnostic Analysis (TDA) was carried out of the Eastern Kalahari-Karoo Transboundary Aquifer system (EKK-TBA), which is shared between Botswana and Zimbabwe. The main aim of the TDA is building a comprehensive understanding of the state of the surface water and groundwater resources in the EKK-TBA system, their uses, spatial and temporal variability, interactions, and impacts as well as human benefits derived from various ecosystem services and existing infrastructure. This report presents a scientific and technical assessment, through which water-related environmental issues and problems of the basin were identified and prioritised, their causes and impacts analyzed, both environmental and economic. The TDA provides a technical basis for the development of a Strategic Action Plan (SAP). The TDA formed part of a facilitative process that involved key stakeholder engagement and consultation from both Botswana and Zimbabwe.

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. The topography of the EKK-TBA is generally flat and ranges between 750 and 1 300 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 in October. Surface water drainage is through the ephemeral Boteti and Nata Rivers in Botswana and Zimbabwe respectively towards the Makgadikgadi Pans and through the Gwayi River in the eastern part of the EKK-TBA in Zimbabwe towards the Zambezi River. The basin's population stands at about 523 000 (Botswana: 83 062 and Zimbabwe: 439 796), revised from an original estimated population of 240 000. Close to 50% of the Botswana's EKK-TBA population is accounted for by the villages of Letlhakane and Tutume whilst close to 85% of the Zimbabwe's EKK-TBA population is from Matabeleland North Province. The literacy rates for Botswana and Zimbabwe are 90% and over 95% respectively. Unemployment rates were estimated at about 50% for Botswana and 20% for Zimbabwe. Apart from few wards from the northern outskirts of Bulawayo City, there are no major cities within the basin except for the towns of Nata, Sowa and Orapa (Botswana) and Tsholotsho, Kusile and Nkayi (Zimbabwe). The basin's economy is mostly driven by diamond mining (Botswana), ecotourism and agriculture (Botswana and Zimbabwe). Agriculture in the form of livestock ranching and cropping is important to the communities' livelihoods, with irrigated agriculture taking place in the Pandamatenga area in Botswana and the Nyamandlovu area in Zimbabwe.

The EKK-TBA is endowed with a rich biodiversity represented by the Hwange, Makgadikgadi and Chobe National Parks and several wildlife management areas and forests. The basin is home to around 400 bird species, more than 100 animal types and is habitat to one of the

world's largest population of elephants, estimated at around 50 000. The basin's population relies on wood for fuel and this is causing massive deforestation and land degradation. The situation is exacerbated by an over-population of elephants.

Groundwater forms the main source of potable water supply within the basin for both humans and animals. Shallow aquifers are constituted by the Kalahari Sand whereas the main aquifers are the deep Ntane/Forest Sandstone and the Mea Arkosic Sandstone. Wellfields (e.g. Dukwi, Letlhakane, Maitengwe, Nyamandlovu and Orapa) have been developed along the fringes of the basin where the sandstone aquifers outcrop and are recharged from rainfall, with the groundwater being generally fresh. The groundwater becomes highly saline with increasing depth and movement towards the central portions of the basin. The groundwater flows southwest and southwards and is discharged in the Makgadikgadi Pans in Botswana. The Ntane/Forest Sandstone is overlain by a thick Karoo basalt which makes drilling into the underlying sandstone very difficult and costly, hence most rural water supply boreholes are drilled into the Kalahari Sand which overlies the basalt. Water availability is a major challenge in the basin and the demand is outstripping the supply for both human and wildlife. The water supply for mining operations within the Botswana side of the EKK-TBA is demand driven and pays little to no attention to the sustainability of the resource.

Climate variability and change is affecting the EKK-TBA through increasing temperatures, decline in rainfall and high interannual rainfall variability and these trends will impact the availability of water resources, particularly surface water and shallow groundwater. Climate variability and change will exacerbate the harmful effects of poor land-use practices, notably deforestation and overgrazing. Hence the urgent need to establish resilient and adaptation strategies that combat the effects of climate variability and change. The applicability of remote sensing in estimating crop water use in the Nyamandlovu area of the EKK-TBA (where historic data for validation of the remote sensing simulations exists) was tested and established to be a promising tool in estimating the cropped land and the crop water use and can thus be incorporated in groundwater management strategies.

Keys issues that emanated from combining shared water risks and key messages of the TDA include:

- Data and databases:
  - Data unavailability/scarcity and inaccessibility (especially from Zimbabwe) and poor quality (accuracy and gaps)
  - Lack of good quality hydro(geo)logical databases and limited standardisation of data and information
- Water insecurity:
  - Projected decline in rainfall, high interannual rainfall variability and increasing temperature

  - Upconing of saline groundwater and intrusion into shallower and lower salinity aquifers
  - Potential water related conflicts could ensue in the EKK-TBA between water users
- Groundwater management:
  - Lack of adequate resources to carry out effective and efficient groundwater management (e.g. monitoring, uncontrolled drilling, etc.)
  - Groundwater over-exploitation: water demand for domestic water use currently exceeds supply; water supply in mining is demand driven and negates sustainability of supply
  - Unregulated borehole drilling posing a risk to groundwater overexploitation and unwarranted competition of the groundwater resource.
  - Inadequate use of innovative technologies: remote sensing has been proven to be an alternative tool that can be used in the timely determination of active crop areas and the crop water requirements in the EKK-TBA and consequently, the amount of groundwater used.
- Biodiversity: the EKK-TBA is endowed with a rich biodiversity which is critical to the countries' economies and the livelihoods of the basin communities and needs to be better protected
- Deforestation and poor agricultural practices are resulting in rapid land degradation
- The EKK-TBA boundary asymmetry adds additional complexity to the governance challenges (OKACOM and ZAMCOM)
- Lack of political will and improved regulation hampering enforcement of government laws, policies, and regulatory instruments
- The EKK-TBA population needs to be properly quantified in order to determine the risks and opportunities that arise from the available natural resources

Following the identification of key issues, a gap and barrier analysis was carried out to obtain a broader perspective of the issues. A causal chain analysis was conducted to better understand immediate and underlying causes and impacts. Mitigation measures were formulated next as well as quick-win measures (QWMs) to address the key issues. For both countries, the most preferred QWMs were institutional mapping followed by the designing and implementing a (pilot) groundwater monitoring network for the EKK-TBA.

The key issues, gap and barrier analysis, causal chain analysis and the mitigation and QWMs all form part of the Strategic Action Planning process.

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ACRONYMS

^{14}C	Carbon 14 isotope (radioactive carbon)
AfDB	African Development Bank
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AIDS	Acquired Immune Deficiency Syndrome
amsl	above mean sea level
BAP	Basin Action Plan
bgl	below ground level
BH	Borehole
BOS	Botswana Bureau of Standards
CMB	Chloride Mass Balance
CNRG	Centre for Natural Resource Governance
CO_2	Carbon dioxide
Covid-19	Coronavirus disease 2019
CRD	Cumulative Rainfall Departure
CRU	Climate Research Unit
CV	Coefficient of Variation
DNs	Digital Numbers
DQC	Data Quality Control
DWNP	Department of Wildlife and National Parks (Botswana)
DWS-BW	Department of Water and Sanitation - Botswana
EC	Electrical Conductivity (µS/cm)
EIA	Environmental Impact Assessment
EKK-TBA	Eastern Kalahari-Karoo Basin Transboundary Aquifer System
EMA	Environmental Management Agency
ENSO	El Nino Southern Oscillation
ET	Evapotranspiration
EWH	Equivalent Water Heights
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GIP	Groundwater Information Portal
GIS	Geographic Information System
GMI	Groundwater Management Institute
GRACE	Gravity Recovery and Climate Experiment
GRES	Groundwater Recharge and Evaluation Studies
GW–SW	Groundwater-surface water
ha	hectare
HCL	Hwange Communal Lands

HCL	Hwange Communal Lands
HGM	Hydrogeological Map
HIV	Human Immunodeficiency Virus
HNP	Hwange National Park
IDW	Inverse Distance Weighting
IGRAC	International Groundwater Resources Assessment Centre
KDM	Karowe Diamond Mine
LEA	Local Enterprise Authority
MAR	Managed Aquifer Recharge or Mean Annual Rainfall
MCDA	Multi-Criteria Decision Analysis
MLAWRR	Ministry of Lands, Agriculture, Water and Rural Resettlement
Mm^3	Million Cubic Metres
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetation Index
NIR	Near Infrared
Obs	Observed
OKACOM	Okavango River Basin Water Commission
OLDM	Orapa, Letlhakane and Damtshaa Mines
PE	Potential Evaporation
QWM	Quick Win Measure
RBO	River Basin Organisation
RDC	Rural District Council
SADC	Southern African Development Community
SAP	Strategic Action Plan
SMMEs	Small Micro and Medium Enterprises
SWL	Static Water Level (m bgl or m amsl)
TBA	Transboundary Aquifer
TDA	Transboundary Diagnostic Analysis
TDS	Total Dissolved Solids (mg/l)
TOA	Top-Of-Atmosphere
TWS	Total Water Storage
TWSA	Terrestrial Water Storage Anomaly
UB	University of Botswana
UN	United Nations
UNESCO	United Nation Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children's Emergency Fund
UNOCHA	United Nations Office for the Coordination of Humanitarian Affairs
UTM	Universal Transverse Mercator projection
UZ	University of Zimbabwe

WAB	Water Apportionment Board
WGS84	World Geodetic System 84
WHO	World Health Organisation
WTF	Water Table Fluctuation
WUC	Water Utilities Corporation
WWF	World Wide Fund (for nature)
ZAMCOM	Zambezi Watercourse Commission
ZIMPARKS	Zimbabwe Parks and Wildlife Management Authority
ZIMSTAT	Zimbabwe National Statistics Agency
ZINWA	Zimbabwe National Water Authority
ZPC	Zimbabwe Power Company

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Cover: Digital Elevation Model of the Eastern Kalahari-Karoo Transboundary Aquifer system

1. INTRODUCTION

1.1. Background

Transboundary Waters in Southern Africa Most of the population in Southern Africa relies on groundwater for basic needs, and many aquifers from which groundwater is abstracted constitute transboundary aquifers. A growing body of work has now identified and delineated more than 30 transboundary aquifers in the Southern African Development Community (SADC) and many more in Africa as a whole (Altchenko and Villholth, 2013). Joint management of these aquifers can foster progress towards the region's socio-economic development goals including strengthening of resilience to climate change and variability, improving agricultural production, enhancing water security and achieving sustainable economic growth. However, despite the seemingly prolific activity in transboundary water cooperation and River Basin Organisation (RBO) development in Africa in general and SADC in particular, actual cooperation on the ground on SADC's shared aquifers is currently low (Lautze and Giordano, 2005; Saruchera and Lautze, 2016).

Management of Shared Water in SADC Experience from SADC suggests that it is mostly advisable to scale up groundwater management in the context of a systems approach where multiple sources of water and ecosystems are considered and are holistically managed. For instance, harnessing subsurface capacities to store seasonal excess surface water resources (artificial recharge) or treated wastewater may provide hitherto un(der)explored solutions to increase resilience and water security. Further, failing to include groundwater in cooperative surface water frameworks may undermine attempts to manage the surface water effectively and efficiently since surface water and groundwater are part of the same hydrologic cycle.

Project Vision Optimal transboundary water management results from taking integrated and conjunctive approaches that optimize water use across a diversity of water resources and scales. Incorporating diverse water sources into transboundary water management frameworks can expand the range of cost-effective and sustainable solutions for the riparian states. An example is where an aquifer is considered as a storage solution to enhance water security for both drinking water supply and small-scale crop cultivation during dry spells and drought periods. Another example is where shallow groundwater systems are used, through managed aquifer recharge (MAR), to store freshwater on top of saline groundwater for use at a later stage when needed, or where they support natural attenuation and purification of wastewater – at national and/or transboundary scales. Issues of pollution in MAR schemes, however, always require expertise consideration.

Project Objectives The Water Resources Management Research Project in the Eastern Kalahari-Karoo Basin Transboundary Aquifer System (EKK-TBA), shared between Botswana and Zimbabwe, aims to provide a basis for enhancing and strengthening the understanding and the establishment of a platform for joint management of the EKK-TBA. The specific objective of the Project is to enhance the capacity in SADC and its member states to collaboratively manage integrated groundwater and surface water resources. In particular, the project will identify issues and solutions that support the achievement of equitable and sustainable water use, and will build upon lessons learned from the Transboundary Diagnostic Analyses of the Shire (Malawi and Mozambique), Tuli Karoo (Botswana, South Africa and Zimbabwe) and Kalahari-Karoo or Stampriet (Botswana and Namibia) Transboundary River/Aquifer Systems (UNESCO, 2016; SADC-GMI, 2019a; 2019b - Figure 1.1).

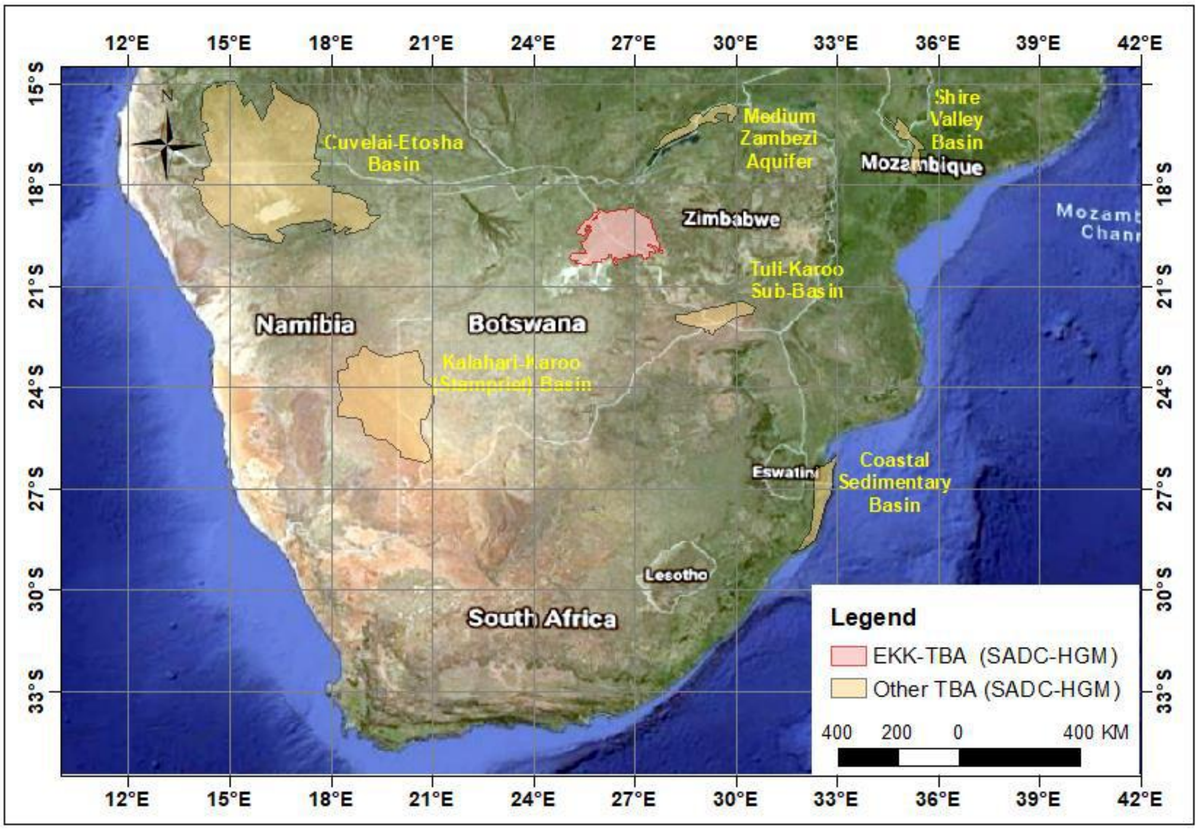

Figure 1.1: TBAs in Southern Africa
Source: SADC-HGM (2010)

Project Approach Supporting cross-border water management in the EKK-TBA system will be pursued through three approaches:

1) **Transboundary Diagnostic Analysis (TDA):** Conduct a TDA to gather the state of knowledge in the TBA to facilitate identification of priority issues and establish the way forward

2) **Strategic Action Plan (SAP):** Implement Stakeholder Dialogues to understand relevant issues and forge consensus on the joint management of water resources in the TBA. This includes performing a joint SAP for enhanced national and transboundary water management of the EKK-TBA

3) **Knowledge Management and Research Results:** Sharing the experiences of the EKK-TBA as a case study

Time Frame and Partners The project ran from April through November 2020 with L2K2 (Pty) Ltd. as the lead consultant under the auspices of the SADC-Groundwater Management Institute (GMI). A wide range of organizations contributed to the project such as: the Department of Water and Sanitation, Botswana (DWS-BW), University of Botswana (UB), Ministry of Lands, Agriculture, Water and Rural Resettlement (MLAWRR), Zimbabwe, the Zimbabwe National Water Authority (ZINWA) and the River Basin Organisations Permanent Okavango River Basin Water Commission (OKACOM) and the Zambezi Watercourse Commission (ZAMCOM). SADC-GMI was the contracting partner and financier who played an important role in facilitating engagement with national partners, the organisation of virtual meetings and workshops (Annex 4) and review of project documents.

1.2. Transboundary Diagnostic Analysis

This report presents a Transboundary Diagnostic Analysis (TDA) of the EKK-TBA. TDA is a scientific and technical assessment, through which the water-related environmental issues and problems of a region are identified and quantified, their causes analyzed and their impacts, both environmental and economic, assessed. TDA provides the technical justification for the development of Basin Action Plans (BAPs) and Strategic Action Plans (SAPs), if absent or the refinement of both, where they do exist. TDAs have been developed over time in projects on transboundary waters financed by the Global Environment Fund (GEF, 2013), since the approach provides a framework for a thorough analysis of all issues around transboundary water bodies.

TDA is part of a larger facilitative process that involves key stakeholder engagement and consultation from the initial TDA steps through to the subsequent development of alternative solutions during the formulation of the SAP. TDA can be seen as a process that can help create confidence among the partners concerned as they are engaged and involved at every step of the process.

Aim of this report This report aims to build a comprehensive understanding of the current state of the surface and groundwater resources in the EKK-TBA System, their uses, spatial and temporal variability, interactions, and impacts as well as human benefits derived from various ecosystem services and existing infrastructure. The report draws primarily on existing data from: (i) key government ministries and institutions in the Member States, such as DWS-BW, MLAWRR, ZINWA, OKACOM, ZAMCOM and SADC-GMI, (ii) key research institutions such as the University of Botswana and the University of Zimbabwe (UZ), and (iii) remote sensing-derived data such as topography, land use and Gravity Recovery and Climate Experiment (GRACE) data. Data were compiled, synthesized, analyzed and interpreted according to relevant themes including demography and socio-economics, climate, surface water and groundwater resources, water uses, environment, and institutions. Synthesising data in a shared water system is not straightforward, as countries tend to have different protocols for data collection and categorisation. Ultimately, information collected as part of the TDA was synthesized to reveal a set of critical issues related to achieving water security, with specific attention to the opportunities that can be harnessed and challenges that can be addressed.

Advances and limitations of this report The major advancements of this report are that it is an inclusive, joint effort that includes: i) focus on the full EKK-TBA which is now a threefold expansion of the original area, including major wellfields in both Botswana and Zimbabwe for both domestic (urban and rural), agricultural and industrial water supply and mining activities, ii) focus on precious environmental assets such as water for wildlife and tourism including the Makgadikgadi Pans and Hwange National Park and iii) focus on both surface water and groundwater. There have undoubtedly been other hydrogeological investigations on different aspects of water management in the EKK-TBA. In Botswana, the Department of Water and Sanitation (DWA, 2000) and Debswana (2015; 2020) carried out detailed studies of wellfields in the Orapa, Letlhakane, Dukwi, Chidumela and Maitengwe areas, whereas ZINWA (Beekman and Sunguro, 2015) studied in detail the Nyamandlovu area and wellfield in Zimbabwe along the south-eastern margin of the EKK-TBA. WWF (2019) recently concluded a hydrogeological study on the Hwange National Park. Most past study efforts heavily focused on the margin of EKK-TBA. The added value of this current assessment is that it is water-source-inclusive and integrating knowledge on portions of the basin in both countries.

1.3. Structure of the TDA Report

The structure of the TDA Report was discussed during an on-line (virtual) Inception Workshop of 8 May 2020 involving SADC-GMI, country focal persons and the Consultants. The initial structure that drew on formats used in other TDAs was proposed and adopted. The following chapters capture the context and key aspects of water management within the EKK-TBA:

1. Introduction
2. Methodology
3. Demographics and Socio-economics
4. Climate
5. Surface Water
6. Groundwater
7. Water Use
8. Land Use and Land Cover
9. Groundwater Governance
10. Key Issues

2. METHODOLOGY

Given the multi-dimensional dynamics of water and water management, production of a TDA for a shared surface water-groundwater system is by nature a multi-faceted effort. It requires insight into the hydrogeology of the aquifer(s), surface water flows, environmental issues, relevant socio-economic aspects of the area as well as legal and institutional contexts in riparian countries. The multidisciplinary character of the assessment and the complexity of the transboundary aquifer system necessitated the involvement of several governmental bodies/organisations. The following key governmental organizations were thus regularly consulted during the production of this document: in Botswana, the Department of Water and Sanitation (DWS-BW) and the University of Botswana (UB) and in Zimbabwe, the Ministry of Lands, Agriculture, Water and Rural Resettlement (MLAWRR) and the Zimbabwe National Water Authority (ZINWA). As the new EKK-TBA System partly overlaps two river basins, the Okavango River Basin and the Zambezi River Basin, the River Basin Organisations OKACOM and ZAMCOM were also a major constituency of consultation during the development of the TDA report. The production of the TDA report was further bolstered by the expertise of the Consultant's team and the professional input from SADC-GMI staff and had diverse specializations ranging from demography and socio-economics to hydrogeology to transboundary water management.

As part of the TDA, the Consultants spent a great effort towards data collection, quality control, and interpretation (section 2.1) as well as redefining the extent and boundary of the EKK-TBA System (section 2.2).

2.1. Data and Information

Data and information needs Data and information needs for each chapter of this report were discussed during the on-line Inception Workshop on 8 May 2020. These include climatic data, borehole data, socio-economic data, remote sensing imagery, and national water laws and policies in the two countries. A complete list of identified data and information needs as per thematic area is given in Annex 1.

Data and information acquisition To encourage swift data and information collection, the Consultant through the focal points followed up with the two countries to support their data collection effort. Frequent follow-ups to facilitate rapid collection of priority data were made. Unfortunately, (field) visits could not be made and neither could some of the data be collected due to the constraints imposed by the Covid-19 pandemic and this mostly affected Zimbabwe. A substantial amount of important data and information was obtained although some key gaps remained, likely resulting from the reality that many of the desired data and information is simply not in existence and/or confidential.

Data and information limitations Attempts to understand the EKK-TBA system is constrained by the reality that i) there are often major limitations on availability of groundwater data and information, ii) poor quality of the majority of the available data and iii) the EKK-TBA System is often located in fairly remote and sparsely populated regions of the two countries, in which 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.

Information consolidation The Consultants extracted data and information for each Chapter from a broader set of data and information collected. Technical documents including reports, peer reviewed publications and any other relevant information were captured in an Excel-based meta-database.

Information synthesis The write-up and presentation of key aspects of different topics were done according to the agreed structure. At the end of each Chapter, key messages were formulated, and these are presumed to reflect the central points and priorities for the way forward. At the conclusion of the entire TDA report, an aggregated set of key issues was distilled. These key issues serve as a basis for development of the Strategic Action Plan (SAP).

2.2. Defining the EKK-TBA system boundary

The EKK-TBA as presented in the SADC Groundwater Information Portal (GIP) and maintained by IGRAC[1] is a multi-layered transboundary aquifer system which is shared between Botswana and Zimbabwe. The boundary of the EKK-TBA, shown in Figure 2.1 (red line), was defined during the SADC-Hydrogeological Mapping Project (SADC-HGM, 2010), and seems to have been mainly based on the topography (Figure 2.2), surface water drainage and to some extent, the areal extent of the basalt cover (Figure 2.4). The surface area of the EKK-TBA is just over 34 000 km^2, and the population living within the EKK-TBA was estimated at about 240 000. From a hydrogeological perspective, the extent of the aquifer system may not necessarily be constrained by surface water divides or topography only, hence the need to redefine the aquifer system boundary using a hybrid of methods. The following assessments were undertaken to determine more precisely the extent and boundary of the EKK-TBA:

- Data and information availability and quality control
- Lithostratigraphy and tectonics
- Regional piezometry

[1] https://apps.geodan.nl/igrac/ggis-viewer/viewer/sadcgip/public/default

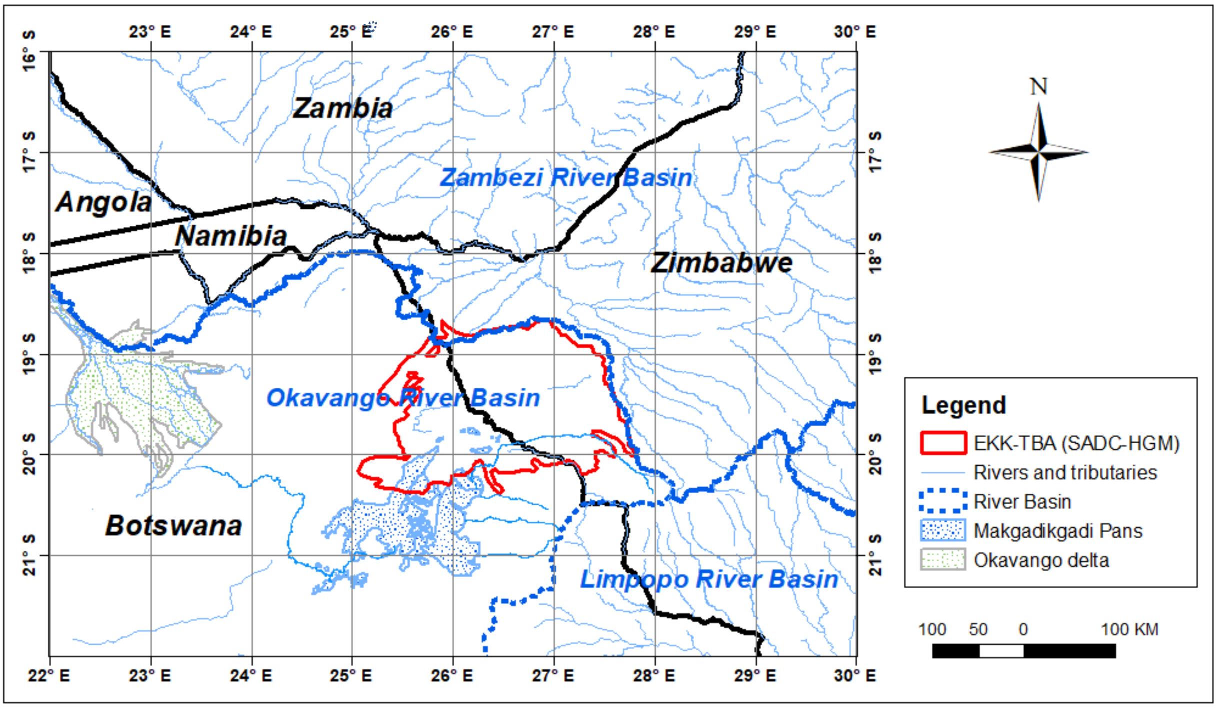

Figure 2.1: EKK-TBA boundary and surface water drainage

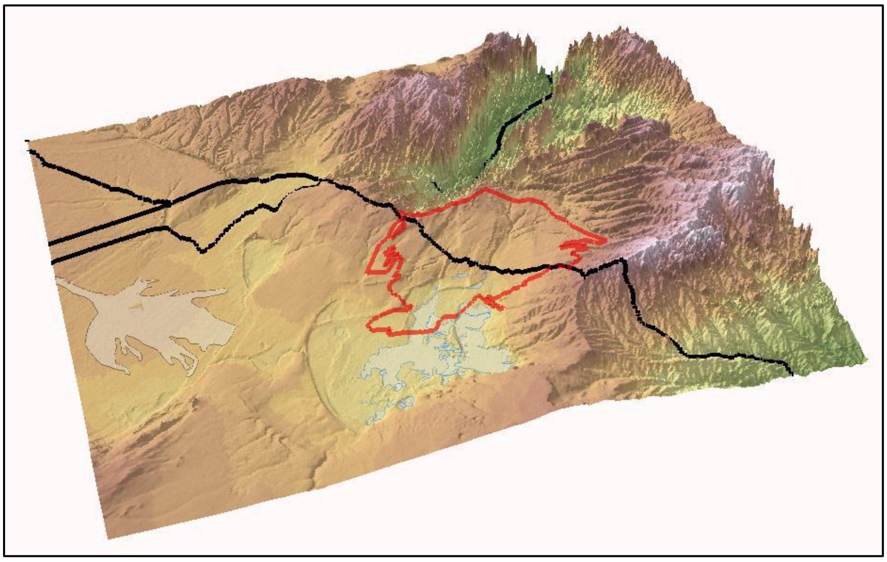

Figure 2.2: Digital Elevation Model of the EKK-TBA and surroundings

2.2.1. Data and information availability and quality control

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) and is the same as that in the SADC-GMI GIP. Table 2.1 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 indicated in Table 2.1.

Table 2.1: Status of hydrogeological information in the SADC-HGM borehole database

			Country			
			Botswana	**Namibia**	**Zambia**	**Zimbabwe**
		Total No. BHs	**1736**	**1352**	**395**	**4940**
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	1537	1309		4802
Filtering process	Depth to SWL	No. BHs	1580	971	395	2398
	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**	**1500**	**969**	**393**	**2398**
	BHs with no depth info.	**Selected BHs**	**92**	**543**	**34**	**110**
	Lithology	**Selected BHs**	**304**	**0**	**62**	**1989**
	EC	**Selected BHs**	**1235**	**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 2.3.

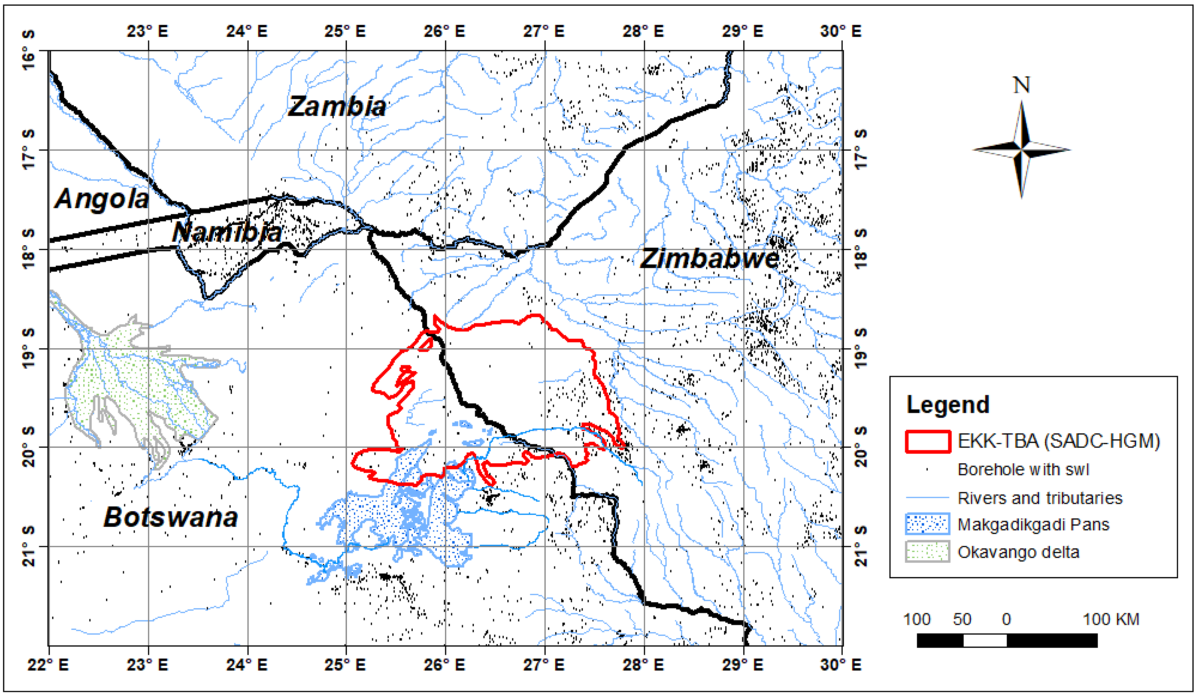

Figure 2.3: Distribution of boreholes with swl data
Source: SADC-HGM (2010)

2.2.2. Lithostratigraphy and tectonics

Figure 2.4 shows the EKK-TBA boundary overlain on the Kalahari-Karoo Basin (Haddon, 2005). From the map, it can be seen that the sedimentary rocks from the Karoo Supergroup extend well beyond the area demarcated by the SADC-HGM (2010). The various lithostratigraphic units of the Karoo Supergroup are well correlated between the Aranos Basin stretching from north-western South Africa into south-eastern Namibia, the main Kalahari-Karoo Basin (NE, Central and SW) in Botswana and the Mid Zambezi Basin in Zimbabwe (ref. Chapter 6).

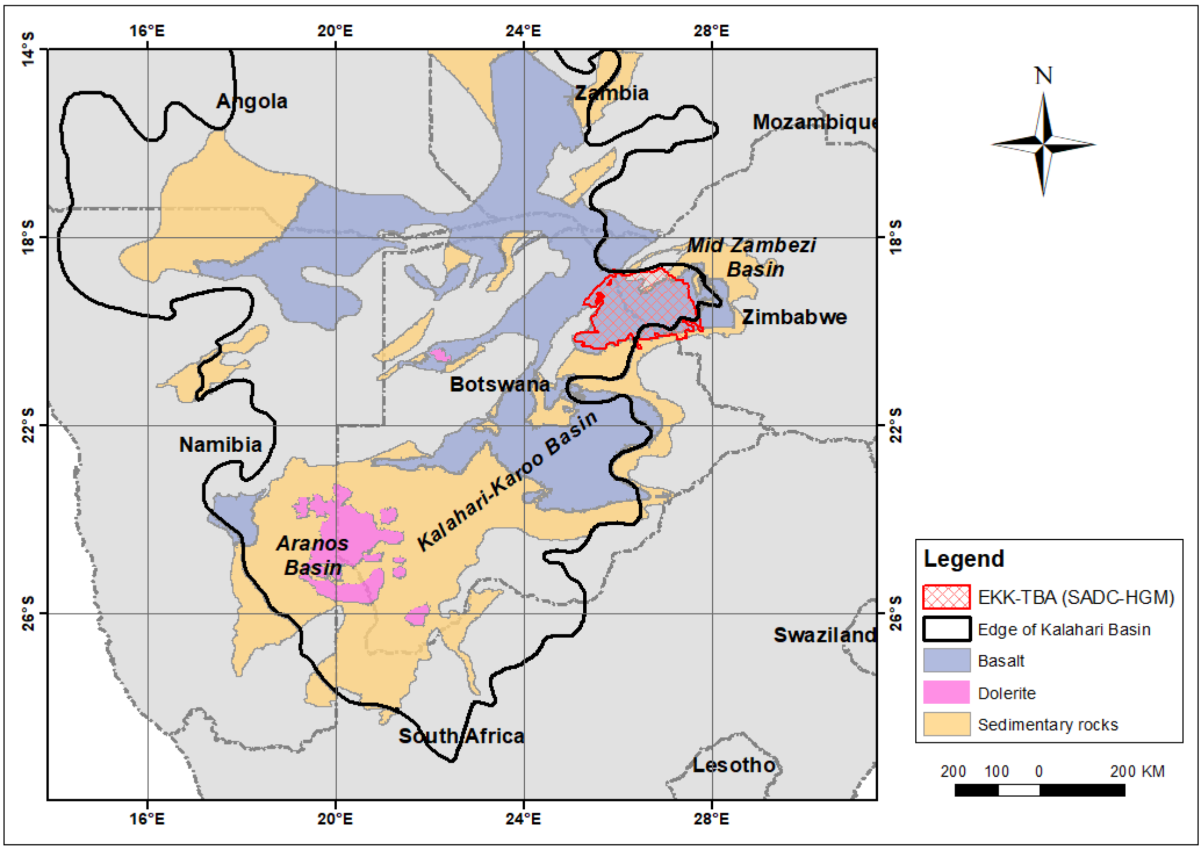

Figure 2.4: EKK-TBA as part of the Kalahari-Karoo Basin
Source: modified after Haddon (2005) and SADC-HGM (2010)

Basement rocks outcropping along the south-eastern margin of the Kalahari-Karoo Basin form a unique (hydro)geological boundary that aid in defining the extent of the EKK-TBA.

Tectonic faults in the Kalahari-Karoo Basin are striking northeast-southwest and northwest-southeast giving rise to block faulting. A dyke swarm cutting through the EKK-TBA is also trending northwest-southeast. It is not clear, however, how the tectonics influence groundwater flow on a basin scale since there is lack of data, especially in the central and northern parts of the EKK-TBA.

From a lithostratigraphic point of view, outcropping Karoo Supergroup along the southern margin of the Kalahari-Karoo Basin, including the Nyamandlovu and Epping Forest areas in

Zimbabwe, should form part of the EKK-TBA. The SADC-HGM (2010) describes these areas as part of the EKK-TBA yet they are left out in the boundary delineation.

2.2.3. Regional piezometry

A piezometric surface, showing areas of identical water level elevations, can be used to derive groundwater flow directions. The flow directions will determine groundwater divides and groundwater recharge and discharge areas and these assist in defining boundaries of a groundwater system.

Figure 2.5 shows groundwater flow directions in the area based on static water levels. Despite the fact that the static water levels represent different aquifers, they still provide an overview of the regional flow direction. The flow directions (blue arrows) have been used in delineating a provisional boundary (yellow dotted line) of the EKK-TBA (Figure 2.5) since groundwater flow tends to 'mimic' the surface topography (albeit in a subdued manner) and a much larger area is proposed for the EKK-TBA.

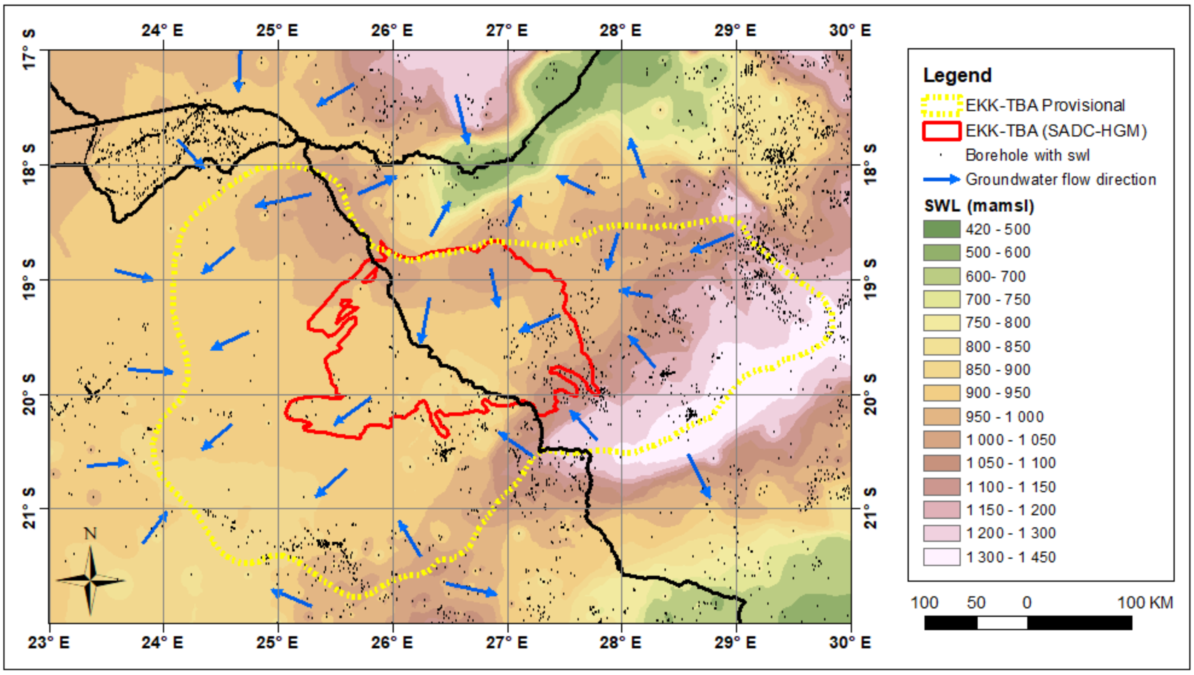

Figure 2.5: Provisional EKK-TBA boundary based on groundwater flow pattern

Groundwater flow in the Zimbabwean part of the EKK-TBA trends to the northwest and then west and southwest over the border into Botswana, and eventually discharges into the Makgadikgadi Pans in the south (Figure 2.5). Away from the fringes of the Kalahari-Karoo Basin, most boreholes are shallow and abstract groundwater from the Kalahari Sands. The general groundwater flow direction from Zimbabwe to Botswana is confirmed by a recent study by WWF (2019) of the Kalahari Sand within the Hwange National Park.

2.2.4. New EKK-TBA system boundary

Combining analyses of the groundwater flow directions and the lithostratigraphy resulted in the delineation of a new EKK-TBA boundary (black dotted line) which is shown in Figure 2.6 and Figure 2.7. The extent of the EKK-TBA has increased to more than triple the size (~127,000 km^2 of which 65% is in Botswana and 35% is in Zimbabwe) of the originally SADC-HGM (2010) demarcated area. The new EKK-TBA boundary was validated during an on-line (virtual) multi-stakeholder workshop involving government officials from Botswana and Zimbabwe and SADC-GMI staff on 25 June 2020.

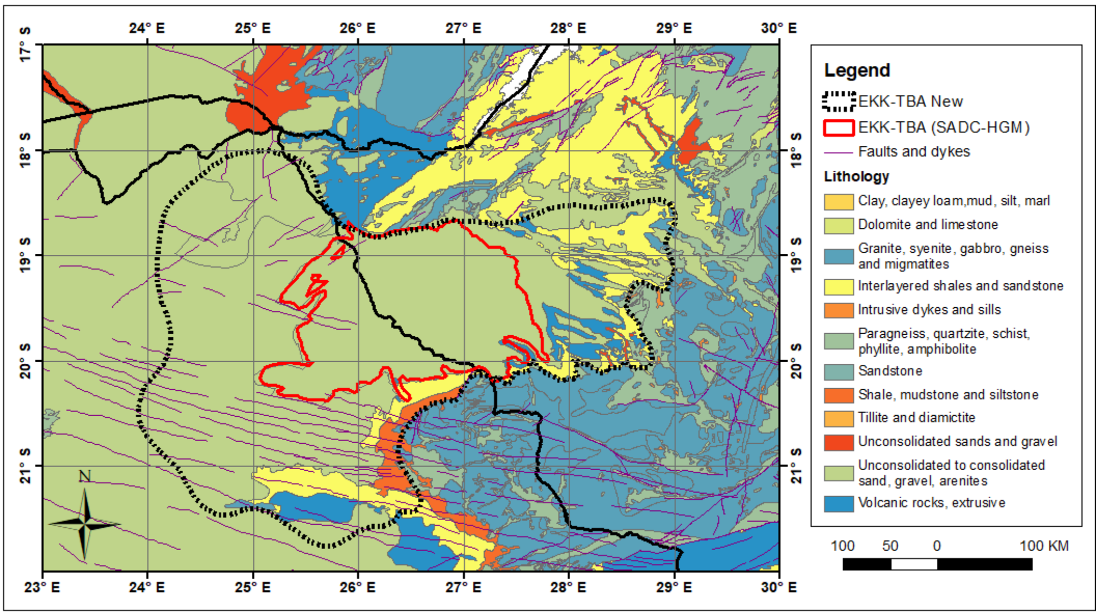

Figure 2.6: Original and new EKK-TBA extent and boundary on SADC-Hydrogeology Map

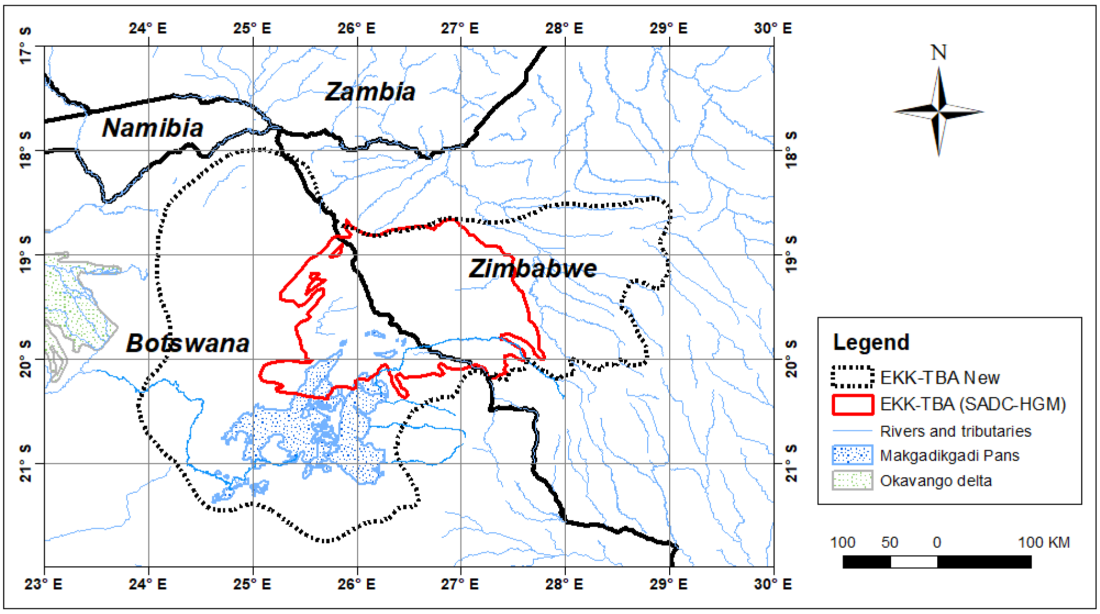

Figure 2.7: Original and new EKK-TBA extent and boundary

The new EKK-TBA boundary overlaps part of the Okavango and Zambezi River Basins and now also includes major wellfields in Botswana (Orapa, Letlhakane, Dukwi, Chidumela in addition to Maitengwe) and Zimbabwe (Nyamandlovu and Epping Forest) as well as the Makgadikgadi Pans which act as the surface water and groundwater discharge zone. The upper course of the Gwayi River system (Khami and Umguza Rivers) in the Gwayi Catchment forms part of the EKK-TBA even though the Gwayi River ultimately drains into the Zambezi River.

The largest proportion of the new EKK-TBA is in Botswana, whereas largest population is living in the Zimbabwe part of the EKK-TBA. The total population living within the boundary of the new EKK-TBA is approximately 595 000 (see section 3.1.1).

3. DEMOGRAPHICS AND SOCIO-ECONOMICS

3.1. Demographics

This section provides an overview of the key demographic variables by country, within the Eastern Kalahari-Karoo Transboundary Aquifer system (EKK-TBA). The current population of the new EKK-TBA is estimated at 595 278. Figure 3.1 shows the location of Bulawayo City, towns, villages and Rural District Councils within and just outside the new EKK-TBA.

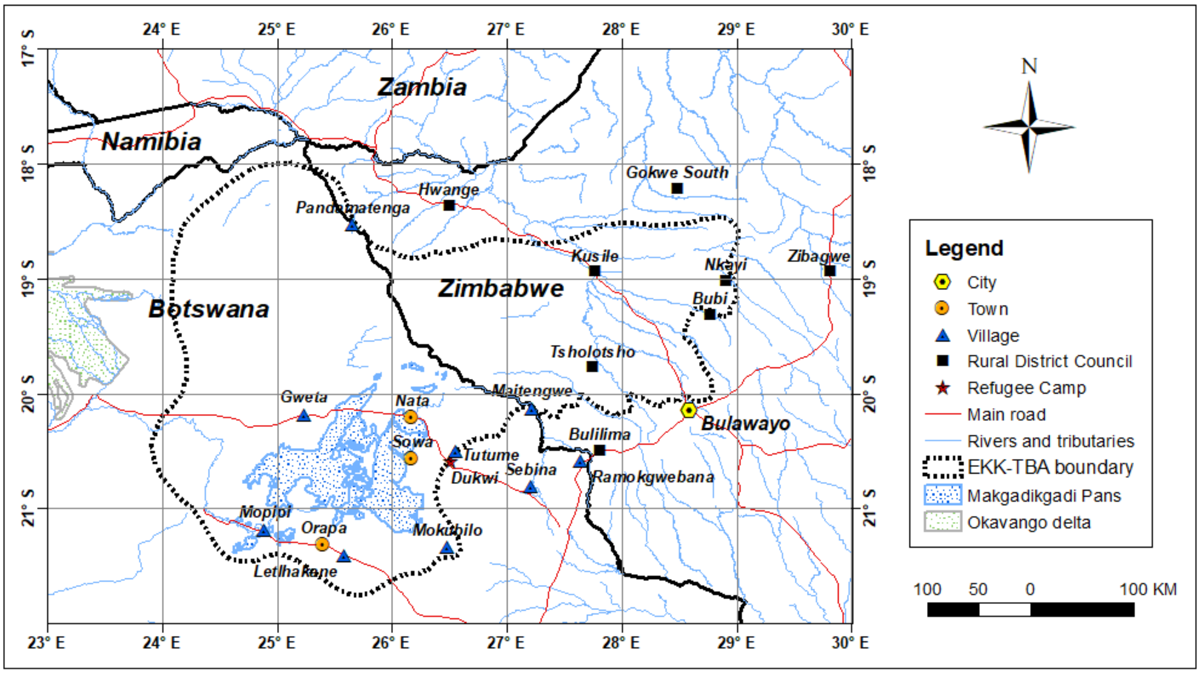

Figure 3.1: Location of Bulawayo City, towns, villages and Rural District Councils

3.1.1. Population

The Botswana's EKK-TBA encompasses villages and towns from the Central, North-East, and North-West Districts. The towns and villages are Nata, Orapa, and Sowa Towns, Gweta, Letlhakane, Maitengwe, Mokubilo, Mopipi, Pandamatenga and Tutume Villages, and Dukwi refugee camp.

A brief overview of the population of Botswana's EKK-TBA is given in Table 3.1. The estimated population of Botswana's EKK-TBA is 83 062 (as at 2011). This estimate is based on the assumption that the towns and villages are fully covered within the boundary of the EKK-TBA. Note that the population figures include neighbouring smaller settlements and cattle posts.

Table 3.1: 2011 Botswana EKK-TBA population[2]

District	Village/Town	Male	Female	Total
North East District	Nata Town	3168	3 546	6 714
North West District	Pandamatenga Village	1625	1 000	2 625[3]
Central District	Dukwi Refugee Camp	1 913	1 192	3 105[4]
Central District	Gweta Village	2 380	2 924	5 304
Central District	Letlhakane Village	11 045	11 903	22 948
Central District	Maitengwe Village	2 602	3 288	5 890
Central District	Mokubilo Village	843	1 064	1 907
Central District	Mopipi Village	1 785	2 127	3 912
Central District	Orapa Town	4731	4 800	9 531
Central District	Sowa Town	1 960	1 638	3 598
Central District	Tutume Village	8 058	9 470	17 528
EKK-TBA Botswana population		**27 044**	**27 367**	**83 062**

Sources: 2011 Botswana Census (Statistics Botswana, 2015; Matenge, 2013)

Nata, is a town in the North-East District of Botswana with 6 714 inhabitants in 2011. It is located close to the Nata River in the northern part of the district and is served by the Nata Airport. The town is situated at an elevation of 916m amsl.

Pandamatenga, is a village situated at an elevation of 1067m amsl in the North-West District of Botswana and had an estimated population of 2 625 inhabitants in 2011 (Statistics Botswana, 2015). The village is located close to the country's border with Zimbabwe and is served by the Pandamatenga Airstrip. Commercial and communal agriculture provides employment to its inhabitants.

Dukwi refugee settlement has a population of 3 105 and accommodates refugees from across Africa (Angola, Democratic Republic of Congo, Namibia, and Zimbabwe among others). Dukwi is home to the Mowana Copper Mines and is situated at an elevation of 996m amsl.

Gweta, is a small village in Central Botswana. It is about 205 kilometres away from Maun and about 100 kilometres from Nata. Its population was estimated at 5 304 during the 2011 national census. It is generally considered the gateway to the Makgadikgadi Pans.

Letlhakane, a village located in the Central District, had a population of 22 948 in 2011 (Statistics Botswana, 2015). The village is situated at an elevation of 989m amsl and is neighbouring to Orapa Town. Letlhakane is a mining village for diamonds.

[2] http://www.citypopulation.de/en/botswana/
[3] https://www.mindat.org/feature-933178.html
[4] https://mspace.lib.umanitoba.ca/bitstream/handle/1993/22253/Matenge%20Mavis.pdf?sequence=1

Maitengwe, is a village in Central District which had 5 890 inhabitants in 2011 (Statistics Botswana, 2015). The village is located on the border with Zimbabwe at an elevation of 1062m amsl. It is known for its festive celebrations.

Mokubilo, also a village in Central District of Botswana, had an estimated population of 1 907 during the 2011 national census.

Mopipi, a village in Central District is located close to the Makgadikgadi Pans. Its population was estimated at around 3 917 inhabitants during the 2011 census.

Orapa, is a town in the Central District, with a population 9 531 in 2011 (2011 census). The projected population for 2019 was 9 630. The town is situated at an elevation of 977m amsl and is known for diamond mining and the Orapa Game Park.

Sowa, is a town, situated at an elevation of 931 m amsl, in the Central District near the Sowa (Sua) Pan with a population of 3 598 inhabitants in 2011, having grown from 2 879 inhabitants recorded in 2001 (Statistics Botswana, 2015). The name Sowa locally translates to salt and sodium carbonate is mined.

Tutume is a large village located in Central District, about 50 km from the Zimbabwe border at Maitengwe and 100km from Francistown City. The 2011 population census estimated the village at about 17 528 inhabitants.

Most of the data on demographics for Zimbabwe's EKK-TBA was obtained and extrapolated from the 2012 Census at district and ward levels for the four provinces which partly fall within the basin, namely, Bulawayo, Matabeleland North, Matabeleland South and Midlands (ZIMSTAT, 2013).

Table 3.2 presents the population of Zimbabwe's EKK-TBA with a breakdown per province, district and district type, local authority and gender as at 2012. The total Zimbabwean population in the basin is 439 796 (as at 2012) and comprised of 208 619 males (47.5%) and 230 734 females (52.5%) and this mirrors the general national male to female ratio of 48:52.

Figure 3.2 shows the population growth of the EKK-TBA starting from the dates of the national censuses (Botswana 2011, Zimbabwe 2012). At present (2020) the EKK-TBA population is estimated at 595 278 (Botswana: 96 919 and Zimbabwe: 498 359) based on national population growth rates[5] . The EKK-TBA population is projected to almost double by 2050, which will put additional pressure on the natural resources.

[5] United Nations – World Population Prospects - https://www.macrotrends.net/countries/BWA/botswana/population-growth-rate; https://www.macrotrends.net/countries/ZWE/zimbabwe/population-growth-rate

Table 3.2: 2012 Zimbabwe EKK-TBA population

Province	District	District Type	Local Authority	Male	Female	Total
Bulawayo	Bulawayo	Urban	Bulawayo City Council	5 527	5 950	11 477
Matabeleland North	Bubi	Rural	Bubi RDC	14 128	15 493	29 621
	Hwange	Rural	Hwange RDC	532	406	938
	Lupane	Rural	Kusile RDC	35 610	38 658	74 461
	Nkayi	Rural	Nkayi RDC	51 215	55 889	107 104
	Tsholotsho	Rural	Tsholotsho RDC	51 765	60 342	112 107
	Umguza	Rural	Umguza RDC	21 244	21 796	43 290
Matabeleland South	Bulilima	Rural	Bulilima RDC	17 219	20 630	37 849
Midlands	Gokwe South	Rural	Gokwe South RDC	9 082	9 273	18 355
	Kwekwe	Rural	Zibagwe RDC	2 297	2 297	4 594
EKK-TBA Zimbabwe population				**208 619**	**230 734**	**439 796**

Source: Zimbabwe 2012 Census (ZIMSTAT, 2013)

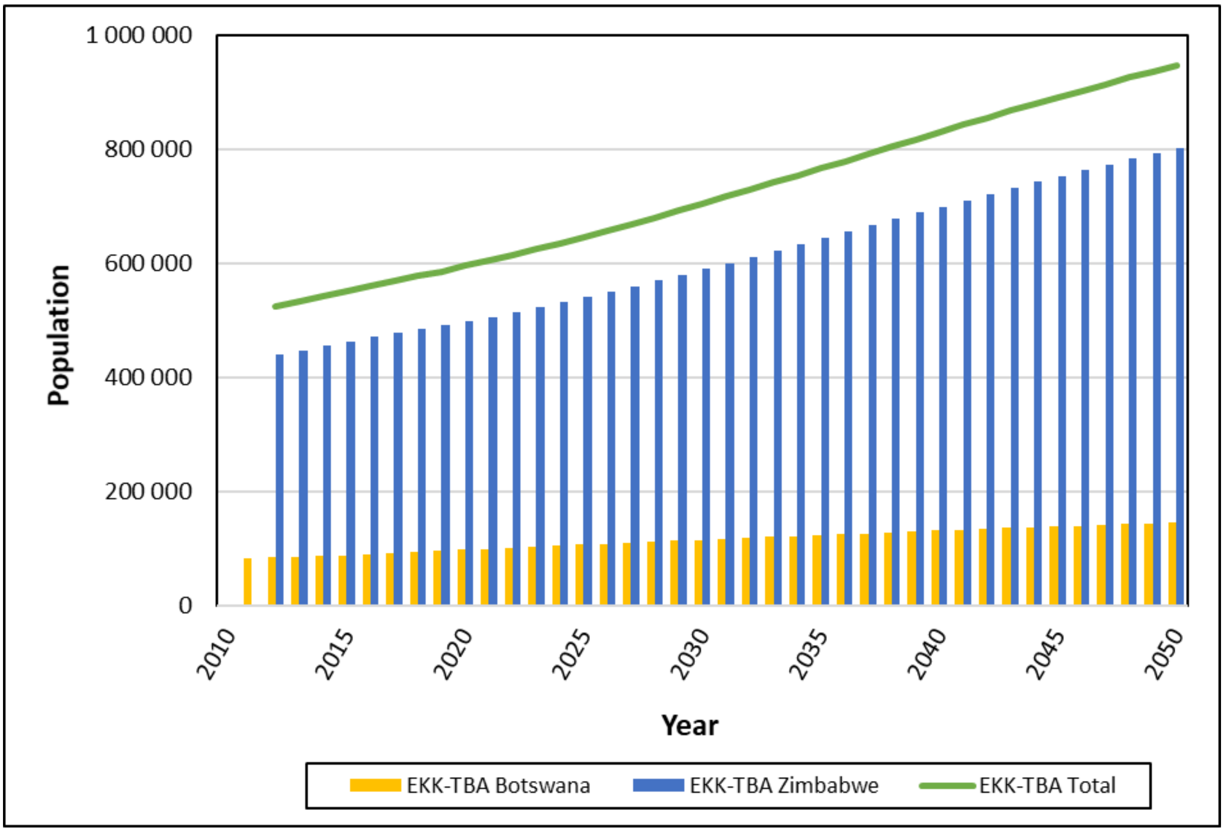

Figure 3.2: EKK-TBA population growth

Sources: United Nations – World Population Prospects - https://www.macrotrends.net/countries/BWA/botswana/population-growth-rate; https://www.macrotrends.net/countries/ZWE/zimbabwe/population-growth-rate

3.1.2. Literacy and education

In 2014, the overall literacy rate for the Botswana population aged 15-65 years was 90%, with a male literacy rate of 88.7% and a female literacy rate of 90.6% (Statistics Botswana, 2016). In comparison, Orapa and Sowa had literacy levels above 90% (Figure 3.3). The North-East District, which is partly covered by the EKK-TBA, recorded a literacy level of 80% (*ibid*).

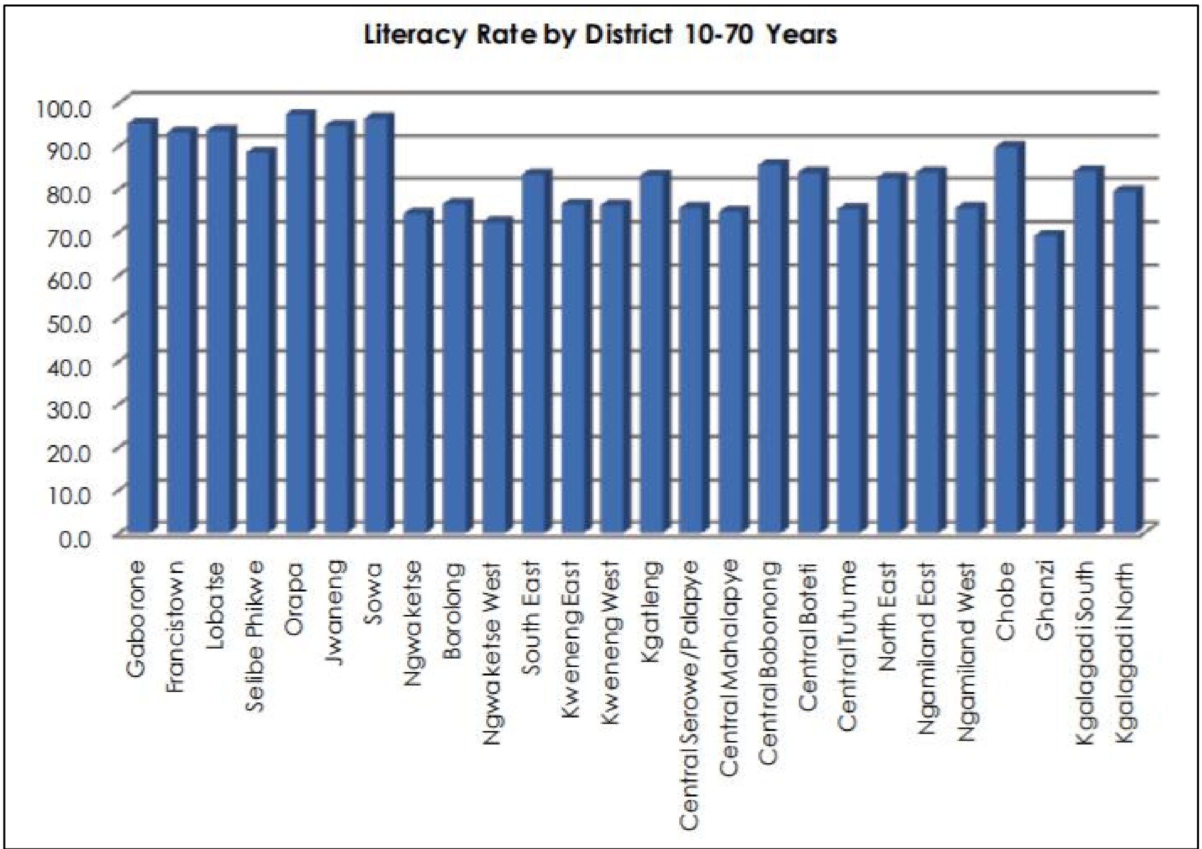

Figure 3.3: Adult literacy levels of Botswana in 2014

Source: Statistics Botswana (2016)

With respect to education, statistics are based on district data since it is not collated at the village level and thus include areas outside the EKK-TBA. In 2011, there were 71 schools in the North-West District of Botswana, with a total of 28 101 and 940 students enrolled in council and private schools, respectively. In the North-East District, there were 66 schools in total, of which 6.7% were private schools. The district had 24 296 and 1 277 students in public and private schools, respectively. The Central District had a total of 264 schools, 23.3% of which were private schools. Council schools had 113 632 students, while private schools had 3 848 students.

The literacy rate in Zimbabwe is defined as the number of persons who have completed at least grade 3 of primary education level per 100 persons (ZIMSTAT, 2013). Table 3.3 shows the literacy rate of the population aged at least 15 years who had completed grade 3. Whilst 96% of those aged 15 years and above were literate, males and females had almost similar literacy rates up to the age of 39 years. However, the literacy rates for females were lower than those for males in the 40 to 44-year category (*ibid*). Notably, literacy rates were highest in the age range of 15 to 44 years and declined with increasing age thereafter. There were no major differences in the literacy rates between Provinces that form part of the basin.

Table 3.3: Literacy Rates for the population aged 15+ (Zimbabwe)

Province	Male	Female	Total
Bulawayo	99	98	98
Matabeleland North	95	92	93
Matabeleland South	96	94	95
Midlands	96	94	95

Source: adapted from ZIMSTAT (2013)

With respect to education, more females (17%) are recorded to have completed primary education than males (15%), while almost equal proportions of males and females (15% and 14%, respectively) completed secondary education and above. The Census data also revealed that about 12% of the population aged 3-24 years had never been to school, of which 84% were below 6 years and with many of them likely to start school later. These statistics are somewhat misleading as children in rural areas of Zimbabwe generally start primary school at the age of 7 years (ZIMSTAT, 2013).

3.2. Socio-economics

3.2.1. The Economy

After its independence in 1966, Botswana moved from being one of the world's poorest countries, becoming one of the world's economic development success stories due to the discovery of diamonds in the mid-1960s. The growth is underpinned by political stability, good governance, prudent economic management and a relatively small population of 2 024 904 inhabitants in the 2011 census (Statistics Botswana, 2015). Despite its good governance, Botswana's economic growth is sensitive to the global demand for diamonds as well as severe and prolonged droughts as illustrated by the decline in growth from 4.5% in 2018 to 3.5% in 2019 (World Bank, 2020)[6]. Besides diamonds, the country is also rich in copper, nickel, and gold and has sizable coal deposits[7]. Other key economic sectors in Botswana include tourism, livestock agriculture (cattle), subsistence farming and financial services[8].

[6] https://www.worldbank.org/en/country/botswana/overview
[7] https://www.nationsencyclopedia.com/economies/Africa/Botswana.html
[8] http://www.limpopo.riverawarenesskit.org/ Distribution of Economic Activities: Botswana

The Zimbabwe population of the EKK-TBA is predominantly rural with significant small-scale and subsistence mining, livestock and farming activities. Note that the Nyamandlovu area in particular is a major commercial farming area which provides fresh produce to the City of Bulawayo and surrounding areas.

Gross Domestic Product

In 2019, Botswana's Gross Domestic Product (GDP) was worth 18.34 Billion US dollars.[9] In 2018, agriculture contributed approximately 2% of GDP, while industry and services sectors contributed 29.32% and 59.52%, respectively (Plecher, 2020), Figure 3.4.

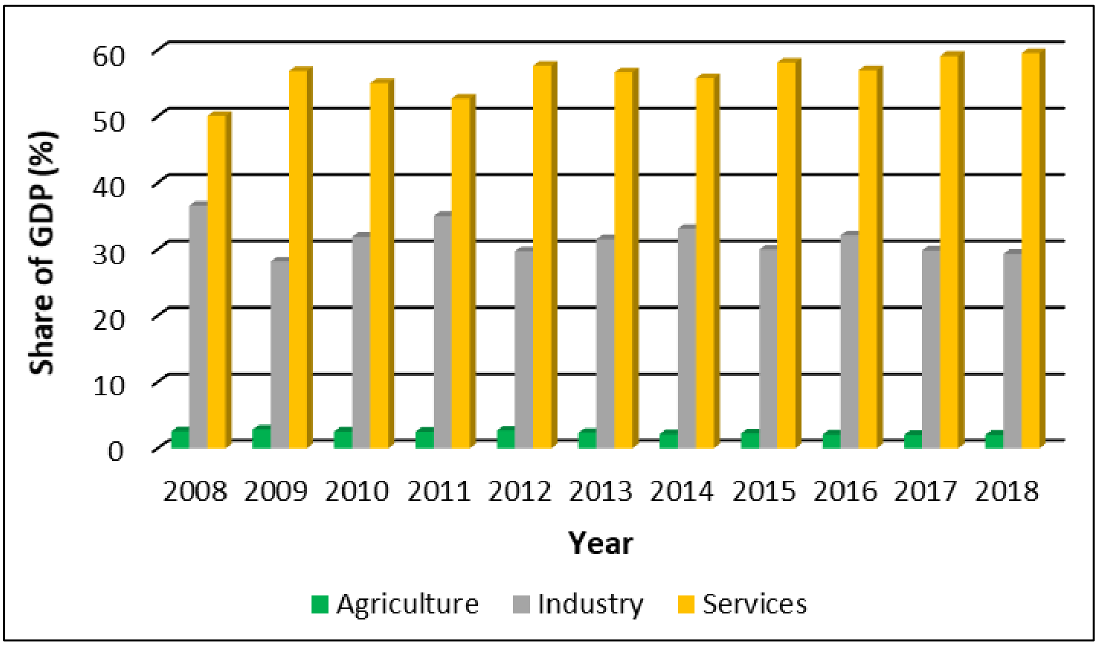

Figure 3.4: GDP distribution across economic sectors (Botswana)
Source: Plecher (2020)

Figure 3.5 shows Zimbabwe's GDP trend since 2010 and the 2020-2021 situation is expected to be gloomy due to the effects of the Covid-19 pandemic, which has had a huge global economic impact. Zimbabwe's GDP was expected to decline to around US$19 billion by the end of 2020 from US$24.31 billion and US$21.44 billion in 2018 and 2019 respectively due to poor mining, tourism, and agriculture performances (AfDB, World Bank and Trade Economics[10]). Foreign currency and electricity shortages are impacting negatively on these key economic sectors. In 2019, agriculture in the eastern parts of the country was immensely affected by Cyclone Idai, whereas prolonged drought affected the rest of the country and caused severe wildlife and livestock deaths. Austerity measures being implemented by the Government through the Transitional Stabilization Program (October 2018–December 2020)

[9] https://tradingeconomics.com/botswana/gdp
[10] https://tradingeconomics.com/zimbabwe/gdp

and attendant monetary reforms are constricting economic activity (AfDB[11]). Economic recovery in 2020–21 would be dependent on quick turnaround in the real sector (*ibid*). In the medium term, however, fiscal and monetary reforms are expected to stabilize the economy and begin to generate positive results (AfDB, World Bank and Trade Economics[12]).

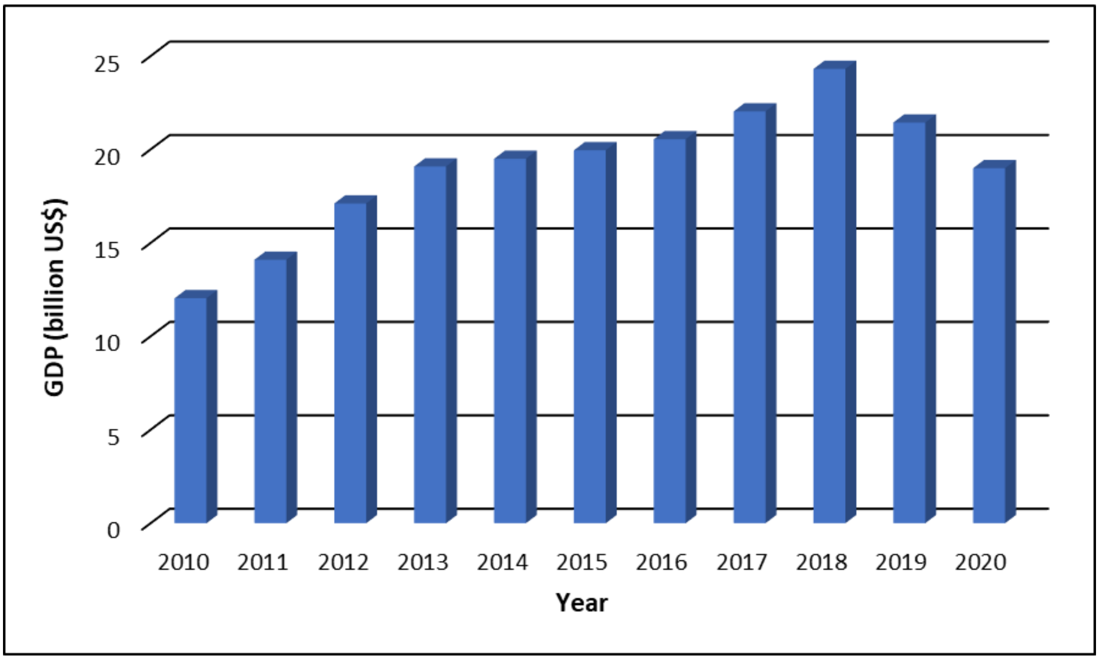

Figure 3.5: Zimbabwe's GDP from 2010 to 2020
Source: modified after Tradingeconomics.com (WB)

On the other end, in 2019, 38.5% of the population was considered to be in extreme poverty, up from 33% in 2017, with the future situation projected to worsen due to the underperformance of the economy and the impact of Covid-19 (World Bank, 2020). Table 3.4 provides the macro poverty outlook for Zimbabwe.

Unemployment

The Botswana census data showed that in 2011 the total unemployed population constituted 50.9% females and 49.1% males (Statistics Botswana, 2015). In the EKK-TBA, there was a 26% unemployment rate recorded in the North-East district, while Orapa and Sowa Towns saw higher unemployment levels for females compared to males, Figure 3.6.

[11] https://www.afdb.org/en/countries/southern-africa/zimbabwe/zimbabwe-economic-outlook
[12] https://tradingeconomics.com/zimbabwe/gdp

Table 3.4: Zimbabwe macro poverty outlook

	YEAR					
	2017	**2018**	**2019e**	**2020f**	**2021f**	**2022f**
Real GDP growth at constant market prices (%)	**4.7**	**3.4**	**-8.1**	**-5.0**	**1.8**	**2.1**
Private Consumption	1.4	2.1	-1`3.4	-11.0	3.2	3.6
Government Consumption	14.5	9.2	-28.1	5.7	-5.2	-2.2
Gross Fixed Capital Investment	23.0	4.5	-5.2	-12.0	8.2	1.2
Exports, Goods and Services	4.7	4.1	-5.1	-5.6	3.5	4.5
Imports, Goods and Services	3.2	7.7	-21.0	-12.3	3.7	4.3
Real GDP growth at constant factor prices (%)	**4.8**	**3.1**	**-8.8**	**-5.1**	**2.2**	**2.0**
Agriculture	10.0	18.3	-18.3	-3.3	4.9	4.9
Industry	2.5	2.1	-6.8	-2.0	2.5	2.5
Services	5.1	1.3	-8.0	-6.7	1.6	1.3
Inflation (Consumer Price Index)	0.9	10.6	255.1	250.0	58.5	33.3
Current Account Balance (% of GDP)	-1.4	-11.7	0.6	-0.6	-1.0	-0.9
Fiscal Balance (% of GDP)	-9.8	-5.1	-2.9	-5.6	-5.7	-6.1
Debt (% of GDP)	63.8	61.4	53.8	61.4	63.2	64.8
Primary Balance (% of GDP)	-8.8	-3.8	-2.0	-4.9	-5.1	-5.3
International Poverty Rate ($1.9 in 2011 PPP)[a,b,c]	33.9	33.4	38.5	40.4	40.6	40.6
Poverty Rate ($1.9 in 2011 PPP)[a,b,c]	61.0	60.7	64.7	66.2	66.3	66.3
Poverty Rate ($1.9 in 2011 PPP)[a,b,c]	81.3	81.1	83.6	84.5	84.6	84.6

Note: e = estimate; f = forecast
a: calculation based on 2017 prices
b: projection using neutral distribution (2017) with pass through = 0.87 based on GDP per capita in constant LCU
c: actual data 2017; nowcast 2018 to 2019; forecast 2020 to 2022

Source: World Bank, Poverty & Equity & Microeconomics, Trade & Investment Global Practices

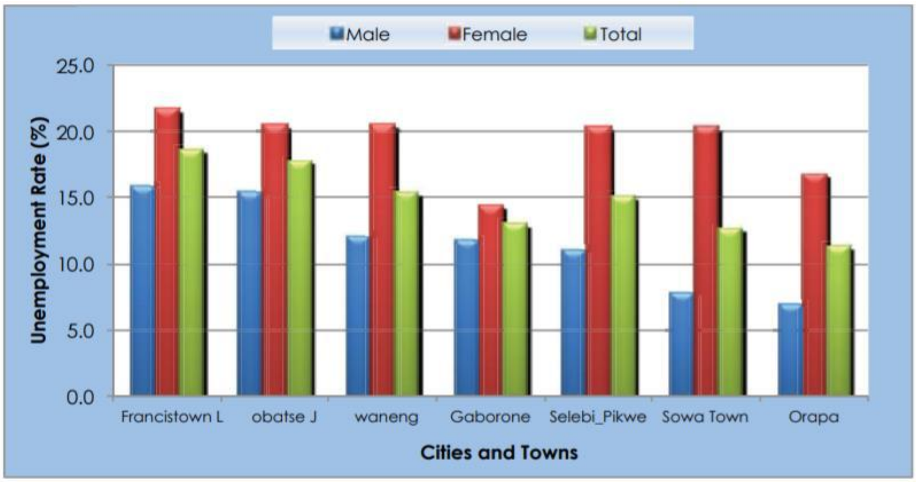

Figure 3.6: Unemployment rates (Botswana)
Sources: Population Census Atlas (2011); Statistics Botswana (2015)

Data from the Zimbabwe 2012 Census indicate that out of the economically active population across the four provinces of which part thereof are within the basin, 20% were unemployed whilst 80% were employed (ZIMSTAT, 2013; Davies et al., 2012). Table 3.5 shows the unemployment rates by province. The data indicate that the highest unemployment rate was recorded in Bulawayo with the lowest rate reported in Midlands Province. However, these figures only present the rates as captured by ZIMSTAT in 2012 when the economy was relatively stable, and these numbers are likely to be higher owing to the decline in the national economy thereafter.

Table 3.5: Unemployment rate (Zimbabwe)

Province	Unemployment rate (%)
Bulawayo	27.4
Matabeleland North	20.3
Matabeleland South	11.3
Midlands	10.0

Source: Adapted from ZIMSTAT (2013)

The data also show that there were more females than males in the categories of unpaid family worker and own account worker. However, more males than females were in categories of paid employee and employer. This is a reflection of societal perception towards females who are generally considered housewives and unpaid workers despite the level of effort and long hours women invest in household chores. The unemployment rate was higher for males (22%) than for females (18%) in most rural districts falling or partly falling within the basin (ZIMSTAT, 2013). Slightly more males than females were employed (53% compared to 47%) (*ibid*). For persons living with a disability, 62.6% of males and 37.4% of females were unemployed respectively across the four provinces (*ibid*).

Mining

The economy of Botswana mostly relies on natural resources, in particular its diamond wealth. Mining provides 86% of the country's export earning, most of which is from diamond sales[13]. The mining sector, however, accounts for only 4.4% of the formal labour force in the country. There are four major diamond mines in the EKK-TBA: Orapa, Lethlakane, and Damtshaa from Debswana (a joint venture between the Botswana Government and De Beers) and Karowe from Lucara Diamond Corporation. The Orapa diamond mine, to the north of Orapa Town, is one of the world's largest diamond producing mines and employs more than 2 800 full-time employees and 237 employees are on fixed-term contracts[14].

In addition to diamonds, the country exports soda ash and salt mined as sodium bicarbonate at the Sowa (Sua) Pan located near Sowa Town. The Sowa (Sua) Pan is one of the largest salt lakes in the world, spanning approximately 24 000 km^2. While sodium chloride is the prime constituent, there are many other salts found within this area such as sodium carbonate (soda ash), sodium bicarbonate, sodium sulphate, and minor amounts of potassium chloride (potash). The sodium carbonate is mined through a company called Botswana Ash (Botash), a joint venture between the government and foreign investors that began its

[13] https://tradingeconomics.com/botswana/gdp
[14] https://www.nsenergybusiness.com/features/worlds-top-five-biggest-diamond-mines/

operations in 2001. The company employs 432 people and the products are exported to South Africa, Zambia, Zimbabwe, Malawi, Namibia and the Democratic Republic of the Congo[15].

Whilst many of Botswana's undiscovered mineral resources are presumed to exist given the country's geology, Central Botswana and the Kalahari Desert are perhaps the most likely sources of new discoveries[16].

Hwange has the biggest coal mines and coal-fired power station in Zimbabwe and falls outside the EKK-TBA. Whilst the mining and power generation companies provide economic support through employment opportunities and availability of power to residents of the basin, there have been concerns raised about the impact of the mines within Hwange district. For example, studies found that there is severe air, land and water pollution due to coal mining and power generation in Hwange (Centre for Natural Resource Governance, 2017). The Centre for Natural Resource Governance (CNRG) further indicated that the noise from blasting and operating plant machinery such as dump trucks and excavators is affecting near-by residents and wildlife, and diesel fumes from machinery and coal-transporting trucks affect the health of local communities. More significantly, there is also massive deforestation in all areas where the mining companies are operating. The indirect impact of the foregoing on the EKK-TBA is yet to be assessed.

Apart from formalised large-scale mining, all the four provinces in Zimbabwe have significant challenges with informal and illegal miners called "*makorokoza*" who usually search and dig for gold with little or no regard for environment. The illegal mining operations also impact negatively on the environment and on water resources through use of heavy metals such as mercury and siltation. However, these have been largely acknowledged for contributing to both their own income and national economy and the Government is in the process of formalising their operations. Notwithstanding these efforts, compliance with environmental and mining regulations has been a major challenge within the sector and requires urgent attention.

Tourism

The EKK-TBA in Botswana is home to a number of tourism activities, helping to boost the national economy while supporting local livelihoods through job opportunities. The Orapa Game Park and the Nata bird sanctuary are key tourism areas.

The Orapa Game Park is situated in the Orapa mining zone and it covers an area of 12 210 hectares. Orapa is a local term that translates to "resting place for lions".

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[15] https://www.gobotswana.com/botswana-ash-pty-ltd

[16] https://www.nationsencyclopedia.com/economies/Africa/Botswana.html

The Nata Bird Sanctuary is located in Nata area and is the only protected bird reserve in Botswana. It lies in the north-eastern periphery of the Sowa Pan. The sanctuary covers an area of 230 km^2 and is managed through a community project managed by the Kalahari Conservation Society, a trust which consists of members drawn from surrounding villages of Nata, with assistance from the Nata Conservation Committee as well as national and international organisations. The sanctuary provides employment to local communities through tourist and lodging activities.

In Zimbabwe, tourism contributes to the country's economy as well as to the rural economy of Hwange and Lupane districts through both direct employment opportunities in tourism facilities such as hotels and lodges and indirectly through selling of handcrafts and wares. However, this sub-sector is largely dominated by medium and large-scale commercial operators with no communal owned schemes/operations. Tourism facilities are mostly utilised by international tourists that bring in the much-needed income for sustaining the ventures and used for environmental and wildlife protection.

Results from a study by Mushawemhuka et al. (2018) showed that the tourism sector in Hwange is affected by extreme weather events, in particular increased occurrence of heat waves which is negatively impacting game viewing operations as is reflected in declining reservations/bookings.

Agriculture

The Pandamatenga Village in Botswana's EKK-TBA is highly suitable for arable agriculture because of the relatively high rainfall of 600mm per year and fertile soil (AfDB, 2008) and was a recipient of the Pandamatenga agricultural infrastructure development project by the African Development Bank (AfDB, 2008). The project sought to address the frequent flooding and poor road networks impeding access to markets, experienced by farmers benefiting from a government allocation of 25 000 hectares in the area. The area practices both commercial and communal agriculture, which provides employment to its inhabitants.

Within Zimbabwe's EKK-TBA, livestock farming makes up the most important part of people's livelihoods but in many cases, the human-wildlife conflicts within the borders of the Hwange National Park has caused significant losses of crops and livestock to wild animals and loss of human lives. This has been exacerbated by the competition for both water and pastures between communal farmers' livestock and wildlife from the park. Besides predation, zoonotic diseases remain a risk, especially rabies.

The World Bank (2020) posited that Zimbabwe has experienced substantial decline in agriculture production and the resultant high food prices caused increased food insecurity with close to 50% of the population being food insecure in 2019. This is largely felt within the EKK-TBA since it falls within a semi-arid region. Livestock and subsistence farming make up the most important part of people's livelihoods in the basin, but in many cases, human-wildlife conflicts within the borders of the Hwange National Park has caused significant losses of crops and livestock to wild animals. This has been exacerbated by the competition for both water and pastures between communal farmers' livestock and wildlife from the park. Besides predation, zoonotic diseases remain a risk, especially rabies (WWF, 2019). Whilst there is commercial agricultural (livestock and irrigated cropping) in the Nyamandlovu area, this remains constrained owing to the macro-economic challenges bedevilling the country.

3.2.2. Water and Sanitation

Botswana's proportion of households with access to piped water source was 90.5% at the 2011 census (Statistics Botswana, 2015). Specifically, Orapa and Sowa towns had 99.3 and 99.9% households with access to piped water (Figure 3.7).

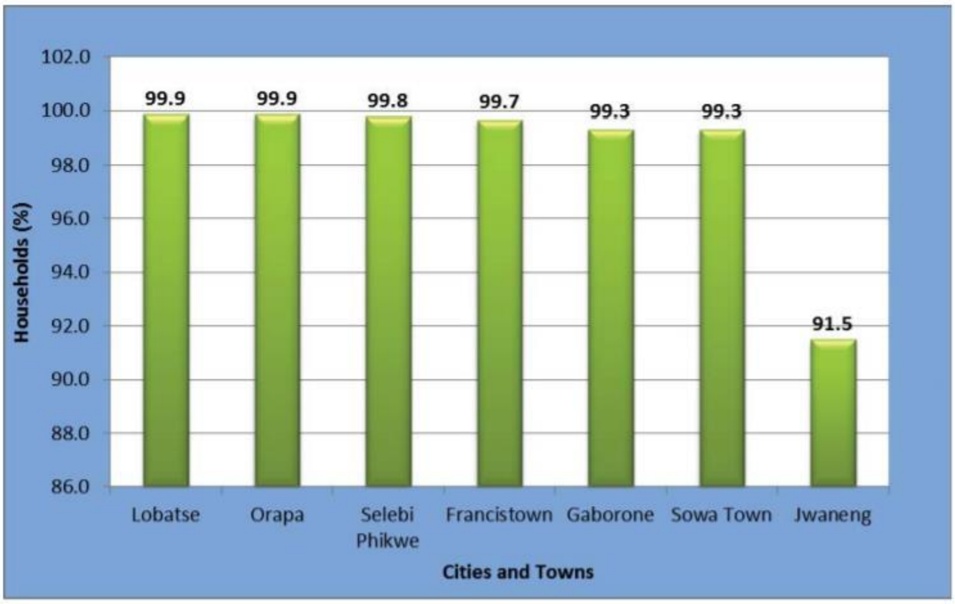

Figure 3.7: Access to piped water (Botswana)
Source: Statistics Botswana (2015)

With respect to sanitation, given the high levels of piped water access, households in Orapa and Sowa Towns had own flush toilets (>70%) and shared flush toilets (>20%), Figure 3.8.

For the largely rural portions of the Zimbabwe's part of the EKK-TBA, only 30.4%, 17.3% and 16.8% of the population in Midlands, Matabeleland North and Matabeleland South respectively had access to water on their premises as depicted in Table 3.6 (ZIMSTAT, 2013). This is in stark contrast to the urban population in Bulawayo where 91.6% of the population had access to water on their premises. Moreover, Matabeleland North and Matabeleland South provinces had the highest percentages of their populations who walked 500 metres to more than 1 kilometre to access water. This is again in sharp contrast to the population of Bulawayo where less than 1% of the population walked more than 500 metres to access water.

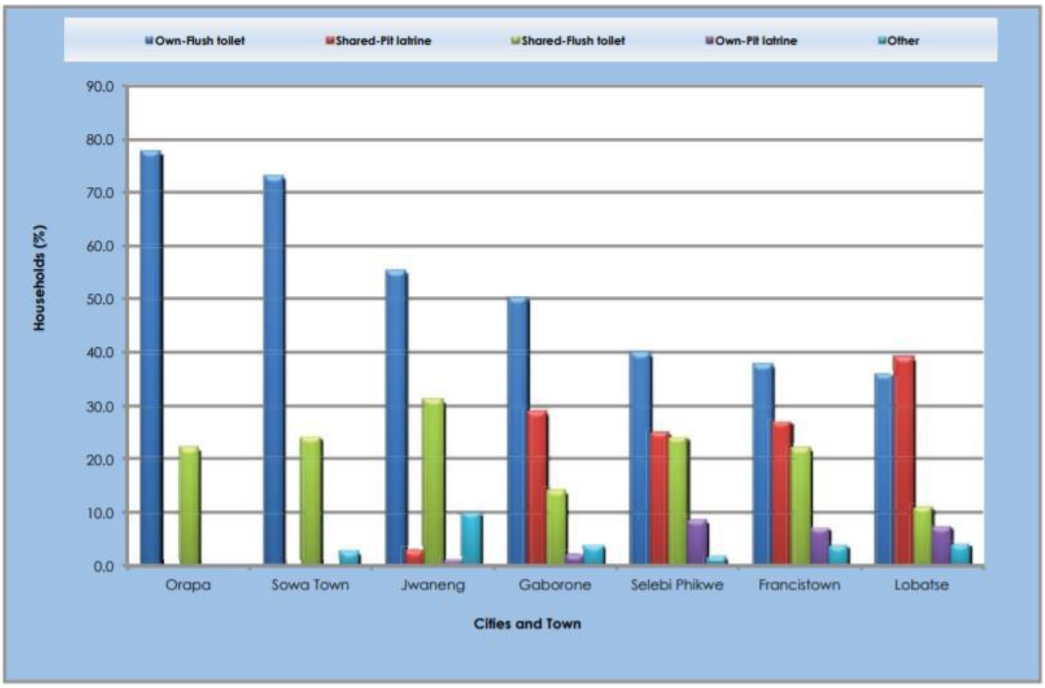

Figure 3.8: Botswana - type of toilet facilities used in 2011

Source: Statistics Botswana (2015)

Table 3.6: Access to water (%) (Zimbabwe)

Province	On premises	Less than 500m	500m to 1km	More than 1km	Missing
Bulawayo	91.6	4.4	0.7	0.2	3.0
Matabeleland North	17.3	24.4	27.4	24.8	6.0
Matabeleland South	16.8	24.6	29.4	23.3	5.9
Midlands	30.4	22.4	23.1	18.9	5.3

Source: adapted from ZIMSTAT data (2013)

It is important to note that longer distances to the nearest water source by rural households places a disproportionate burden on women and girl children as they bear the brunt of fetching water, among other household chores, for their families.

Whilst water and sanitation facilities and access has improved in urban areas, there is a growing concern in some high-density suburbs of Bulawayo where an outbreak of diarrhoeal disease is currently ongoing in the suburb of Luveve (UNOCHA[17]). Whilst the 2012 census data might have recorded higher percentages of water access within premises in most urban centres, the situation could have significantly changed, with access levels reducing especially for urban areas due to incapacities of the municipalities to provide adequate potable water.

[17] https://reports.unocha.org/en/country/zimbabwe/card/7FWM5aGeex/

With regards to sanitation facilities (blair toilets and pit latrines), data for the four provinces within the basin show that Bulawayo had the highest percentage of its population with access and use of the flush toilet system (92.7%), followed by Midlands (24%) and lastly the Matabeleland South Province (15.8%) and Matabeleland North Province (14%), Table 3.7. More significantly, Matabeleland North had 56.3% of its population with no sanitation facility which results in high incidences of open defecation and the associated risks of water borne diseases particularly from unprotected water sources. Matabeleland South and Midlands Provinces had 37% of their populations with no access to sanitation facilities. This is a challenge that requires significant attention within the rural portions of the basin in order to combat water borne diseases such as cholera.

Table 3.7: Access to sanitation (%) (Zimbabwe)

Province	**Percentage of population**						**Population**
	Flush	**Blair**	**Pit**	**Communal**	**None**	**Missing**	
Bulawayo	92.7	1.5	0.3	1.2	1.3	3.0	165 345
Matabeleland North	14.0	17.0	2.0	5.1	56.3	5.6	160 912
Matabeleland South	15.8	35.4	3.7	3.0	36.6	5.5	154 875
Midlands	24.0	16.1	14.4	3.9	36.5	5.1	359 572
Overall	**34.1**	**17.0**	**7.3**	**3.4**	**33.4**	**4.9**	**840 704**

Source: ZIMSTAT (2013)

3.2.3. Covid-19

By 25 July 2020, Botswana had recorded 686 coronavirus (Covid-19) cases and 1 death (WHO Emergency Dashboard, 2020). The global pandemic has severely impacted the tourism sector, which is the country’s second largest revenue earner. The international travel ban has resulted in significant revenue losses previously generated from international tourists from countries such as the United States, Germany and the United Kingdom (Hambira, 2020). A survey conducted by the Botswana Local Enterprise Authority (LEA) covering 382 Small Micro and Medium Enterprises (SMMEs), indicates that the tourism sector suffered a 72% revenue loss in March 2020.

At the same time of 25 July 2020, Zimbabwe had recorded 2 296 confirmed cases and 32 deaths of Covid-19. Like in many parts of the world, the ban on international travels due to the global pandemic has seen significant revenue losses to the Zimbabwe’s tourism sector. Covid-19 has hit hardest all wildlife conservation efforts by the Zimbabwe Parks and Wildlife Management Authority (ZIMPARKS) since its main lifeline is earnings from foreign tourism which have dwindled to critical levels (Tsiko, 2020). ZIMPARKS anticipates losing approximately US$20 million in tourism in 2020 (Kuvawoga, 2020). ZIMPARKS needs to patrol about 13% of the country’s game parks to protect wildlife and this requires human (salaries, allowances, etc) and material (vehicles, fuel, etc) resources which need funding. Similarly, the lockdown measures have also impacted on the national economy and affected many families that rely on informal trading for sustenance as these activities are not permissible under Covid-19 movement restrictions.

3.3. Human Health

Mortality rate is one of the main health indicators, which provides insight into a nations' quality of life.

In Botswana, the national life expectancy at birth in years is 62.6 and 64.6 for males and females respectively[18]. Historical trends in Botswana's life expectancy at birth suggest that during the 1980s until the early 1990's, there was improvement in life expectancy at birth, which seemingly deteriorated during the early 2000's. However, the 2011 census statistics suggest that mortality has been decreasing from around 2005.

The total under-five mortality rate recorded in 2011 was approximately 28%, with the highest mortality rates occurring in the rural areas, at over 30%, compared to around 20% in cities and towns. Urban villages and urban centres had about 27% and 25% respectively (Statistics Botswana, 2015). In 2018, the under-five mortality rate was 36.5 per 1 000 live births and was the lowest on record (World Bank, n.d.[19]).

Botswana's emphasis on primary health care and investment in health care infrastructure has resulted in improved access to healthcare facilities for its citizens who now live within five kilometres of a healthcare facility. The outcome has been a steady decline in the infant mortality and maternal mortality rates[20].

Despite improved access to healthcare, some of the country's healthcare concerns persist. Like many countries in Sub-Saharan Africa, Botswana is still battling high rates of HIV/AIDS and other infectious diseases. With 20.3% of its population having HIV/AIDS (Avert Botswana, 2018), Botswana is ranked 4th highest in HIV prevalence in the world after South Africa, Lesotho and Eswatini. The rapid spread of AIDS in Botswana's population is a major reason that population growth is low. This high prevalence has caused a great number of social problems including labour shortages and a health care crisis. AIDS-related health and safety information is openly available, but cultural practices, social mobility, and the fact that Botswana lies on major trucking routes between South Africa and countries to the north, has contributed to the spread of the disease.

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[18] http://www.statsbots.org.bw/sites/default/files/publications/Botswana%20Population%20Projections%202011_2026.pdf

[19] Mortality rate, under-5 (per 1,000 live births). World Bank Data. World Development Indicators.

[20] https://www.cia.gov/library/publications/the-world-factbook/geos/bc.html World Bank Fact Book

Botswana recorded only 533 indigenous cases of malaria with 9 deaths from the disease in 2018, down from 71 000 cases in 2000, which is a significant progressive reduction. Challenges experienced by the national malaria programme include some communities' perception that malaria is a low priority disease, with people not protecting themselves from mosquitoes as recommended by the World Health Organisation (2020).

In Zimbabwe, the national life expectancy at birth in years is 59.5 and 62.6 for males and females respectively[21]. From 1960 to 1986, there was an improvement in life expectancy at birth from 53 to 61.2%, followed by a drastic decline up to 2004 to 43.1%, and followed by a remarkable steep rise to 61.2% in 2018 (*ibid*).

Infant mortality rate for Hwange District shows a mortality rate of 46 deaths per 1 000 live births (ZIMSTAT, 2013). It is important to note that male infant mortality was higher than female mortality in all the districts. In terms of maternal mortality rate, Matabeleland South had the highest rate of 677 deaths per thousand whilst Midlands had the lowest at 502 as illustrated in Table 3.8. These numbers are significantly higher than the global average of 211 deaths per 100 000 (UNICEF, 2017[22]). The figures might not be reflective of the situation on the ground given the state of the economy and that of rural public health services, which are battling shortages of qualified personnel and lack of medicines.

Table 3.8: Maternal mortality by Province (Zimbabwe)

Province	Maternal mortality per thousand
Bulawayo	550
Matabeleland North	578
Matabeleland South	677
Midlands	502

Source: Zimbabwe 2012 Census (ZIMSTAT, 2013)

Access to public health facilities in the rural portions of the basin is limited and communities walk long distances to access health services. The government, non-governmental organisations and international cooperating partners subsidise the cost of health care for expecting mothers, children under 5 years old and the elderly (over 65 years old).

In general, Matabeleland North and South Provinces have the least number of health care facilities in the country, resulting in communities walking very long distances to the nearest health facilities (ZIMSTAT, 2013). This makes it exceedingly difficult especially for girls, women and other vulnerable members of the communities to access health services. The situation is

[21] https://countryeconomy.com/demography/life-expectancy/zimbabwe
[22] https://data.unicef.org/topic/maternal-health/maternal-mortality/

exacerbated by the inadequacy or lack of medicines in most of the health facilities, a result of the economic challenges the country is experiencing. Note that malaria is a major health risk within the Zimbabwean EKK-TBA.

3.4. Key Messages

- There is need for the population of the EKK-TBA to be properly quantified or estimated in order to determine the risks and opportunities that arise from the available natural resources. Doing so will also further assist in estimating the pressure the population might impose on the basin's environmental resources such as water, land and the ecosystem. On the Zimbabwean side of the basin, the population has been estimated with the highest level of confidence because the census data is recorded at ward level.
- The impact of mining and mining pollution has the potential to affect rural and vulnerable communities who ordinarily do not have easy access to public and private health services. The impact of coal and gold mining operations (outside the EKK-TBA) on the basin population and environment is not well understood.
- Illegal mining operations are impacting negatively on the environment and on water resources and this needs to be addressed.
- High mortality rates, particularly among children under 5 years old have been reported in Zimbabwe and this needs to be addressed.
- High open defecation has been reported within the basin, particularly in Zimbabwe and can pose a serious risk of water borne diseases.
- The impact of the global Covid-19 pandemic has presented critical challenges to the protection and preservation of wildlife in the EKK-TBA in both countries. The severe losses in revenue generated from foreign tourists have impacted governments' economies in general and in particular, the livelihoods of communities dependent on tourism.

4. CLIMATE

This chapter presents key climatic variables, mainly rainfall, temperature and evapotranspiration and their trends in the EKK-TBA. It starts by looking at the data sources and the quality of the climatic data.

4.1. Data sources

Data from five (5) climate stations covering the study area were available for analysis (4 from Botswana and 1 from Zimbabwe) as shown in Table 4.1. 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 available. The climate dataset used are precipitation (rainfall), and minimum and maximum temperature. Virtual climate stations were assumed at the centre of each grid as shown in Figure 4.1, 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. This was done in order to determine 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 could be available in the two countries. Note that Figure 4.1 also shows the five observation stations and spatial rainfall interpolated over the EKK-TBA using the 79 virtual stations.

Table 4.1: 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	25.98	28.16
Latitude (deg. S)	17.82	17.82	21.42	20.63	19.52
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

4.1.1. Quality of climate data

As shown in Table 4.1, almost all the datasets have missing values. Although the percentages of missing values are low, they present a challenge when analyses were to be done at a daily time step as there would be data gaps. Further, interaction with the data revealed other issues, for example, the presence of questionable 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.

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 for a semi-arid region. Other issues relate to duplicate values, for example, a single day had dual records which had different values. It is advisable that data handling authorities should dedicate time and resources to data quality control (DQC) in terms of its completeness, consistency, accuracy, validity, and timeliness. Good quality data yields reliable predictive outcomes. Similarly, the users should be aware of the quality of the data before carrying out any detailed analysis and reporting of the results since flawed data would yield inaccurate results from which wrong decisions would be formulated.

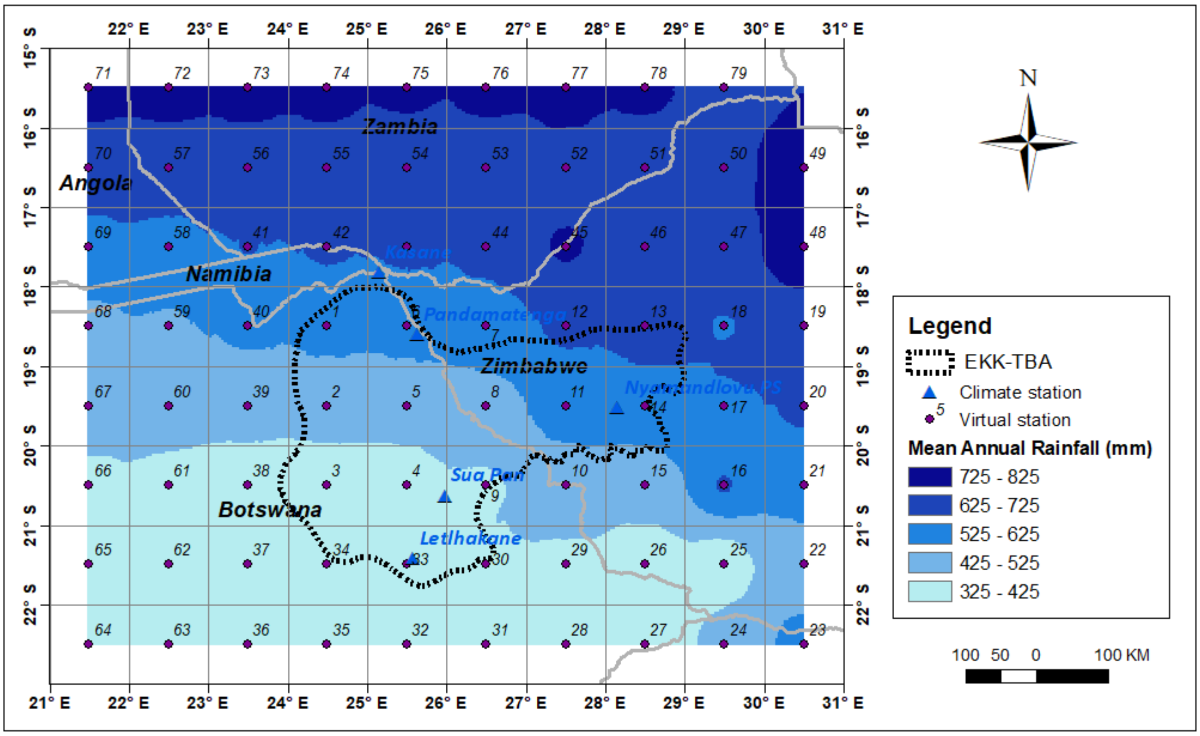

Figure 4.1: Spatial distribution of virtual stations and mean annual rainfall

4.2. Rainfall

4.2.1. Climate stations

4.2.1.1. Monthly and annual values

Monthly rainfall values from the five climate stations are presented in Table 4.2 as well as mean annual rainfall (MAR) and coefficient of variation (CV). It is clear from the table that rainfall occurs between October and April, with January having the highest rainfall (about 128 mm) and July and August being the driest months.

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 the consultants had access to, the annual rainfall for the Nyamandlovu station (564 mm), and from the Gwayi Catchment[23] (647 mm) both in Zimbabwe show that the Zimbabwean part of the EKK-TBA receives high rainfall compared to the Botswana part of the EKK-TBA, with a mean annual rainfall of 477 mm.

The coefficent of variation (CV) is generally high, ranging between 0.30 and 0.37. A high CV usually indicates high interannual variability common in arid and semi-arid areas. It is also linked to rainfall uncertainty, which is expected to increase mainly due to climate variability and change.

Table 4.2: 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**
CV	**0.32**	**0.30**	**0.33**	**0.37**	**0.32**	**0.35**	**0.33**

4.2.2. Virtual stations for CRU data

4.2.2.1. Monthly and annual rainfall

In order to test the usefulness of the CRU dataset, rainfall values from the CRU, data were extracted at the same locations as the climate stations, with an assumption that the CRU is able to match or fit the observed rainfall well. The monthly results (from January to December: 1-12) are plotted in Figure 4.2. The results show that the CRU data captures the seasonality of the observed rainfall. However, the magnitude of rainfall is overestimated by

[23] 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).

the CRU data for some stations such as Kasane (for January) and Pandamatenga (for almost all the months). The last plot (EK-TBA) shows average values from the five climate and virtual stations.

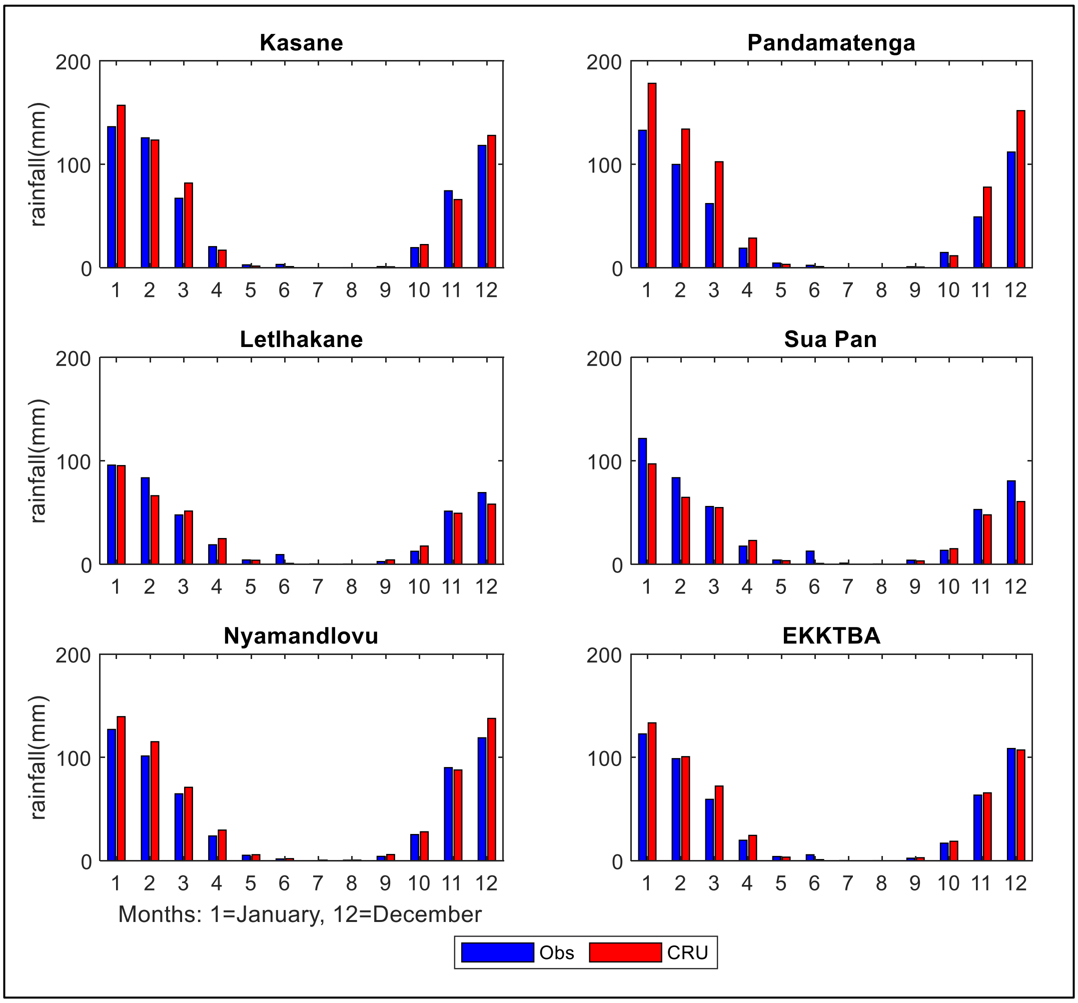

Figure 4.2: Mean monthly rainfall of climate (Obs) and virtual stations

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 4.3. The CRU data is able to track inter-annual variability particularly for Kasane, Pandamatenga and Nyamandlovu despite some discrepancies in certain years (particularly very wet or dry years). The variability of Sua Pan and Letlhakane stations are not well represented by the CRU data. The last plot in this figure which makes use of all the available datasets in the EKK-TBA shows that long term inter-annual variability is well represented. In terms of rainfall trends, it is not easy to detect the trends in most plots, except for the Pandamatenga stations, which clearly shows a decreasing trend for both observations and CRU data (although the CRU overestimates rainfall) (Figure 4.3). To obtain more insights on the rainfall trends, the Mann-Kendall statistics were computed (Mann, 1945; Kendall, 1975) and the results are presented in Table 4.3.

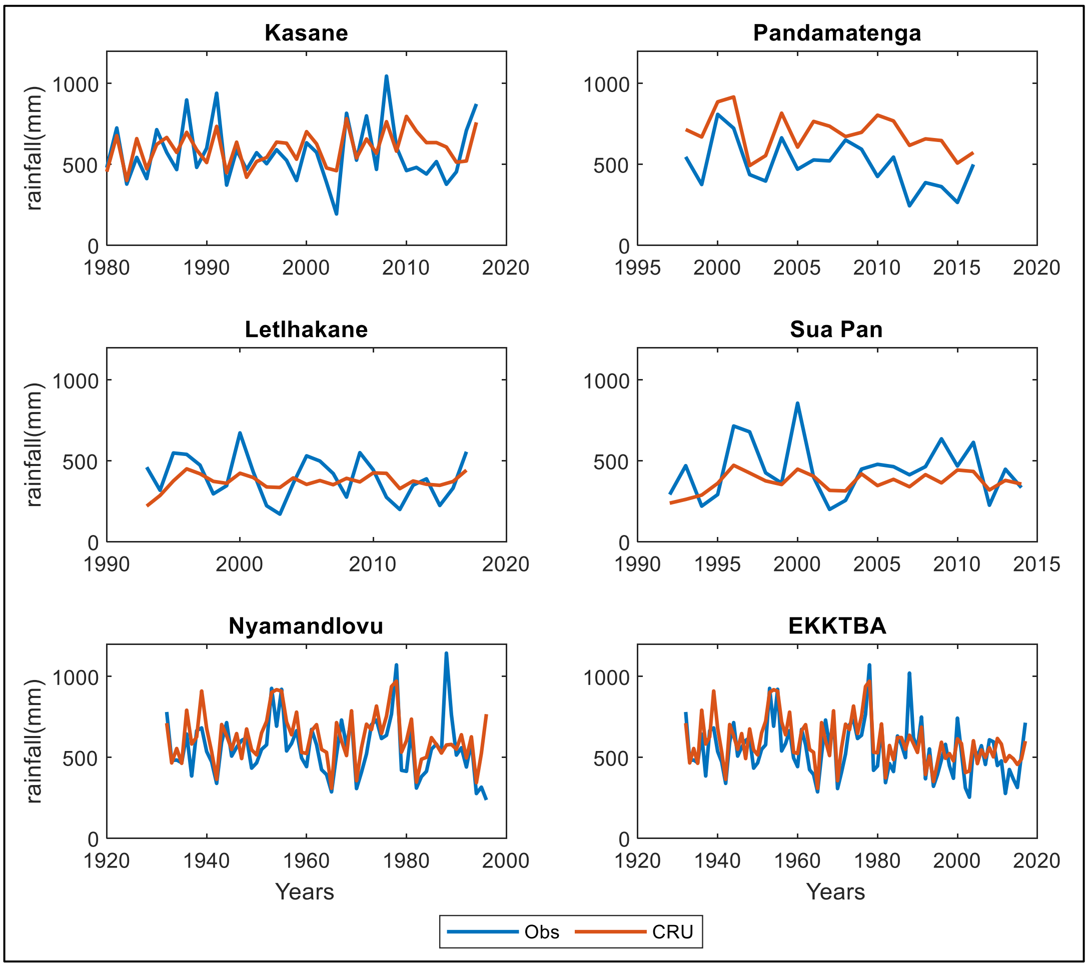

Figure 4.3: Annual rainfall of climate (Obs) and virtual stations

Table 4.3: Rainfall trends obtained using the Mann-Kendall Statistics

Stations	MK-Z	Sen's S	p
Kasane	-0.035	-0.155	0.972
Pandamatenga	-0.35	-1.838	0.726
Letlhakane	-2.122	-4.602	**0.034**
Sua Pan	0.423	2.247	0.673
Nyamandlovu	-0.793	-1.185	0.428
EKK-TBA	-2.354	-1.321	**0.019**

The Mann-Kendall (MK-Z) statistic indicates the magnitude of the trend, while the Sen's slope (S) shows the direction of the trend (negative or postive). The p value is used to determine whether or not a trend is significant at a desired confidence interval (i.e. usually at 95% level). The results show that all the stations except Sua Pan have a negative slope (S), indicating a potentially decreasing trend. However, these trends are not significant except for Letlhakane (p value of 0.034), and for the average station rainfall (EKK-TBA) with p value of 0.019. The trends established here are in agreement with studies previously undertaken in Botswana, for example, Byakatonda et al. (2018) found similar results for Kasane, Pandamatenga, Letlhakane and Sua Pan stations.

4.2.2.2. Spatial rainfall over the EKK-TBA

Since the climate stations are limited (no spatial basin coverage), CRU data from the 79 virtual stations were used to understand the regional climate distribution over the EKK-TBA and surrounding areas (Figure 4.1). The point/grid rainfall with a resolution of 0.5⁰ x 0.5⁰ (same resolution as the CRU data) were then interpolated over the entire area using the inverse distance weighting (IDW) method in ArcGIS. Results from Figure 4.1 show a moisture gradient increasing from the south (Botswana) to the north and north-eastern part of the EKK-TBA (Zimbabwe). The mean annual rainfall ranges between 327 and 869 mm over the entire area under consideration. However, the bulk of the EKK-TBA boundary falls within the range of 327 and 625 mm. These rainfall values are reasonable given that the observed annual rainfall values recorded at Kasane and Nyamandlovu stations are about 564 and 568 mm respectively and are within the range of 525 and 625 mm depicted in Figure 4.2. 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.

As can be seen from Figure 4.2, and pointed out earlier, there are only a 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 stations in the area or that access to available data is restricted. The lack of adequate data limits in-depth analysis and understanding of spatial rainfall (and other climate variables) trends in the EKK-TBA. However, the CRU datasets have presented itself a useful resource to mitigate against this limitation.

4.3. Temperature

Four climate stations with mean monthly minimum and maximum temperature data were available from the Botswana side of the EKK-TBA (Table 4.4 and Table 4.7), and their analysis is presented in Table 4.5 and Table 4.8.

4.3.1. Minimum temperature

4.3.1.1. Mean monthly minimum temperature

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). In general, and on average, low temperatures occur in July (7.75 °C) while December appears to be warmer than other months (19.61 °C). The station with the least CV is Pandamatenga while the highest CV was recorded at Sua Pan (0.06). The observed minimum temperatures were compared with data from virtual stations whose locations coincided with the climate stations, and the results are shown in Figure 4.4. The seasonal observations are well represented by the CRU data, albeit with overestimation at the Pandamatenga and Kasane stations. The Gwayi Catchment data shows 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.

Table 4.4: 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	8.4	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	**8.4**	**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**
CV	**0.05**	**0.03**	**0.05**	**0.06**	**-**	**0.05**

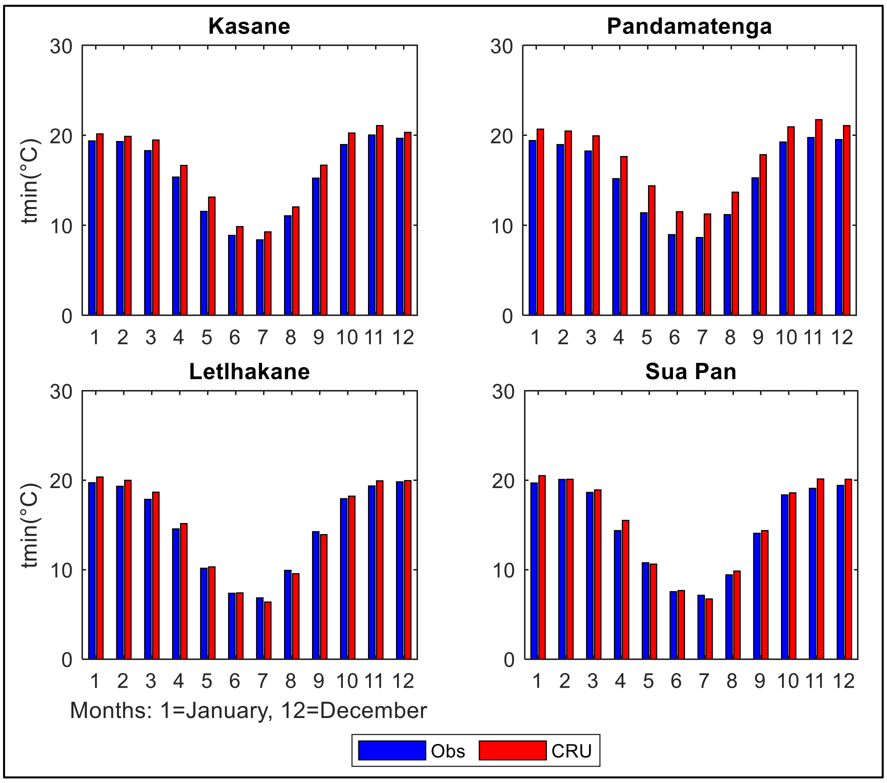

Figure 4.4: Mean monthly minimum temperature for climate (Obs) and virtual stations

4.3.1.2. Mean annual minimum temperature

Annual temperatures for the four climate stations stations were plotted against the corresponding CRU data as shown in Figure 4.5. The results show that CRU data overestimate minimum temperature at Kasane and Pandamatenga although the interannual variability seem to be reasonable. Trend analyses (Table 4.5) reveal significant increasing trends for Pandamatenga, Letlhakane and Sua Pan ($p<0.05$). Kasane station on the contrary, shows a decreasing trend. The trends for selected virtual stations covering Botswana and Zimbabwe were investigated and their results are presented in Table 4.6 and show increasing trends for the minimum temperatures.

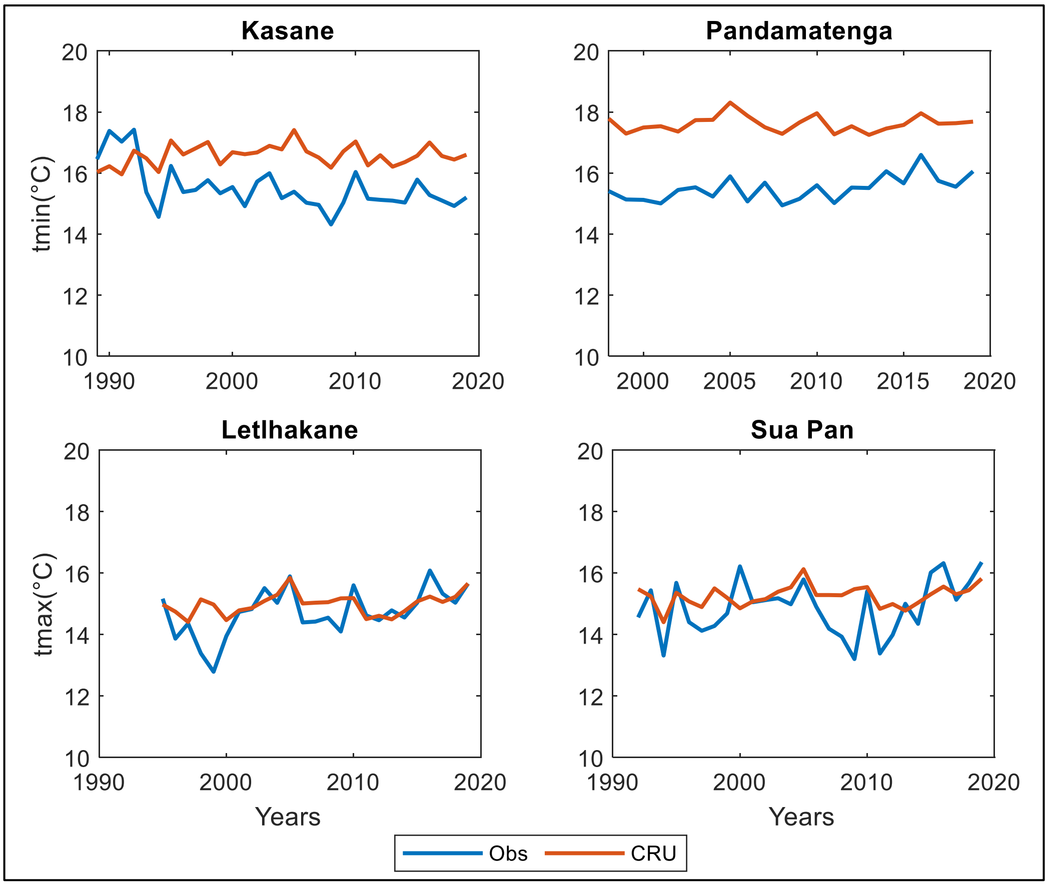

Figure 4.5: Annual minimum temperatures for climate (Obs) and virtual stations

Table 4.5: Mann-Kendall Statistics of mean monthly minimum temperatures

Stations	MK-Z	Sen's S	p-value
Kasane	-2.787	-0.355	0.005
Pandamatenga	2.538	0.033	0.011
Letlhakane	3.977	0.052	0.000
Sua Pan	3.141	0.058	0.002

Table 4.6: Mann-Kendall Statistics of mean monthly rainfall and temp. of virtual stations

	Rainfall (mm)			Min Temp (deg C)			Max Temp (deg C)		
Stations	**MK-Z**	**Sen's S**	**p**	**MK-Z**	**Sen's S**	**p**	**MK-Z**	**Sen's S**	**p**
EKKTBA1	-1.27	-1.73	0.20	2.08	0.04	0.01	6.78	0.05	0.00
EKKTBA2	-0.59	-0.87	0.56	2.48	0.04	0.01	7.07	0.05	0.00
EKKTBA3	-0.14	-0.21	0.89	3.43	0.03	0.00	7.09	0.05	0.00
EKKTBA4	-0.57	-0.75	0.57	2.89	0.03	0.00	6.69	0.05	0.00
EKKTBA5	-0.91	-1.08	0.36	2.73	0.03	0.01	6.92	0.05	0.00
EKKTBA6	-1.29	-1.67	0.20	2.52	0.04	0.01	5.43	0.05	0.00
EKKTBA7	-1.29	-1.92	0.20	2.66	0.03	0.01	6.55	0.05	0.00
EKKTBA8	-1.27	-1.57	0.20	2.74	0.03	0.01	6.99	0.05	0.00
EKKTBA9	-1.16	-1.32	0.25	3.18	0.03	0.00	5.62	0.04	0.00
EKKTBA10	-1.29	-1.86	0.20	3.02	0.03	0.00	5.68	0.05	0.00
EKKTBA11	-1.46	-1.74	0.14	3.22	0.03	0.00	5.66	0.05	0.00
EKKTBA12	-1.21	-1.96	0.23	2.42	0.03	0.02	6.57	0.05	0.00
EKKTBA13	-1.14	-2.56	0.26	3.66	0.03	0.00	5.28	0.04	0.00
EKKTBA14	-0.81	-1.47	0.42	3.27	0.03	0.00	5.39	0.04	0.00
EKKTBA15	-1.59	-2.13	0.11	3.23	0.03	0.00	5.43	0.04	0.00
EKK-TBA	**-1.07**	**-1.52**	**0.32**	**2.96**	**0.03**	**0.01**	**6.21**	**0.05**	**0.00**

4.3.1.3. Spatial mean monthly minimum temperature

The CRU mean monthly temperatures from the virtual stations were interpolated over the EKK-TBA as shown in Figure 4.6. The mean monthly minimum temperature in the EKK-TBA appears to be increasing from east (Zimbabwe) to west (Botswana), from about 12.24 °C to 15.63 °C. From the Botswana side, the spatial trends is in agreement with the results obtained in Table 4.5, where areas around Letlhakane and Sua Pan are cooler than areas around Pandamatenga and Kasane (Figure 4.6). With no data received from the Zimbabwean side, it was not possible to validate the results for that part of the EKK-TBA.

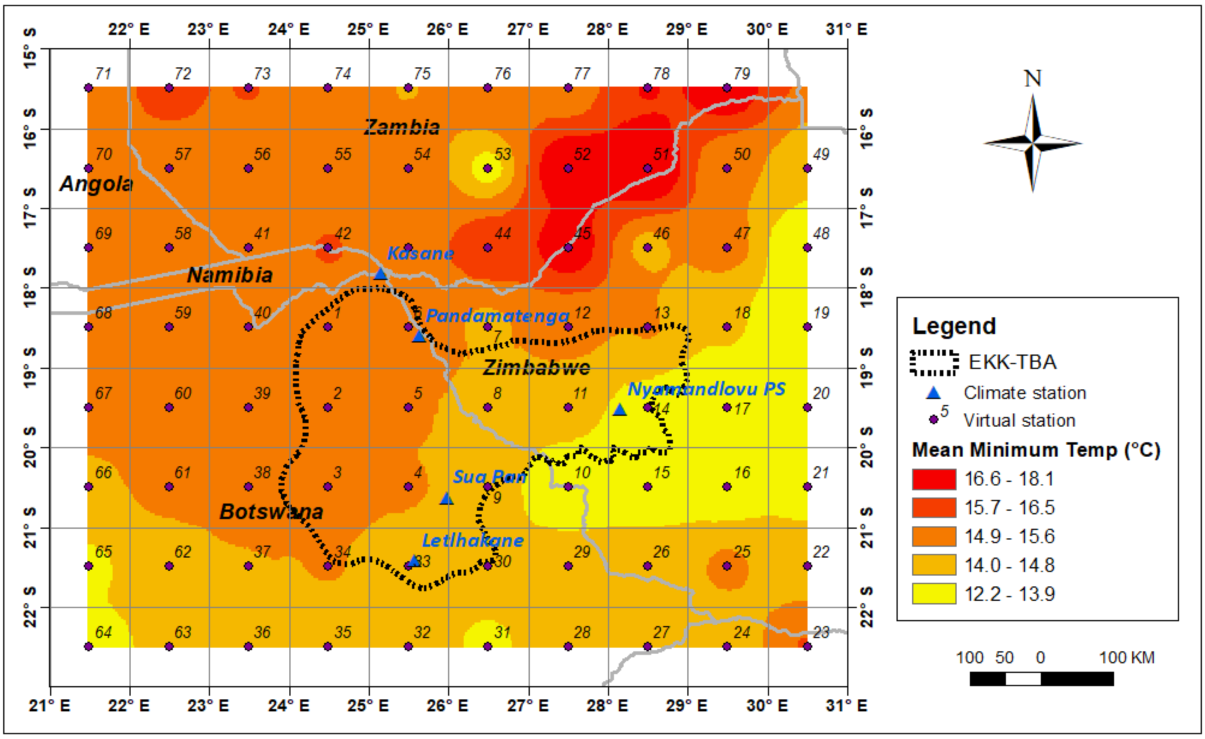

Figure 4.6: Mean monthly minimum temperatures derived from the CRU data

4.3.2. Maximum temperature

4.3.2.1. Mean monthly maximum temperature

Table 4.7 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 temperatures occur in July while high temperatures are in October across all the stations. The mean monthly maximum temperature range between 29.83 °C at Pandamatenga and 30.72 °C at Sua Pan. Sua Pan displaying warmer temperatures compared to other stations, and this is also shown by a higher CV (0.04). Data from the Gwayi Catchment shows that maximum temperatures are generally low in Zimbabwe, compared with Botswana, with a mean annual temperature of 28.91 °C compared to 30.31 °C in Botswana. Highest maximum temperatures in the EKK-TBA are experienced in October and November whereas the lowest maximum temperatures occur in June and July.

The information from these stations is however, limited to make any reasonable spatial inference for the EKK-TBA. The observed data was compared with CRU temperatures from virtual stations as shown in Figure 4.7. The seasonal variation is reasonably captured by the CRU data (matching of observed data and simulated data), with October generally displaying high temperatures while low temperatures are experienced in June and July.

Table 4.7: 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**
CV	**0.02**	**0.02**	**0.02**	**0.04**		**0.03**

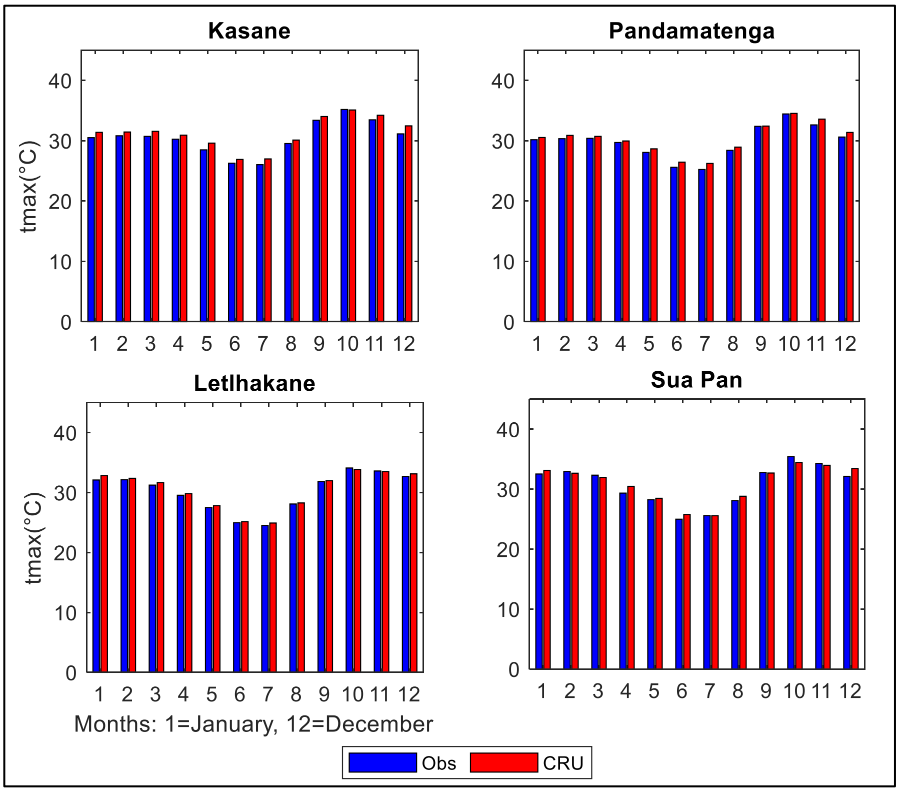

Figure 4.7: Mean monthly maximum temperatures for climate (Obs) and virtual stations

4.3.2.2. Mean annual maximum temperature

Annual temperatures from the climate and CRU stations are plotted in Figure 4.8. There is a reasonable match between observed and simulated temperatures except for the Sua Pan station where the CRU temperature is higher than the observed temperature. There are generally no discernible trends in maximum temperature across all the stations, and this is confirmed by high p-values shown in Table 4.8. However, long term data from CRU show increasing trends for maximum temperatures across the EKK-TBA (Table 4.6) and this is evident in Figure 4.9 to Figure 4.12 for minimum and maximum temperatures.

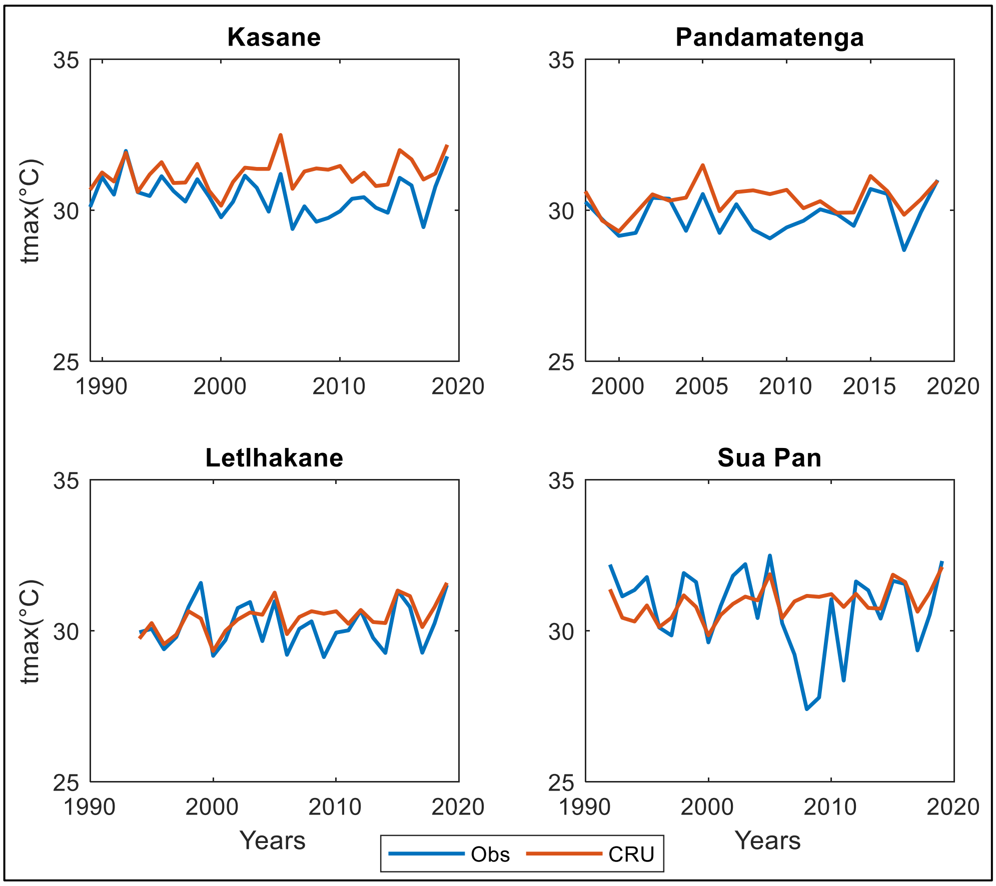

Figure 4.8: Annual maximum temperature for the climate (Obs) and virtual stations

Table 4.8: Mann-Kendall Statistics of mean monthly maximum temperatures

Stations	MK-Z	Sen's S	p
Kasane	-1.088	-0.015	0.277
Pandamatenga	0.959	0.021	0.338
Letlhakeng	1.145	0.018	0.252
Sua Pan	-0.375	-0.011	0.707

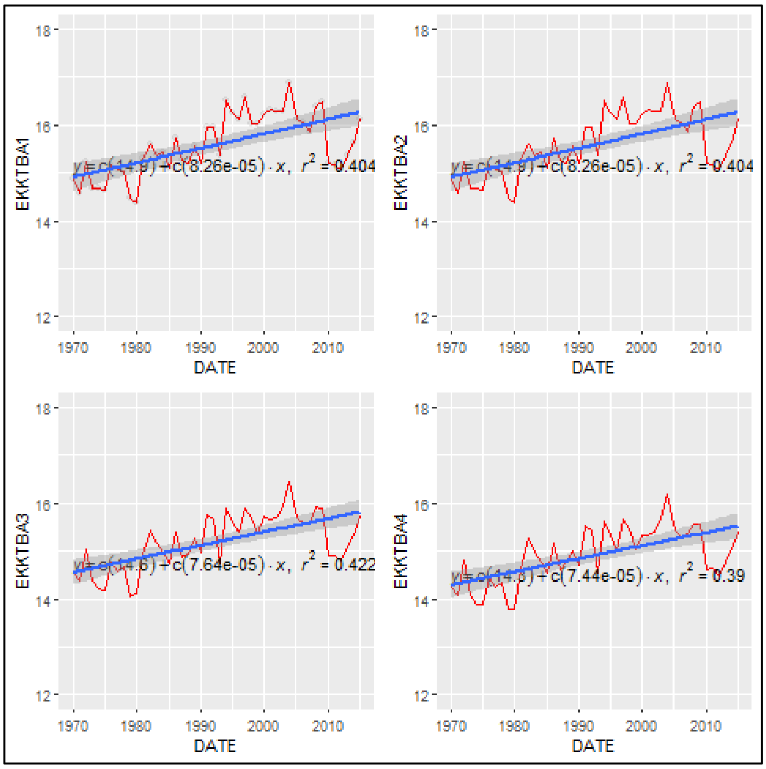

Figure 4.9: CRU minimum temperature trends (Botswana)

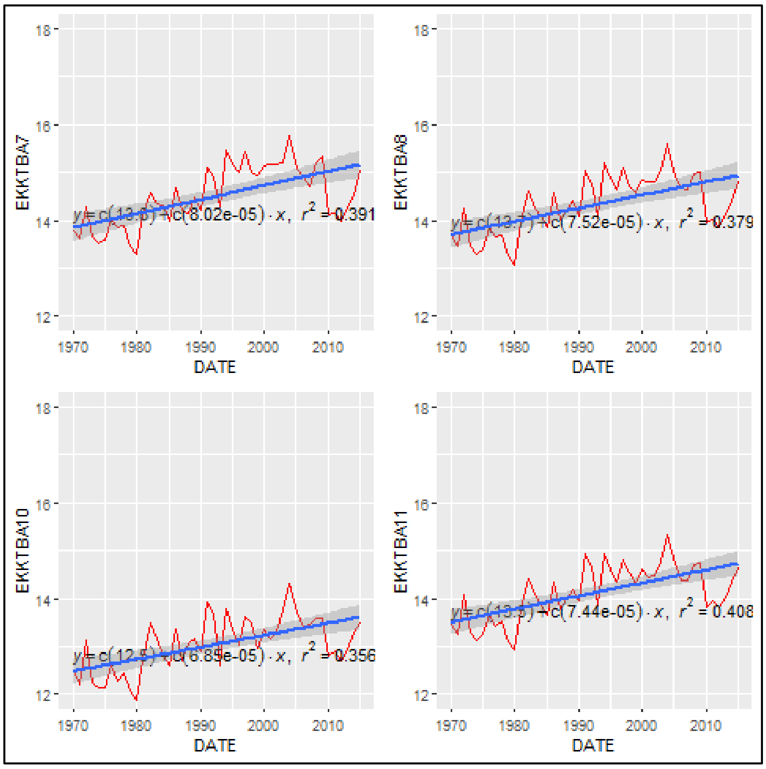

Figure 4.10: CRU minimum temperature trends (Zimbabwe)

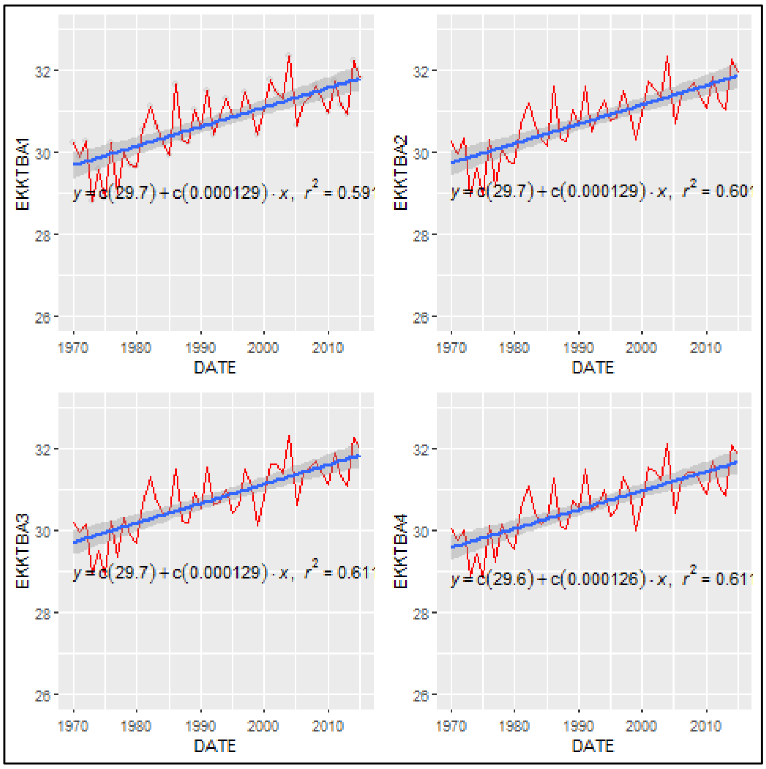

Figure 4.11: CRU maximum temperature trends (Botswana)

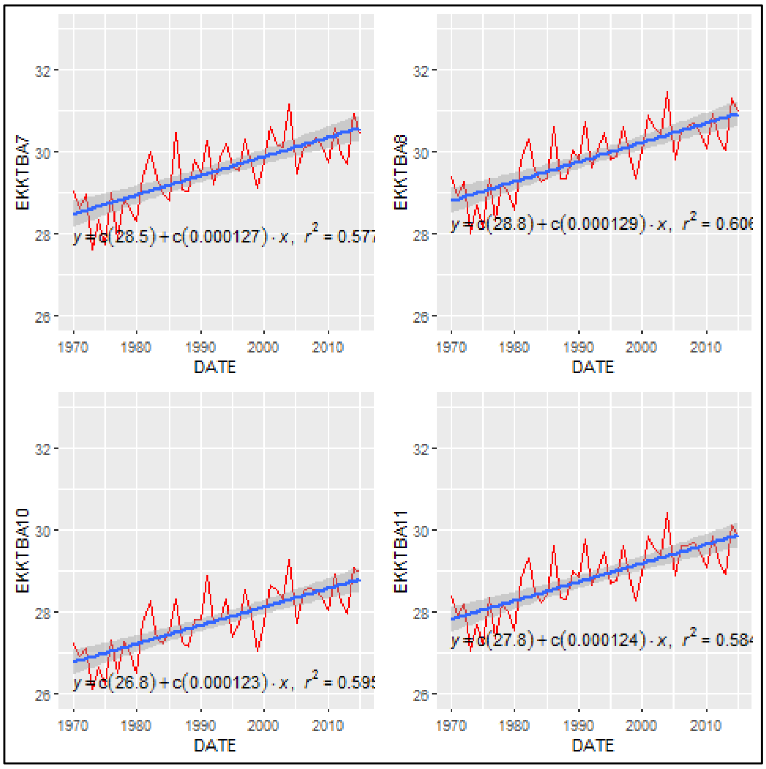

Figure 4.12: CRU maximum temperature trends (Zimbabwe)

4.3.2.3. Spatial maximum temperature

Maximum temperatures from the CRU stations (Figure 4.13) show that the temperatures are higher in Botswana compared to Zimbabwe, with the north-western part of the EKK-TBA displaying high temperatures of more than 30 °C. This spatial trend was also observed for mimimum temperatures.

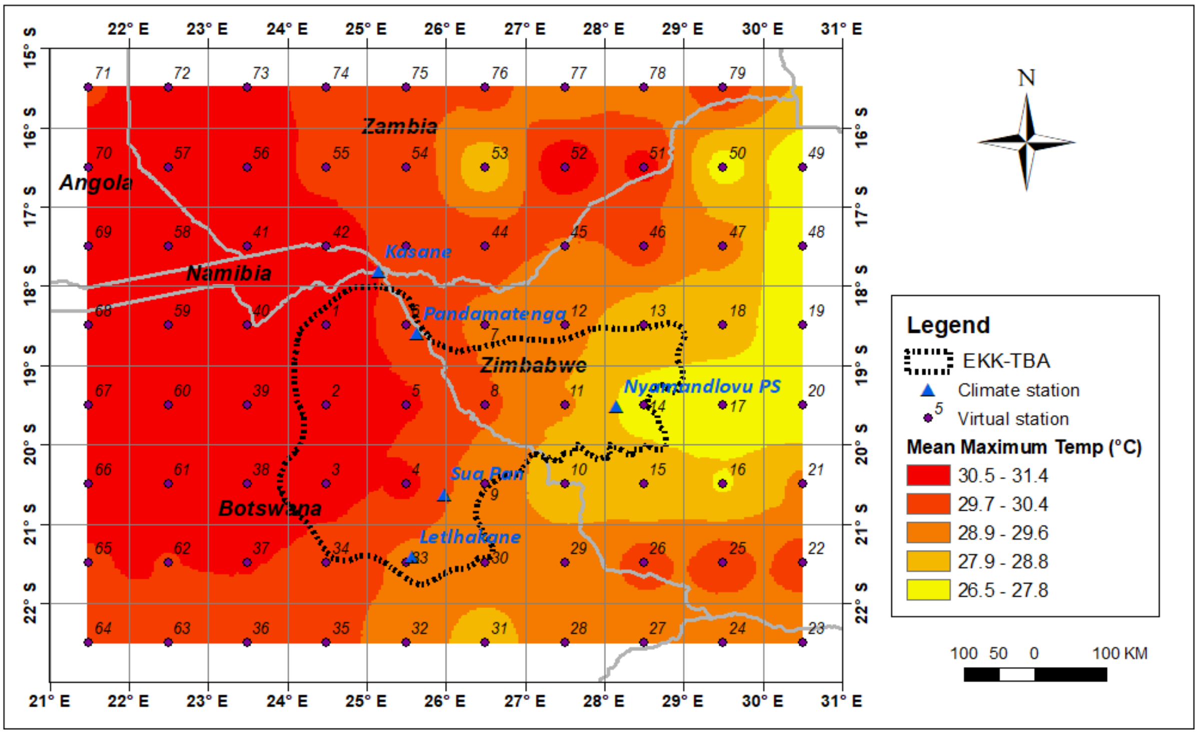

Figure 4.13: Mean monthly maximum temperatures derived from the CRU data

4.4. Evapotranspiration

Evapotranspiration (ET) is a combination of water losses from the soil surface and open water bodies (evaporation) and losses through plants (transpiration), and this accounts for water losses from water resources (particularly reservoirs and shallow aquifers). This is more critical in the wake of climate change where temperature is expected to rise, potentially leading to increased evapotranspiration. However, evapotranspiration is difficult to quantify because of several atmospheric parameters to be included in its computation are difficult to measure (see equation 4.1). As such, evapotranspiration data is often not readily available from meteorological agencies. For this reason, there are several estimation methods used in the literature. The method that is widely documented and used is the FAO-56 Penman Monteith (FAO-56PM) by Allen et al. (1998). This method was used in this report since no data was available in the EKK-TBA. The main data required for its computation are daily minimum and maximum temperatures. The standardised reference ET equation (4.1) is as follows:

$$ET_z = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (4.1)$$

Where ET_z is the standardised reference ET (mm/day); R_n is net radiation at the crop surface (MJ/m^2/day); Δ is the slope of the saturation vapour pressure (KPa/°C); G is soil heat flux density (MJ/m^2/day) which is usually considered negligible for computation of daily values; T is mean daily air temperature (i.e. an average of daily minimum and maximum temperature) in °C; u_2 is wind speed at 2m height (m/s); e_s is saturation vapor pressure (kPa); e_a is actual vapour pressure (kPa); γ is psychometric constant (0.0677 kPa/°C); C_d is the denominator constant for the reference crop type and time step; and C_n is the numerator constant for the reference crop type and time step.

For a short crop (similar to cut grass), ET_z is equal to the reference ET_o, and is reduced to the following equation (4.2):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{100}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (4.2)$$

For further reading, and computation of all data required for estimating ET_o, the reader is referred to the step-by-step calculation procedure proposed by the FAO (Allen et al., 1998; Zotarelli et al., 2010).

ET was computed using data from the Letlhakane climate station and CRU dataset at the same location, as well as from the surrounding catchments (Nata and Boteti catchments). This was done to provide some form of validation of PE values in the area. The results (monthly and annual ET[24]) are plotted in Figure 4.14. The annual time series for the period under consideration does not provide any clear picture on the direction of trends.

4.4.1. Seasonal variation of evapotranspiration

Monthly evapotranspiration (ET) is shown in Table 4.9 and Figure 4.15. From Figure 4.15 and Table 4.9, it can be seen that monthly ET values from Botswana are generally higher than those for Zimbabwe. It is also evident from these plots that October has the highest ET values while June has the lowest. The annual ET values for Letlhakane station in Botswana is 1 751 mm while the annual ET on the Zimbabwean side of the EKK-TBA is 1 465 mm, Table 4.9. The ET estimated using CRU data at Letlhakane is generally lower than the observed values, and has an annual total ET of 1 656 mm.

[24] The low Monthly ETo in the plot for the years 2012-2013 is a result of extended period of missing values (for the months of Jan-Feb in 2012, July 2012 and Jan 2013)

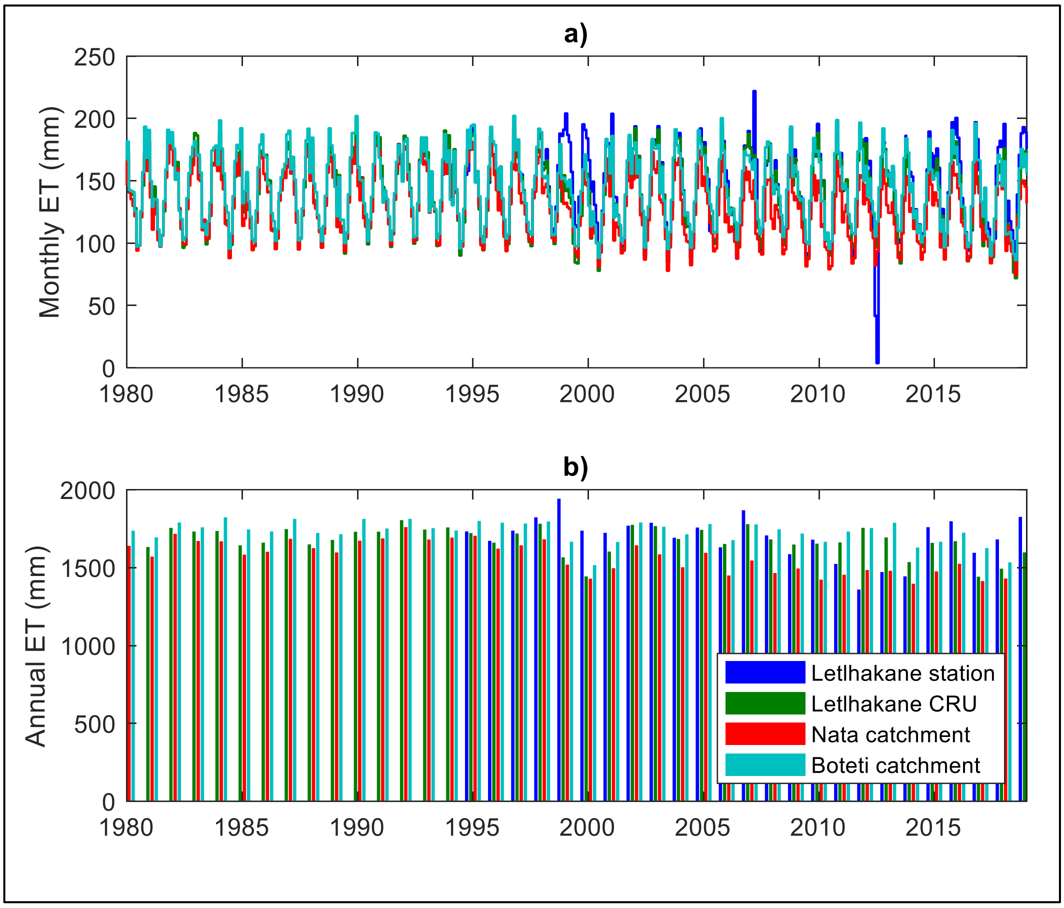

Figure 4.14: Obs and simulated ET at Letlhakane station and Nata and Boteti Catchments

Table 4.9: 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**

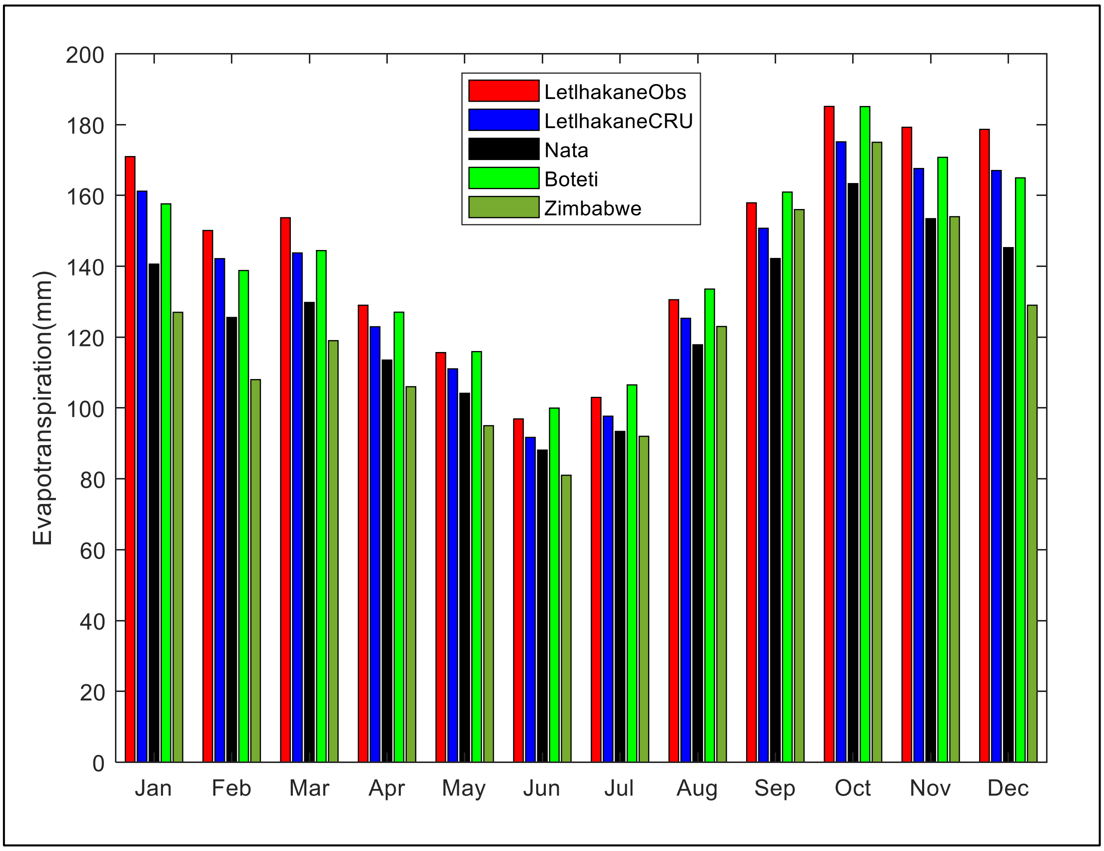

Figure 4.15: Monthly evapotranspiration in the EKK-TBA

4.5. Trends related to climate variability and change

One of the ways in which change in total water storage (surface and groundwater) is evaluated over large basins such as the EKK-TBA is through the use of alternative techniques such as the Gravity Recovery and Climate Experiment (GRACE) satellite data. GRACE was launched by NASA in 2002 and is the first satellite mission able to provide insights into the global observations of changes in total water storage (ΔTWS) by making use of gravity anomalies as proxy for change in water storage (Richey et al. 2015; Chen et al. 2016). Full details about GRACE and its applications at regional and transboundary aquifer scales can be found at https://grace.jpl.nasa.gov/mission/grace/, (Gurdak et al., 2007; Carvalho-Resende et al., 2019; Thomas and Famiglietti, 2019).

Through a series of processing steps, the gravity anomaly measured by GRACE satellite is converted into a monthly Terrestrial Water Storage Anomaly (TWSA) which is the sum of the water masses that are contained in the terrestrial water column i.e. surface water, soil moisture, groundwater and snow in case of colder climates. The challenge is to vertically disaggregate the GRACE data to isolate the individual components using auxiliary information or assimilating into a land surface model so as to derive the change in groundwater storage and to evaluate the potential of impacts of climate change on the water resources. This is even more challenging where long term observed data such as groundwater levels are not available to validate GRACE data. Where such data is available, and coupled with water balance models, large scale climate indices such as El Nino Southern Oscillation (ENSO), GRACE data can be used to provide insights into the dynamics of climate change and its effects on total water storage (Carvalho-Resende et al., 2019).

In this section, GRACE data covering the extent of the EKK-TBA was extracted from the GRACE plotter website (http://thegraceplotter.com/). Equivalent water heights (EWH) data was extracted from 2002 to 2016 (current end limit of GRACE data) and is a proxy for change in total water storage at the scale of the EKK-TBA. As seen from Figure 4.16, the EWH shows a declining trend, with a volumetric loss of about 0.25 cm/year. The declining trend is consistent with climatic trends reported in the previous sections. No attempt was made to validate the GRACE data due to lack of long term groundwater levels in the EKK-TBA, and therefore the GRACE results in Figure 4.16 should only be viewed as demonstration of the applicability of the technique.

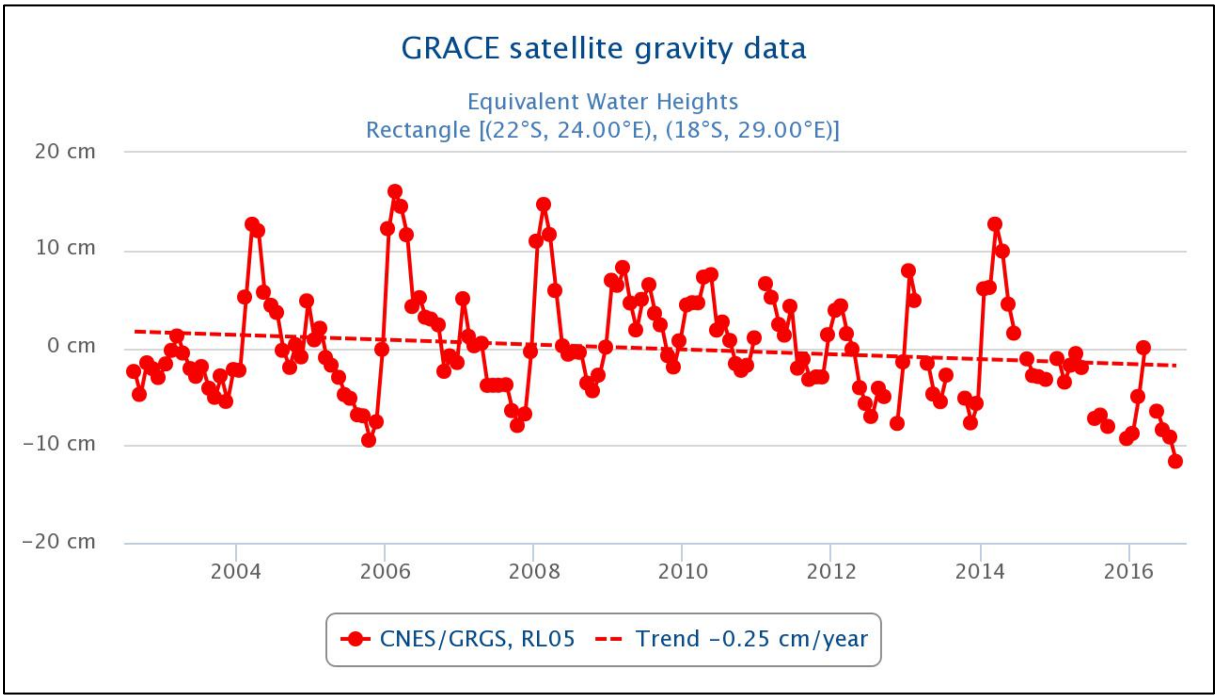

Figure 4.16: GRACE data extracted for the EKK-TBA
Source: http://thegraceplotter.com/

4.6. Key Messages

- Access to climate data is a challenge particularly from the Zimbabwean side of the EKK-TBA. Where climate data for both countries is available, the quality of data is not good, i.e. there are extended periods of missing daily values (up to 3 months in some cases). Other issues are questionable values within the datasets. These issues need to be resolved through proper data quality control systems. Accessibility to data should also be addressed since good technical inferences can only be achieved when adequate data is made available.
- The EKK-TBA is also affected by climate variability and change, in that the temperature seems to be increasing. Although rainfall trends are not significant, there is the potential for decreased rainfall. The decline in rainfall series, high interannual rainfall variability as well as increasing temperature trends in the EKK-TBA is consistent with studies conducted in Botswana (Byakatonda et al., 2018) and Zimbabwe (Mazvimavi, 2010). These trends likely impact the availability of water resources, particularly surface water and shallow groundwater. Hence the urgent need to establish resilient and adaptation strategies that combat the effects of climate variability and change.

5. SURFACE WATER

5.1. Surface water drainage

The EKK-TBA covers part of the Okavango and Zambezi River Basins and is neighbouring the the Limpopo River Basin on the south-eastern side (Figure 5.1). The Okavango River starts from the highlands of Angola and flows through Namibia and terminates in the Okavango Delta in Botswana. The Zambezi River flows from Angola through Botswana, Zambia, Zimbabwe, Malawi and 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 5.1). Similarly, on the eastern side, the Nata River, which originates from Zimbabwe, flows into the Makgadikgadi Pans. The Gwayi River in Zimbabwe in the eastern part of the EKK-TBA, with the Khami and Umguza Rivers as tributaries in its upper reaches, flows north-west towards the Zambezi River. The Okavango and Zambezi River basins are both key in the management of water resources in the EKK-TBA.

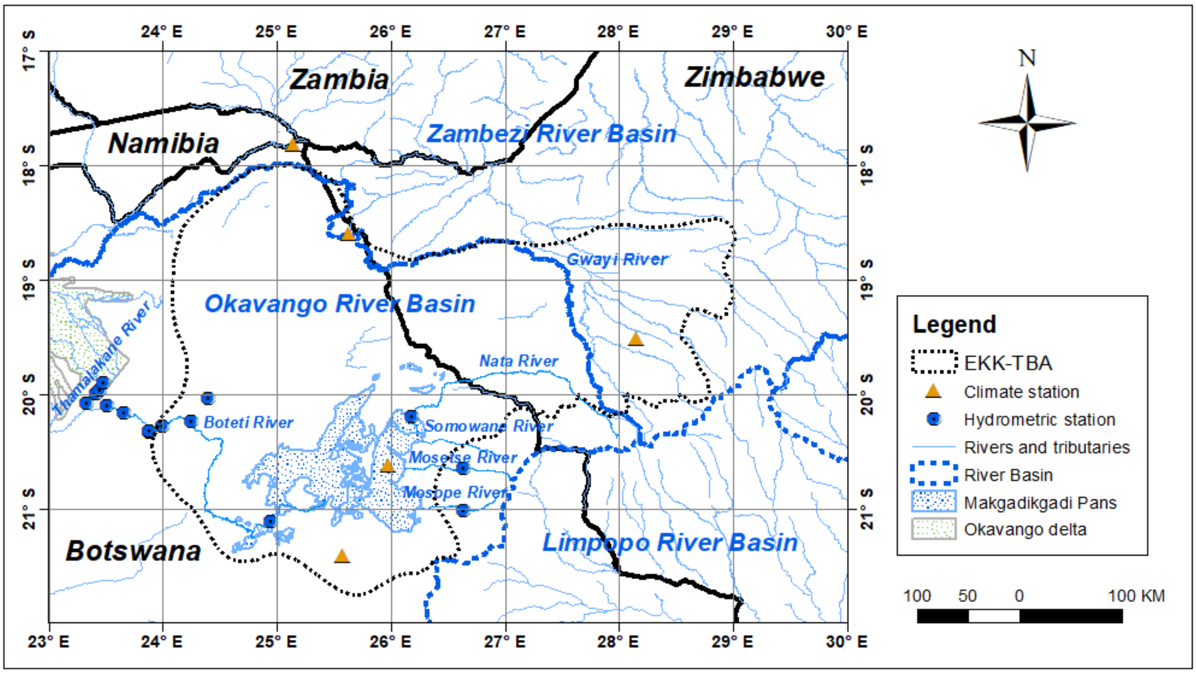

Figure 5.1: Surface water drainage in the EKK-TBA

5.1.1. Nata River

The Nata River, an ephemeral river, with flows only produced between December and March (Table 5.1) 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). Makgadikgadi being an important tourism ecosystem, requires environmental flow releases to maintain a healthy ecosystem in the pans and due to the generally flat topography, the Nata River has been considered not feasible for any major water resource in Botswana (DWA, 2006; MLWS and MLIT, 2018). The only realistic development of the river is an off-river storage system or can be developed for artificial recharge to aquifers.

As one of the major sand rivers in Botswana, the depth of sand exceeds 7 m in many sections along the Nata River channel. 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 (DSM, 2000).

Table 5.1: Monthly streamflow of Botswana's EKK-TBA rivers

Runoff	River	Nata River	Boteti River	Thamalakane River
	Station	**Nata Old Bridge**	**Samedupe**	**Maun Bridge**
Average Monthly Runoff (m^3/s)	Jan	26.3	2.2	2.2
	Feb	20.3	2.1	2.5
	Mar	8.7	2.1	5
	Apr	1.4	2.7	6.4
	May	0.1	3.4	8
	Jun	0	6.7	11
	Jul	0	13.3	14.5
	Aug	0	16.5	14.9
	Sep	0	14.1	12.5
	Oct	0	10.1	8.7
	Nov	0.02	6	5.9
	Dec	3.7	3.7	3.3
Average Annual Runoff	**m^3/s**	**5.0**	**6.9**	**7.9**
	Mm^3	**158.7**	**217.9**	**249.4**

5.1.2. Thamalakane River

The Thamalakane River (Figure 5.1) receives its flows from the Okavango River, and flows along the Thamalakane Fault in a south-westerly 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 normally occurring in between July and August (Table 5.1) 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 5.2 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.

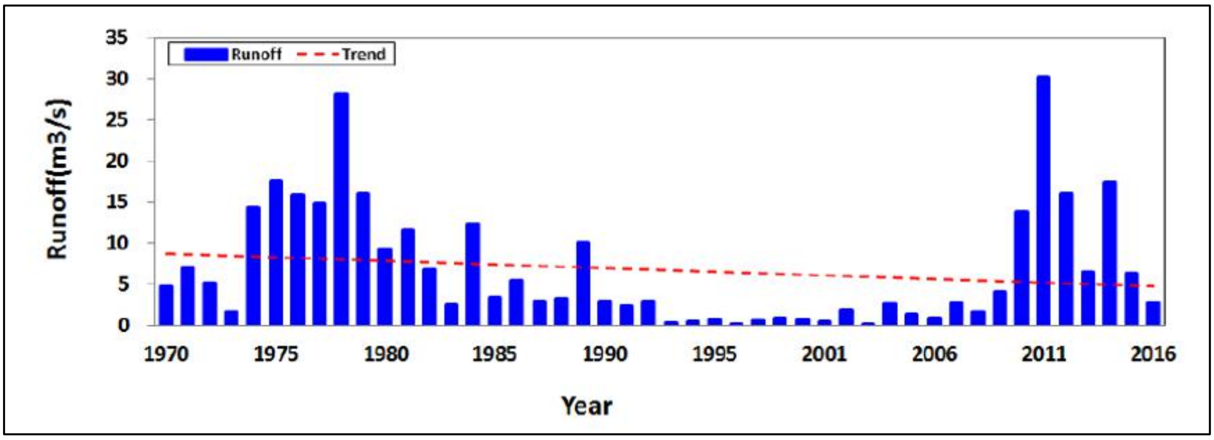

Figure 5.2: Flow of the Thamalakane River

Source: (MLWS)-Botswana and (MLIT) Korea (2018)

5.1.3. Boteti River

The Boteti River 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 obtained in August (Table 5.1). The Boteti River has many gauging stations (about 10) compared to any other river in the EKK-TBA as shown in Figure 5.1. Most stations, however, have incomplete data. Figure 5.3 also shows a weak declining trend in runoff between 1970 and 2016 for the Boteti River as well as the distinct wet and dry periods, with the latter running from 1993 to 2008.

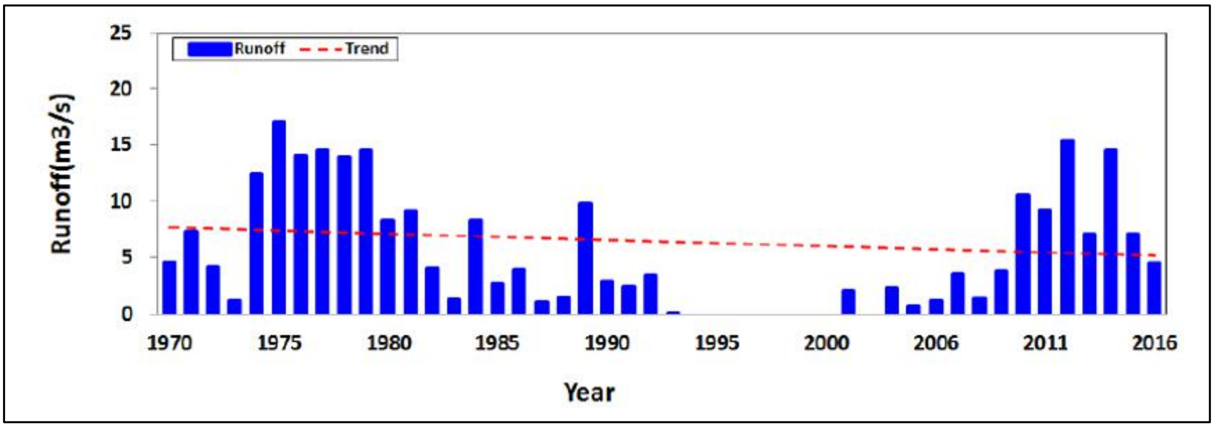

Figure 5.3: Flow of the Boteti River

Source: National Water Master Plan Update (2018)

In 2010, the Boteti River flowed after some 20 years of no flow and the flow was captured by NASA[25] on 29th September 2010 as a historical newsworthy event (Figure 5.4). Note that the river stopped short of Makgadikgadi pans, which lies to the east in the image.

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[25] https://earthobservatory.nasa.gov/images/46309/boteti-river-botswana#:~:text=Starting%20in%20the%20late%201990s,again%20flowed%20through%20this%20riverbed.&text=Arising%20from%20overflow%20in%20the,expansive%20salt%20pans%20of%20Makgadikgadi.

Figure 5.4: Boteti River flow as captured by NASA in September 2010
Source: NASA[23]

5.1.4. Gwayi River system

The Gwayi Catchment in Zimbabwe has 25 sub-zones including the Nyamandlovu area and constitutes hydrological zone A (Figure 5.5). The catchment covers an area of 87 960 km^2 (ZINWA, 2020[26]) and has an altitude ranging from 600 to 1500m. The Gwayi River system, which flows through the EKK-TBA in the east, drains into the Zambezi River. Note that the Nata (Manzamnyama) River in the south provides a link between Zimbabwe and Botswana river systems. The mean annual runoff for the Gwayi Catchment ranges between 4 and 36 mm (mostly between 4 and 10 mm within the EKK-TBA) as shown in Figure 5.5, and occurs between November and May, with the peak flow occurring in January. Compared to other catchments in Zimbabwe, the Gwayi Catchment has the lowest runoff of about 1.8×10^6 Ml/year and this is projected to significantly decrease by 2050 due to climate change (Davis and Hirji, 2014).

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

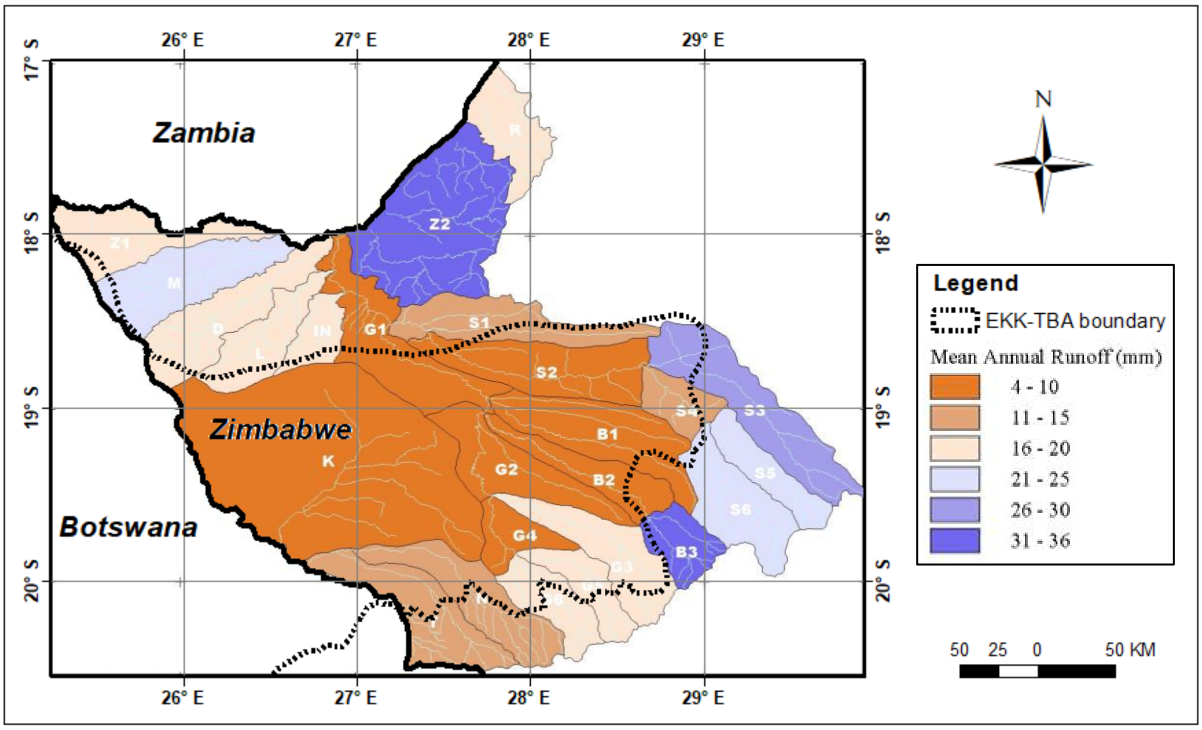


Figure 5.5: Mean annual runoff of sub-zones of the Gwayi Catchment

Source: modified after ZINWA (2020)

5.2. The Makgadikgadi Pans

The Makgadigkadi Pans (Figure 5.1 and Figure 5.6) are among the largest salt pans in the world, and are important destinations for Botswana's tourism sector. The Pans are in part oriented along a Tertiary graben of the Pan African rift and occupy the lowest point (890 m amsl) in the Kalahari semi-desert, which in the past received water from the proto Zambezi resulting in a significant inland lake (Cooke, 1980) of around 66 000 km^2. They are located in the south-east of the Okavango Delta and south of the Chobe River front (DEA and CEAR, 2010). The surface water catchment area of the Makgadikgadi Pans extends into Zimbabwe in the east and north through the Nata River system. It is also linked to the Okavango system on the north-western side through the Boteti River. The 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) and the Mosetse (1 500 km^2), Semowane (1 500 km^2), and Mosupe (3 000 km^2) Rivers in the east of the Makgadikgadi drainage system. 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 which is the western half of the Makgadikgadi (4 700 km^2) is linked to an overflow from the Okavango Delta via the Boteti River.

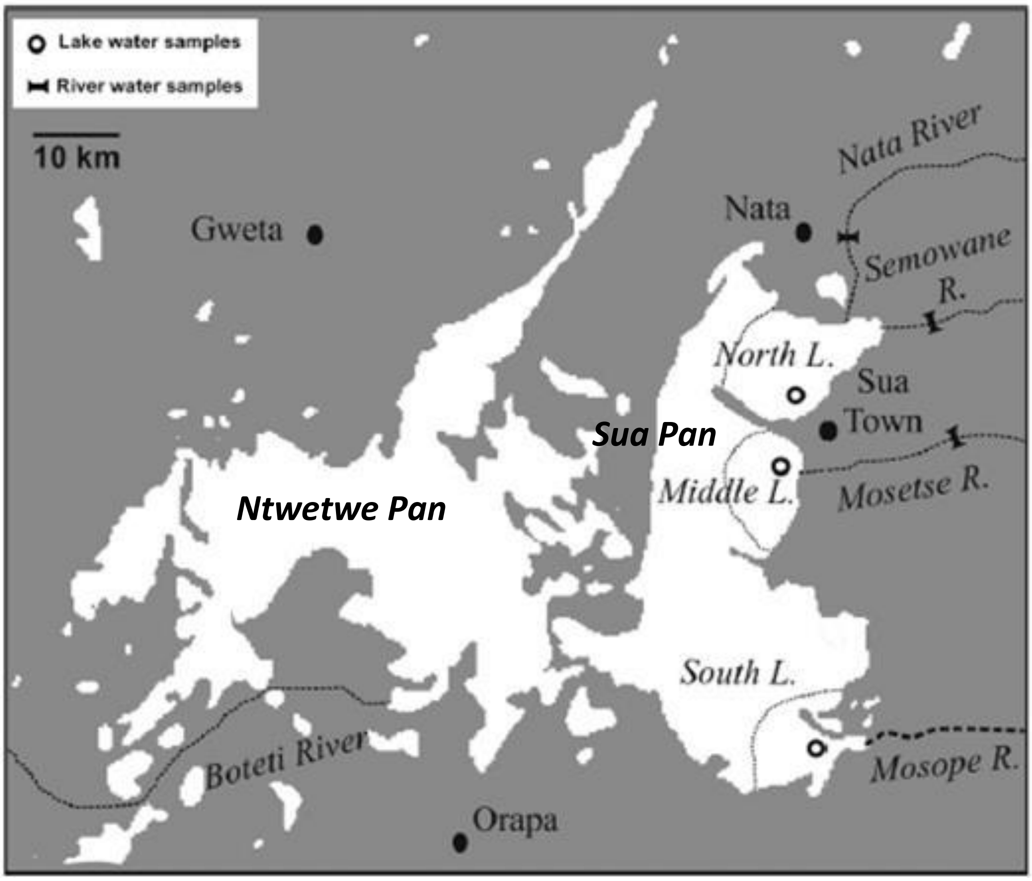


Figure 5.6: Boteti River and Nata River system draining into the Makgadikgadi Pans
Source: Eckardt et al. (2008)

5.3. Surface water quality

Land use may play a role in determining the quality of surface water in the area (Chapter 8). 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 and groundwater pollution. Concentration of livestock in pans during wet periods has led to increased nitrates 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.

5.3.1. Water quality in 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 5.6). 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 north basin of Sua Pan and aims to expand southward of their current well field (DEA and CAR, 2010).

The Boteti River discharges into the Ntwetwe Pan while Nata River, Semowane, Mosetse and Mosope Rivers discharge into the Sua Pan. Water in the proximity of pans 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, 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 bedrock driven (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.

Calcium and magnesium contribute to calcite and dolomite precipitation in the lake pan environment. The deep-seated brine which is spatially homogenous in the Sua Pan is pumped by BotAsh (Botswana Ash (Pty) Ltd.[27]) 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.

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

5.3.2. Water quality of the Thamalakane and Boteti Rivers

Table 5.2 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 river channel, and were mostly carried out monthly, with the longest period between subsequent tests being four months (*ibid*). A solution is considered acidic when the pH is below 5.6 and alkaline when 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 River channel (*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 out 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 5.2: pH of Thamalakane-Boteti River Channel surface water: 2009-2013

Date	No. of stations tested	No. below 6.5	No. above 8.4	% below 6.5	% above 8.4	Date	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) [28]

Table 5.3 shows that all except one of other parameter tests carried out recorded within the standards. Only Manganese (Mn) showed a level beyond the guideline in one of the 29 tests.

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

Table 5.3: 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)

5.3.3. 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 has not yet shown any major problems as they were all below the World Health Organisation (WHO) guidelines for drinking water (Murwira et al., 2014).

5.4. Groundwater-surface water interactions

Groundwater-surface water (GW–SW) interactions in wetlands are mostly controlled by factors such as differences in head between the wetland (or river) surface water and groundwater (or aquifer), the local geology and geomorphology of the wetland (in particular, the texture and chemistry of the wetland bed and banks), and the wetland and groundwater flow geometry (Jolly et al., 2008). The GW–SW regime can be broadly classified into three types of flow regimes: (i) recharge—wetland loses surface water to the underlying aquifer; (ii) discharge—wetland gains water from the underlying aquifer; or (iii) flow-through—wetland gains water from the groundwater in some locations and loses it in others (*ibid*). However, it is important to note that individual wetlands may temporally change from one type to another depending on the geometry and configuration of the aquifer, how the surface water levels in the wetland and groundwater levels change over time in response to climate, land use, and management (Barthel and Banzhaf, 2016).

5.4.1. Methods of evaluating GW-SW interactions

In general, there are three categories of methods used to evaluate GW-SW interactions:

1. Statistical methods relating to groundwater levels and river flows
2. Geohydrochemical (environmental isotopes, physico-chemical parameters)
3. Numerical and integrated models

Statistical methods: This involves using measured variables such as long term groundwater levels and stream flows to establish spatial and temporal (seasonal) variability of groundwater and surface water relationships in response to river flows, or groundwater flows (mainly from baseflow - the component of streamflow that can be attributed to groundwater discharge into streams) (Nathan and McMahon, 1990; Brodie and Hostetler, 2005; Newman et al., 2006). Determination of baseflow is usually undertaken to identify and quantify the contribution of groundwater to the river, and one of the methods widely used is the recursive digital filter method introduced by Nathan and McMahon (1990), and applied in many studies in southern Africa (Ebrahim and Villholth, 2016; Ebrahim et al., 2019).

Geohydrochemical methods: These methods include studying relationships between groundwater and surface water sources using environmental isotopes (such as stable isotopes), physicochemical parameters to deduce if there is any similarity (interactions) between groundwater and surface water (Kumar et al., 2008).

Numerical distributed methods: These methods are used to quantify fluxes resulting from interactions between groundwater and surface water (El-Zehairy et al., 2018; Lekula et al., 2018; Mitiku, 2019).

5.4.2. GW-SW interactions in the EKK-TBA

Recently, Mitiku (2019) investigated GW-SW interactions in the Boteti River system 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 groundwater and the river throughout the simulation period. The total loss of water from the Boteti River to the shallow Kalahari Aquifer system throughout the two hydrological years of 2016 and 2017 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 GW-SW interactions in the Boteti River area were found to be dependent on inflows from the Okavango Delta system.

Another study by Eckardt et al. (2008) investigated the possibility of surface water and groundwater (brine) linkages in the Sua Pan using Strontium isotopes ($^{87}Sr/^{86}Sr$). They established that the Nata River is the main source of lake water at Sua Pan and they also found that the Nata River (and Mosetse, Semowane and North lake in Sua Pan) is not connected to the underlying brine (Eckardt et al., 2008).

Baseflow separation was undertaken for one of the Boteti flow stations which had reasonable streamflow data (Samedupe Flow Station). The baseflow separation was done using the Nathan and McMahon method (1990) as applied by Ebrahim et al. (2019), and the results are plotted in Figure 5.7. A baseflow index (BFI) was determined as the ratio of baseflow over the total streamflow (Smakhtin, 2001) and was established to be 0.305 (or 30.5%). This indicates that baseflow accounts for about 31% of the total river flow in the Boteti River, supporting the findings of Mitiku (2019), that there is indeed GW-SW 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.

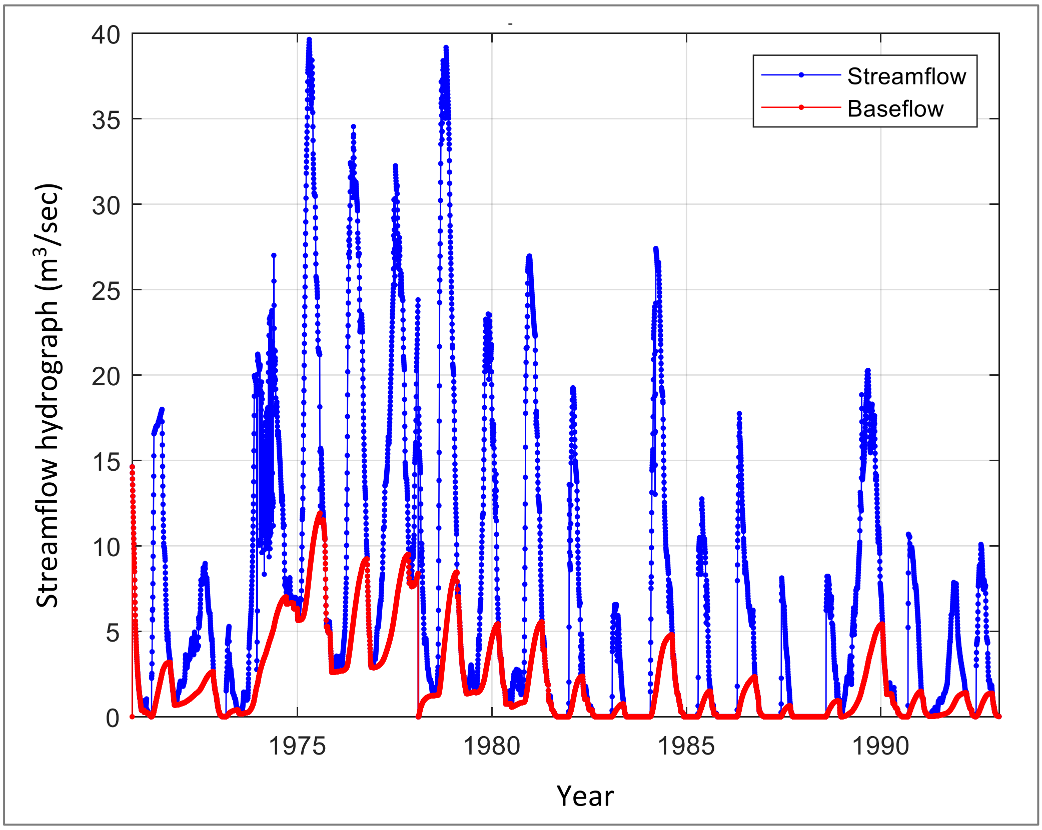


Figure 5.7: Baseflow separation for Boteti River flow at Samedupe Station

5.5. Key Messages

- The EKK-TBA falls within two river basins: the Okavango River Basin and the Zambezi River Basin. There is thus cause for joint management of the EKK-TBA by the two river basin organisations (see also Chapter 9)
- Data quality in terms of its, inter alia, accuracy, gaps and accessibility, is a major issue that need addressing.
- Despite gaps in river flow data, a baseflow index for the Boteti River could be determined whose results indicated evidence of groundwater-surface water interaction. This has also been noted in previous studies.

6. GROUNDWATER

This chapter presents an overview of the hydrogeology of the Eastern Kalahari Karoo Basin Transboundary Aquifer (EKK-TBA) system, with particular focus on the areal extent of the multi-layered aquifer system, nature of the layering, groundwater availability, flow direction, groundwater use and quality. The chapter has been developed based on primary and secondary data obtained from Botswana and Zimbabwe. The EKK-TBA data and information provided by both countries is sparse, especially in the central part of the EKK-TBA. Most data and information were not collected during groundwater development (geophysical investigations, borehole construction and pumping test) which presents huge data gaps. There is also inadequate to no monitoring data on abstractions, groundwater level fluctuations and groundwater quality. Regardless of the challenges expended by the data and information paucity, the chapter presents informative findings that assist in the understanding of the hydrogeology of the transboundary aquifer system as a whole. The chapter is cleaved into various sections that include the Geology, Hydrogeology, regional groundwater flow, groundwater recharge, groundwater quality, groundwater availability, groundwater quality and EKK-TBA wellfields.

6.1. General geology of the Kalahari-Karoo Basin

6.1.1. 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 cover of about 4.5 million km^2 and had 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. Figure 6.1 shows the distribution of Karoo aged basins in southern Africa.

Tectonics led to the formation of the basins into which sediments were deposited during the formation and breakup of Pangea (Catuneanu et al., 2005). The sediments 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 and were deposited in an epeirogenic basin during the rising of the marginal mountains of the Great Escarpment of southern Africa (Johnson et al., 2006). The surficial geological formations within the EKK-TBA are represented in Figure 6.2.

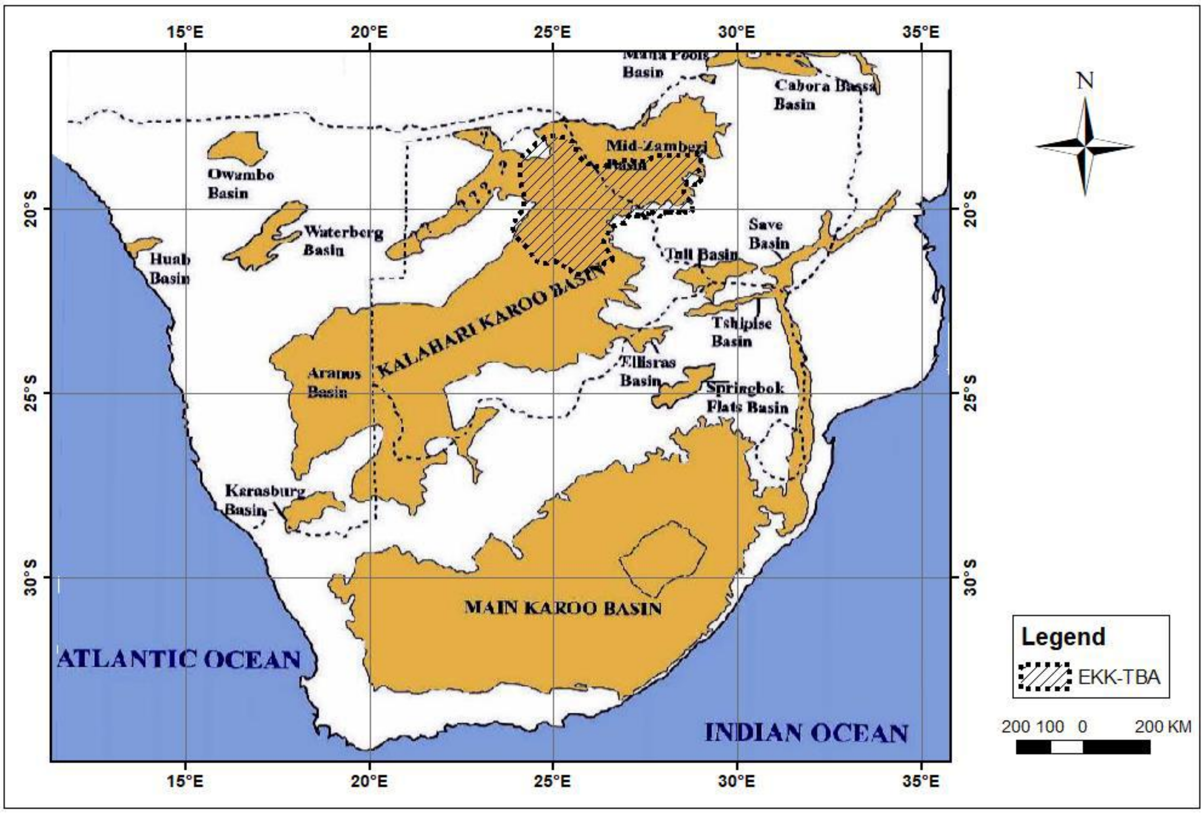


Figure 6.1: Distribution of Karoo-aged basins in southern Africa
Source: modified after Johnson et al. (1996)

6.1.2. Lithostratigraphy

The Karoo Supergroup comprises the most prevalent lithostratigraphic unit in southern Africa and consists mainly 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 (mostly tillite turbidites and shale), deltaic (shale, mudstone), fluvial (sandstone, siltstone, mudstone) and aeolian (sandstone) (*ibid*). The sediments originated from the erosion of the surrounding higher ground into the tectonically formed basins and were eventually capped by basaltic lava flows. The sequence can be classified stratigraphically into the following groups or systems: (i) Dwyka Group, (ii) Ecca Group, (iii) Beaufort Group and (iv) Stormberg Group. These groups can further be clustered into two main units, the Lower Karoo and Upper Karoo. For completeness and general overview purposes, a correlation of the lithostratigraphic units of the Aranos Basin stretching from northwestern South Africa into southeastern Namibia, the main Kalahari-Karoo Basin (NE, Central and SW) in Botswana and the Mid Zambezi Basin in Zimbabwe is shown in Figure 6.3. 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 an assumption 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 6.4 presents a pre-Kalahari map showing the areal extent of the Karoo Supergroup formations.

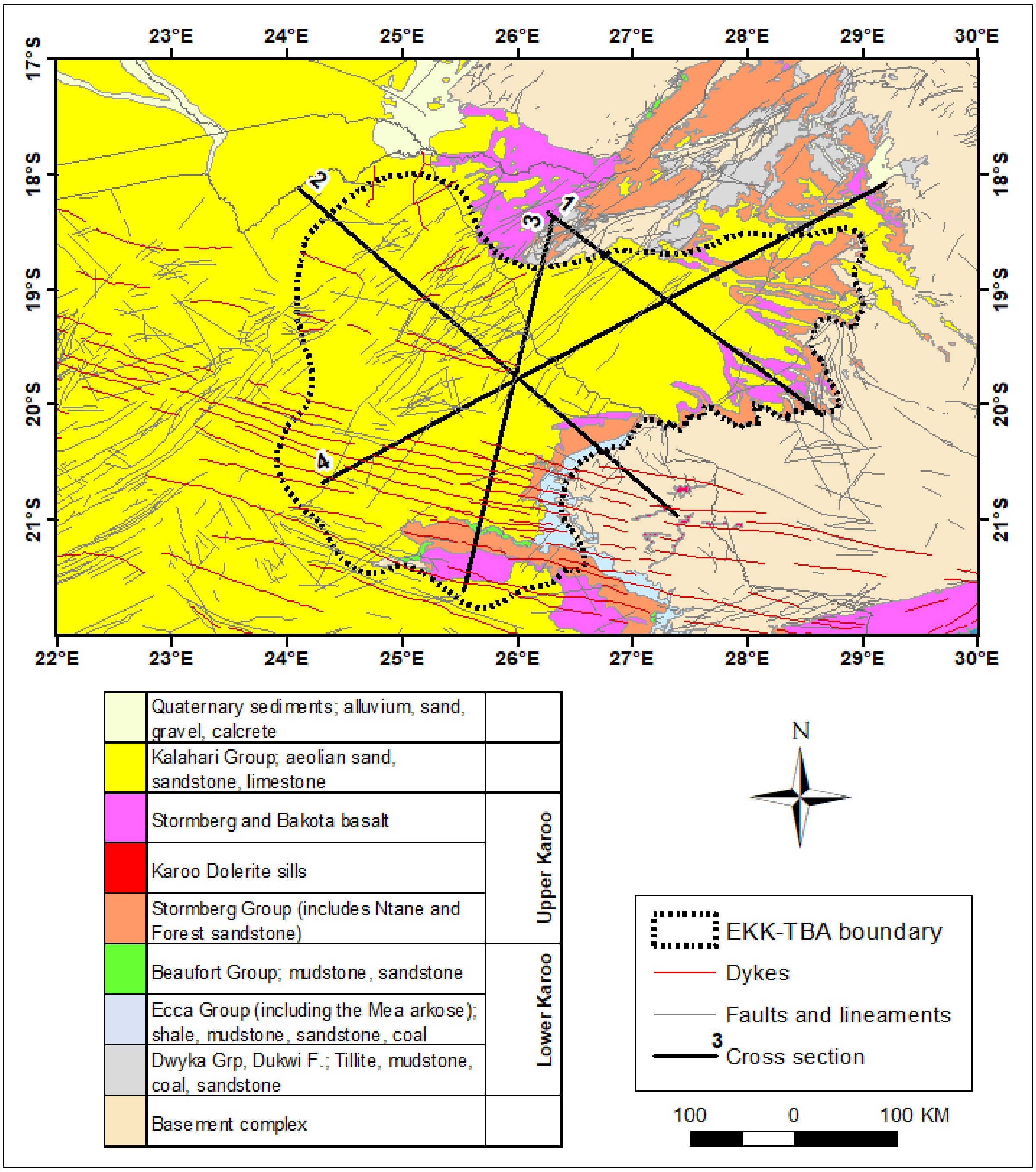


Figure 6.2: Geology of the EKK-TBA and surroundings

Source: modified after Council for Geoscience (2009)

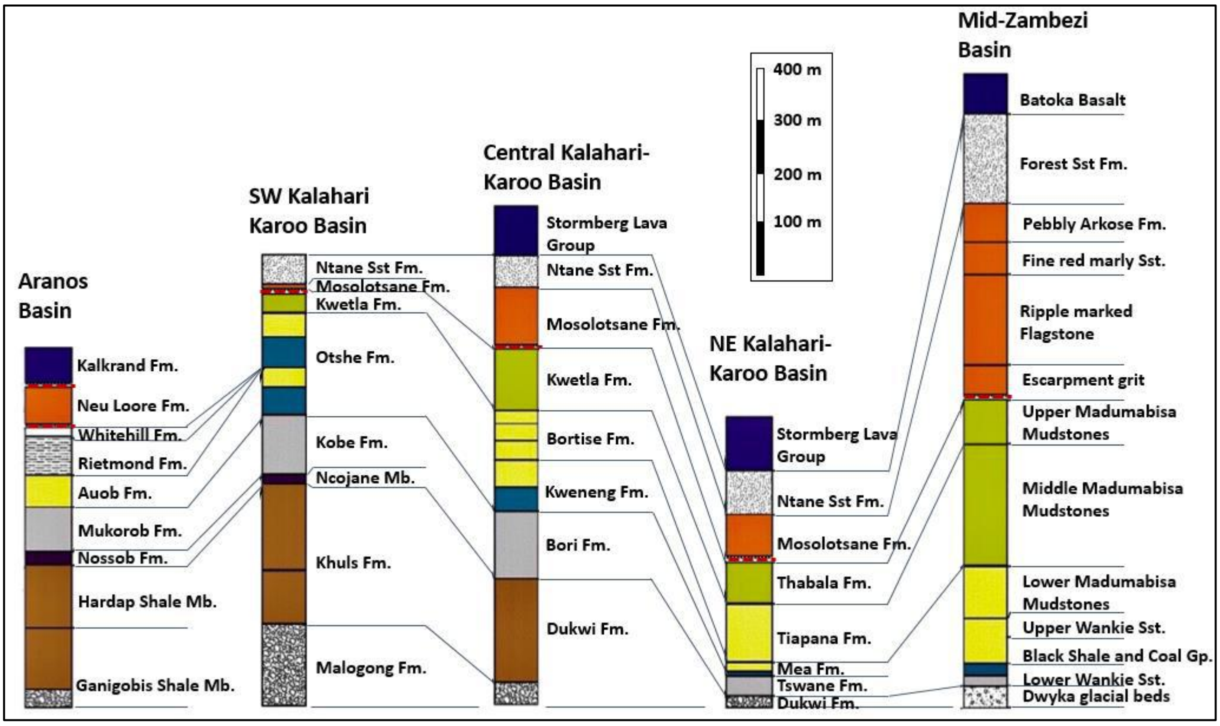


Figure 6.3: Correlation of Karoo Supergroup lithostratigraphic units
Source: modified after Catuneanu et al. (2005)

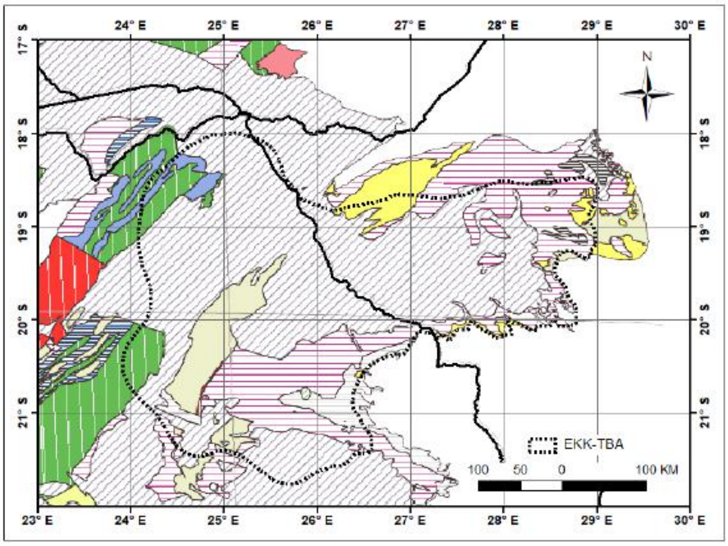


Figure 6.4: Pre-Kalahari Supergroup Formations
Source: modified after Council for Geoscience (2009)

A simplified geological cross section cutting through the central portion of the EKK-TBA from Botswana to Zimbabwe (cross section no. 3, see Figure 6.2) is shown in Figure 6.5 and depicts a general horst and graben morpho-tectonic style, the horsts corresponding to the basement complexes - highlands and the grabens to the Karoo sedimentary basins.

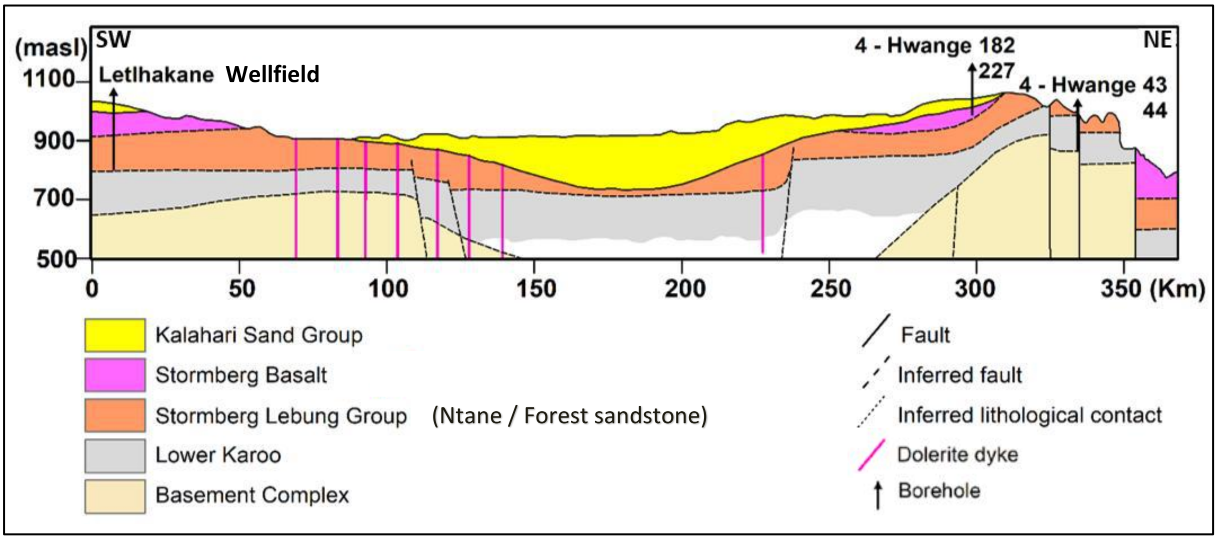


Figure 6.5: Simplified geological cross section 3

6.1.3. Structural Geology

Dominantly SW-NE trending normal faults, and less dominant NW-SE faults as well as NW-SE trending dykes are shown in Figure 6.2 and Figure 6.5. The faults have resulted in block faulting and compartmentalisation of the formations which has had an effect on the groundwater dynamics and the groundwater quality. Figure 6.6 shows a fence diagram with simplified geological cross-sections cutting through the EKK-TBA.

6.2. Hydrostratigraphy

There is general hydrogeological data paucity within the EKK-TBA in both countries. The dearth of data and information is 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. 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 Sand aquifer.

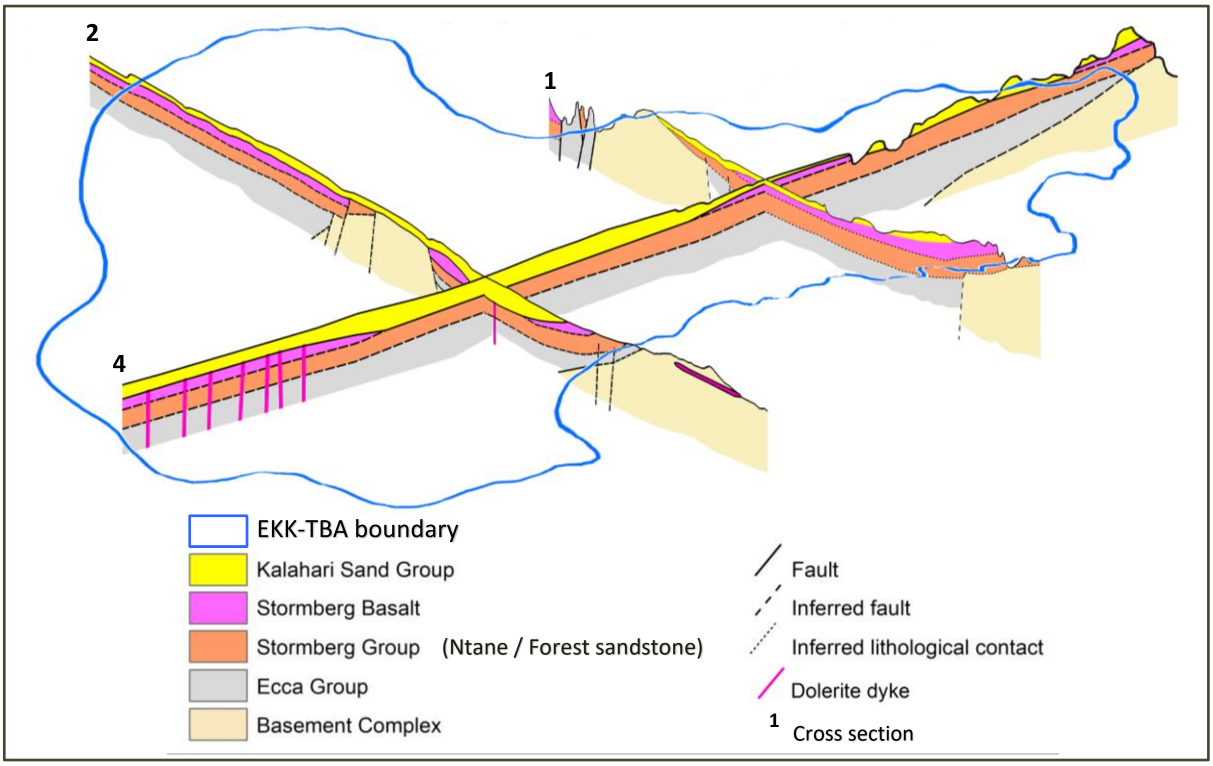


Figure 6.6: Fence diagram EKK-TBA with simplified geological cross-sections

The main hydrogeological information on the Zimbabwean side is from the Nyamandlovu Wellfield) (section 6.7.1.4), 45 km NW of the City of Bulawayo (the second largest city of Zimbabwe), which lies on the eastern fringes of the EKK-TBA where the 'aquiferous' unit of the Karoo sediments (Forest Sandstone) is developed. On the Botswana side, the information is mostly from the Public (Dukwi, Chidumela, Letlhakane and Maitengwe) and Private (OLD Diamond Mines) Wellfields (sections 6.7.1 and 6.7.2). The aquifers of the EKK-TBA are the Kalahari Sand, Karoo Basalt and Upper Karoo Sandstones (Ntane Sandstone and Mea Arkosic Sandstone Formation in Botswana and Forest Sandstone and Wankie Sandstone in Zimbabwe). Basement rocks form the eastern and southern margins of the EKK-TBA and the contact zones with the basin sediments mostly serve as recharge areas. Figure 6.7 shows a simplified hydrogeological map covering the EKK-TBA.

6.2.1. Kalahari Sand

The Kalahari Sand is ubiquitous throughout the EKK-TBA and is generally unconsolidated and thus presenting a primary porosity aquifer. In Zimbabwe, the base of the Sand is indurated into a sandstone and is hollow in certain places due to decayed organic material. The hollow sandstone is referred to as the Pipe Sandstone and presents a good groundwater potential (secondary porosity). The thickness of the Kalahari Sand varies from 0-270m and is deepest in central portions of the basin which lies mostly in Botswana following an East–West strike coinciding with the central part of the EKK-TBA, Figure 6.8. The Kalahari Sand in Botswana is generally <50 m thick and thickens towards the central portions of the basin (Haddon, 2005).

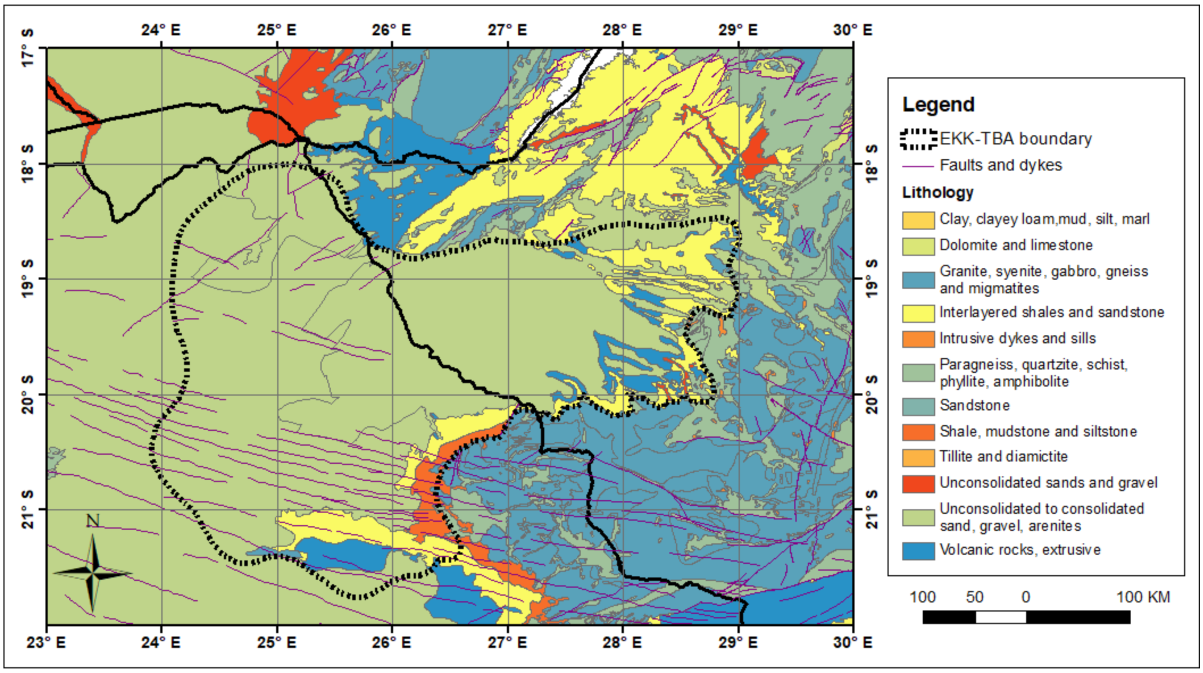


Figure 6.7: Simplified hydrogeological map of the EKK-TBA
Source: modified after SADC-HGM (2010)

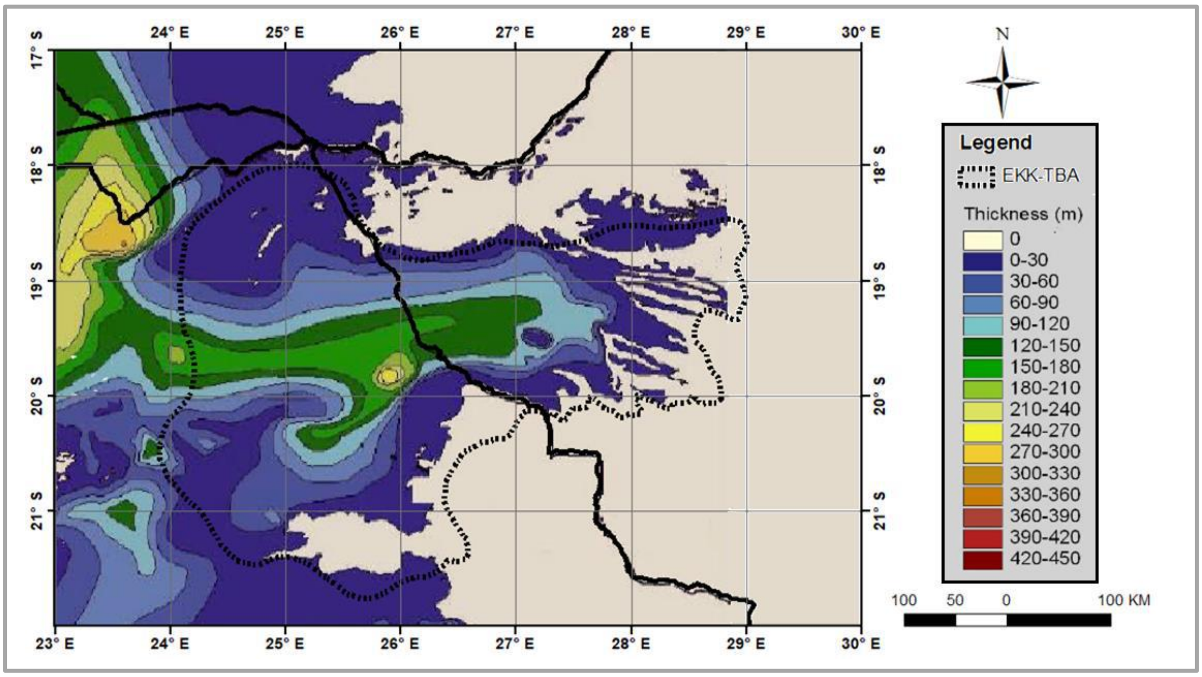


Figure 6.8: Kalahari isopach map
Source: modified after Haddon (2005)

Most rural water supply boreholes tap the shallow Kalahari formation (Figure 6.9) since it would be very expensive to drill through the underlying basalt into the Ntane/Forest sandstone.

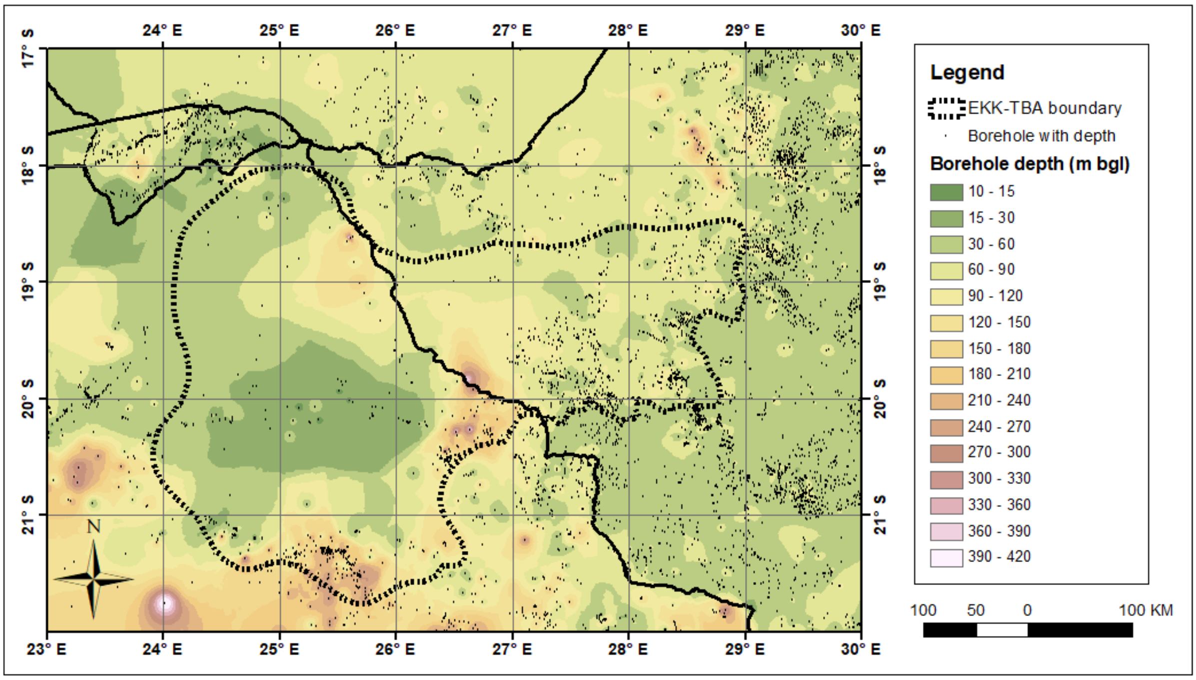


Figure 6.9: Borehole depth distribution

There is also a possibility of the groundwater being saline, particularly towards the centre of the basin. The aquifer characteristics of the Kalahari Sand are quite varied. Within Botswana, the Kalahari Sand does not constitute a major aquifer (DWA, 2002). In certain areas, where the Kalahari Sand 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 Sand has been eroded away along major river channels, exposing the underlying basalt. The transmissivity values of the Kalahari Sand 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 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 Sand does not form a significant aquifer as it cannot meet the abstraction volumes required for urban water supplies or intensive irrigation due to its limited thickness and yields.

6.2.2. Basalt

The Basalt, by and large, forms a confining layer to the Karoo Supergroup formations. The Basalt is known as the Stormberg Basalt in Botswana and the Batoka Basalt in Zimbabwe and extends from Zimbabwe into Botswana (hatched formation in Figure 6.4). It outcrops at the peripheries of the basin in both Botswana and Zimbabwe and is overlain by Kalahari Sand in the greater part of the basin. The basalt mostly acts as an aquitard and only becomes an important ‘aquifer’ at a very local scale when it is adequately fractured and, in such cases, it would be possible to provide domestic water to rural communities (DWA, 2002; Interconsult, 1986). Within the Nyamandlovu area in Zimbabwe, the basalt is absent in the south-eastern fringes of the basin and thickens towards the northwest and west. Its thickness within the area is usually less than 50m (Beekman and Sunguro, 2015). In areas where the basalt is not fractured, it forms a bedrock for the Kalahari Sand and allows for groundwater accumulation within the Sand which can be exploited at local levels. Interconsult (1986) noted that yields 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}. Within Botswana, the basalt thickness ranges from around 35m to about 300m and has an average thickness of 110m. It is absent in certain portions within the fringes of the EKK-TBA (Figure 6.4). The basalt thickens towards the northwest, reaching thicknesses of about 300m within the central portions of EKK-TBA. 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).

6.2.3. Ntane and Forest Sandstone

The sandstone formation underlying the basalt is known as the Ntane Sandstone and Forest Sandstone in Botswana and Zimbabwe, respectively.

In Botswana, the sandstone (Ntane) outcrops in the southern and south eastern margins of the Kalahari-Karoo Basin, whereas in Zimbabwe, the sandstone (Forest) outcrops in the eastern margins of the Basin (see Figure 6.4). The sandstone is overlain by basalt in the greater part of the basin. In the Maitengwe wellfield, the Ntane Sandstone aquifer thickness ranges from 2-76 m and exhibits semi-confined to confined dual porosity conditions and becomes confined when moving towards the central portions of the basin. 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. Borehole yields are very variable, ranging from 24-240 m^3/d (DWA, 2002). The Ntane Sandstone forms a major aquifer in Botswana.

In Zimbabwe, within the Nyamandlovu area, the Forest Sandstone outcrops in the eastern and south eastern sections of the area. The Forest Sandstone is on the average about 100m thick and thickens in a north westerly direction in conformity with the deepening sedimentary basin (Beekman and Sunguro, 2015). The basalt forms a confining layer over the Forest Sandstone in certain places and has been eroded in others giving rise to leaky and water table conditions for the Forest Sandstone. The Forest Sandstone aquifer parameters are varied. The transmissivity (T) values range from 1-100 m^2/d and the hydraulic conductivity (K) values range from 0.02 - ~ 2 m/d (Beekman and Sunguro, 2015; Beasley, 1983). Borehole yields mostly range from less than 10 to 2 000 m^3/d (Beekman and Sunguro, 2015; Martinelli and Hubert, 1996; Beasley, 1983). The Forest Sandstone constitutes the major aquifer from which the Nyamandlovu Wellfield was developed to augment water supplies to the City of Bulawayo.

6.2.4. Mudstones and Siltstones

Various formations (Botswana: Tlhapana, 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. In Botswana, around the Maitengwe area, the mudstones and siltstones are intercalated with sandstone (e.g. the Ngwasha Formation to the equivalent Mosolotsane Formation of the Karoo Supergroup) which makes the unit an aquitard (DWA, 2002). In Zimbabwe, the mudstones and siltstones within the EKK-TBA are ill defined and cannot be considered as aquifers. The unit can be regarded as either an aquiclude or aquitard or both depending on whether it allows vertical leakage. There is very little data and information to definitively classify the unit but as pointed out above, it can generally be specified as 'non-aquiferous'.

6.2.5. Sandstone

The mudstones and siltstones unit discussed in section 6.2.4 is underlain by a sandstone formation that is represented by the Mea Formation in Botswana and the Upper and Lower Wankie Sandstone Formations in Zimbabwe. The formations do not widely outcrop within the basin. In Maitengwe area (Botswana) the Mea Formation is arkosic and has been identified as a potential aquifer and at Dukwi Wellfield, it yields around 400 m^3/d (DWA, 2002). In Zimbabwe, Interconsult (1986) estimated the yield of the sandstone to be in the range of 100-500 m^3/d. There is no data or information on other aquifer properties.

6.3. Regional groundwater levels and flow

There are no groundwater level data and information discretely classified into the various aquifers for the whole EKK-TBA. Data and information are only available for specific wellfields such as the Maitengwe, Chidumela, Dukwi and Orapa-Letlhakane-Damtshaa in Botswana and the Nyamandlovu in Zimbabwe which are both on the southern and eastern margins of the EKK-TBA. A regional groundwater piezometry constructed from lumped static groundwater levels is shown in Figure 6.10.

Figure 6.10 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 DEM data. 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 Sand, 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), thus only providing 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.

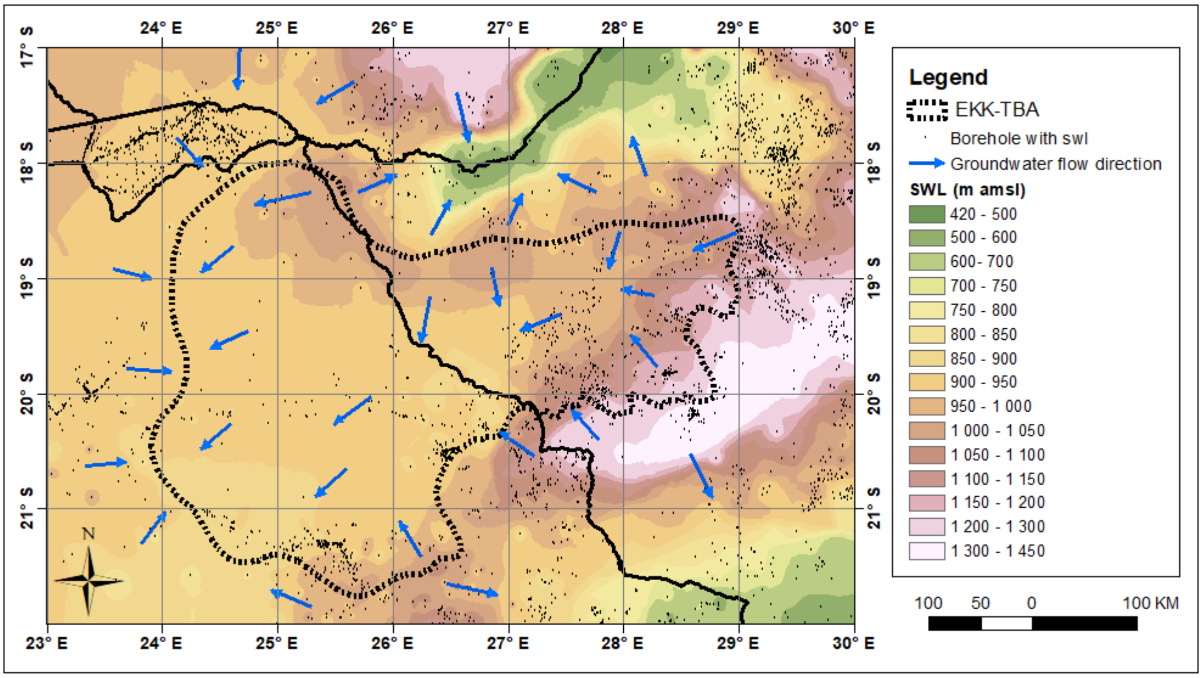


Figure 6.10: Regional piezometry and groundwater flow from boreholes with SWL

Under natural conditions and in the absence of 'artificial' groundwater abstraction, groundwater flow tends to mimic the surface topography albeit at a more subdued scale (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 Sand since the borehole locations coincide or fall within the shallow zones of the Kalahari Sand (see Figure 6.8 and Figure 6.9). Boreholes which tap the Ntane/Forest Sandstone aquifers are mostly along the southern and south eastern margin of the EKK-TBA.

The piezometry represented in Figure 6.10 shows that groundwater flows from Zimbabwe towards the Makgadikgadi Pans in Botswana (from higher to lower swl). The inferred groundwater flow direction is supported by the general groundwater flow direction of the individual wellfields when the effects of localised wellfield drawdowns due to high abstraction rates are ignored (section 6.7).

6.4. Groundwater recharge

Groundwater recharge can be defined as the portion of total rainfall falling into 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 studies were carried out in southern Africa using a multitude of estimation techniques such as the Chloride Mass Balance (CMB), Water Table Fluctuation (WTF), Cumulative Rainfall Departure (CRD), Environmental Isotopes, Groundwater Modelling, etc. The results of these studies indicate that with average annual rainfall below 350 mm, hardly any recharge occurs (Beekman et al., 1996; Xu and Beekman, 2019).

Within the EKK-TBA, recharge studies have been confined to the wellfields and the 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 are indicative of the actual recharge rates whereas the higher values are due to preferential recharge along river systems, faults and fractures and do account for a small percentage of the total areal recharge. Isotope recharge studies indicate that the main groundwater recharge occurred during the last pluvial period, 5 000-10 000 years ago.

Since net recharge is negligible to very low, effective and robust groundwater management systems need to be instituted to ensure the sustainability of the groundwater resource.

6.5. Groundwater quality

Data on general groundwater quality, let alone comprehensive groundwater quality, is very scanty (Chapter 2, Table 2.1). Water quality data exists within the EKK-TBA wellfields.

The groundwater quality in Botswana wellfields 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 recharge zones have TDS values <1000 mg/l and these increase 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 pans and cattle posts along fracture and/or fault zones mostly during seasons of high rainfall (Kefentse, 2004). High nitrate levels within the diamond wellfields of up to 600 mg/l are partly ascribed to nitrate based explosives used in the blasting operations (Debswana, 2015). The Botswana Bureau of Standards (BOS) set the water quality parameters for classifying the water as shown in Table 6.1.

Table 6.1: Drinking Water Classification (BOS 32:2000)

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

Source: Botswana Bureau of Standards

Increased abstractions risk causing 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 and agricultural purposes.

The groundwater quality of the Nyamandlovu Sandstone Aquifer in Zimbabwe is generally good with total dissolved solids (TDS) concentrations below 1 000 mg/l (Interconsult, 1986) and is compliant with the Zimbabwe guideline for drinking water (Table 6.2). The electrical conductivity of the boreholes in the Nyamandlovu Wellfield ranged between 300-500 µS/cm (Sunguro, 1991). Isolated high nitrate levels were recorded in some 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 (*ibid*).

Table 6.2: 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	1000	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)

6.6. Groundwater availability

Groundwater availability in the EKK-TBA is determined by the nature of the aquifer, its location, groundwater development costs and water quality. The main source of groundwater comes from the Ntane Sandstone and Mea Arkosic Sandstone Aquifers in Botswana and the Forest Sandstone Aquifer in Zimbabwe. The positioning of these 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 Sand 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 animal consumption and cropping without prior treatment.

6.7. EKK-TBA wellfields

Several wellfields exist in the EKK-TBA, Figure 6.11. The wellfields have been classified into public sector (WUC in Botswana and ZINWA in Zimbabwe) and private sector (diamond mining companies) owned and managed wellfields. The DWS in Botswana is obligated with monitoring the aquifers but rarely do so due to limited resources. 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.

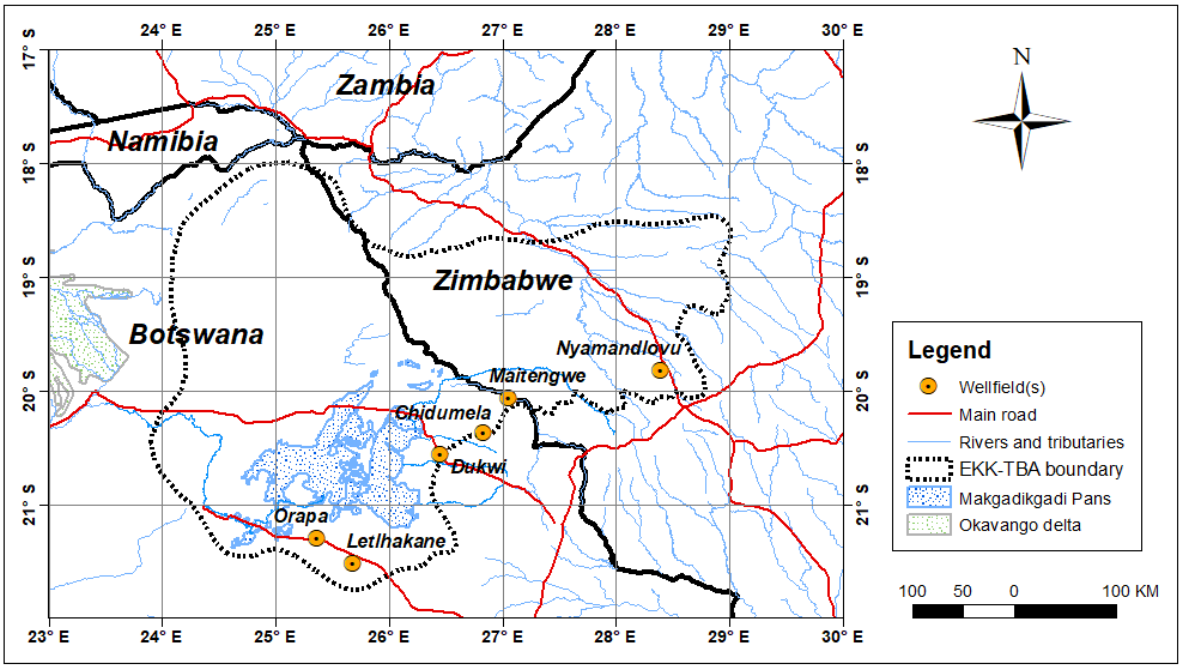


Figure 6.11: Approximate location EKK-TBA Wellfields

6.7.1. Public owned and managed wellfields

Several potable wellfields were developed within 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.

6.7.1.1. 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 6.11. 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.

The Mea Arkose Formation (equivalent to the Hwange Sandstone in Zimbabwe) constitutes the main aquifer and has an average thickness of 58m (Jennings, 1974; Legadiko, 2015). The stratigraphy is strongly structural controlled by faults and dykes and these have resulted in compartmentalised aquifer zones.

The groundwater quality falls within the maximum allowable range of chemical parameters of the Botswana Bureau of Standards (BOS 32:2000) (Table 6.1) and hence the groundwater can broadly be considered suitable for human consumption (Legadiko, 2015). The basalts and doleritic contact zones have groundwater which is highly saline (TDS >20 000 mg/l) and is not suitable for human consumption. The Kalahari Sand and other recent formations are generally shallow and have localised ephemeral perched aquifers which have potable groundwater that are exploited through hand dug wells, particularly along the Semowane River (DWA, 1976).

Groundwater recharge occurs where the aquifers outcrop and ranges from 0.2-6 mm/yr and is mostly around 2 mm/yr (DWA, 2000a; 2000b).

Groundwater level monitoring is manually conducted by the DWS from 28 boreholes. Groundwater levels are impacted by the amount of rainfall and abstraction, Figure 6.12. Prolonged high abstraction rates cause a decline in the groundwater levels.

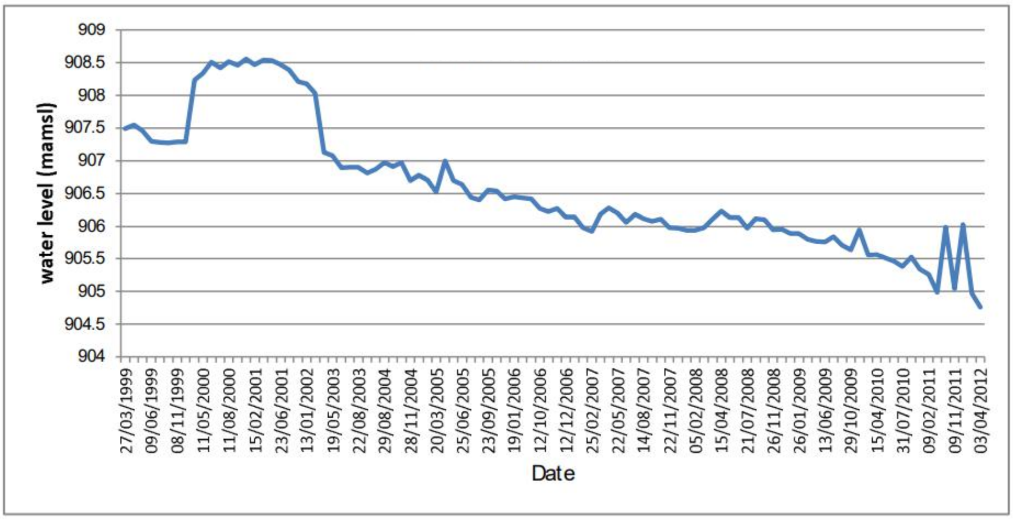


Figure 6.12: Groundwater level response to rainfall and abstraction in borehole 7547
Source: Legadiko (2015)

Figure 6.13 and Figure 6.14 show that the general groundwater flow direction in the Dukwi Wellfield has remained southwestwards over a period of 20 years towards the Makgadikgadi despite the 5-10m drop in groundwater levels caused by pumping.

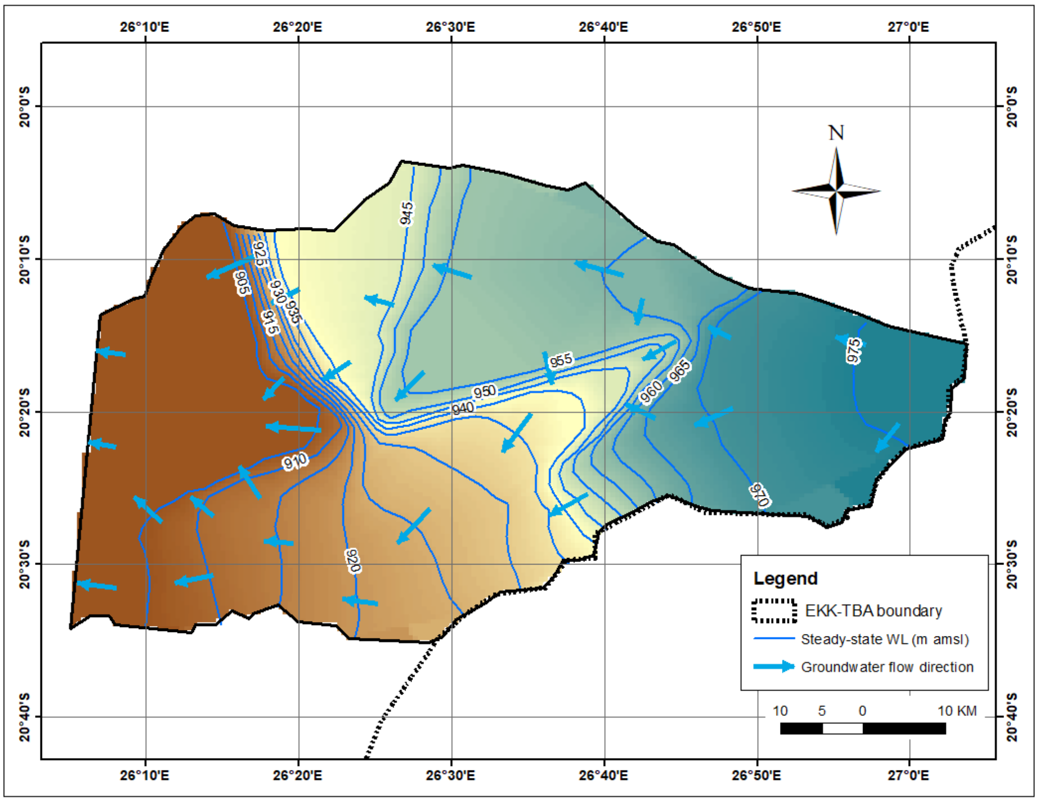


Figure 6.13: Steady-State calibrated groundwater contours prior to abstraction in 1995

Source: modified after Legadiko (2015)

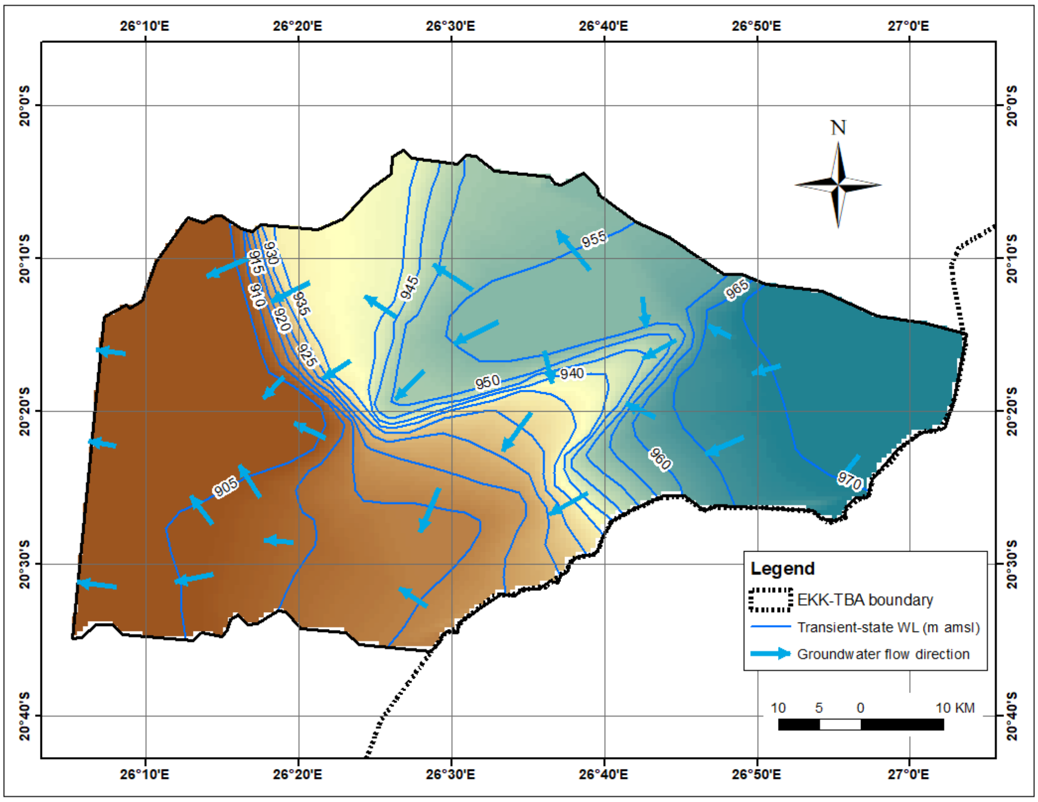


Figure 6.14: Transient-State calibrated groundwater levels as at January 2014

Source: modified after Legadiko (2015)

6.7.1.2. 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 6.11. It supplies groundwater to the Letlhakane village.

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

The groundwater quality is generally considered potable (BOS 32:2000) though elevated nitrate concentrations have been recorded and these have been attributed to leaching of the nitrate from pans and cattle posts along fracture and/or fault zones during seasons of high rainfall (Kefentse, 2004). The groundwater chemical type is adjudged Na-Cl, HCO_3 type of water (Geoflux, 2005). The TDS generally increases in a south-westerly direction, Figure 6.15, based on the available limited measuring points. An even spatial distribution of measuring points would provide a clear picture on the evolution of the groundwater chemistry.

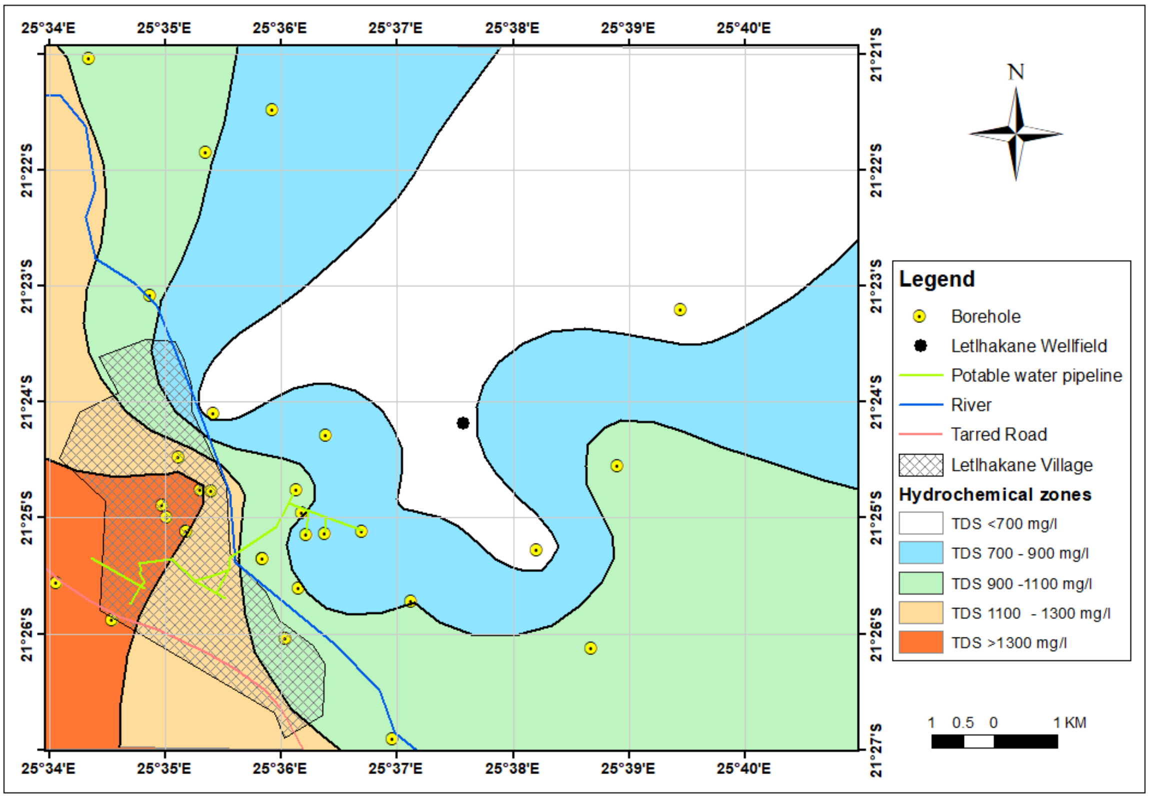


Figure 6.15: TDS of groundwater around Letlhakane Wellfield

Source: modified after Geoflux (2005)

Groundwater recharge, using the chloride mass balance method, was estimated at 2.69 mm/yr Geoflux (2005).

There is limited groundwater level monitoring data to definitively conclude on the groundwater flow pattern. Figure 6.16 is representative of groundwater level fluctuations in some of boreholes and shows that these have largely been unchanged for the large part of the time and are only of late showing a conspicuous drop as a result of low rainfall and increased abstraction.

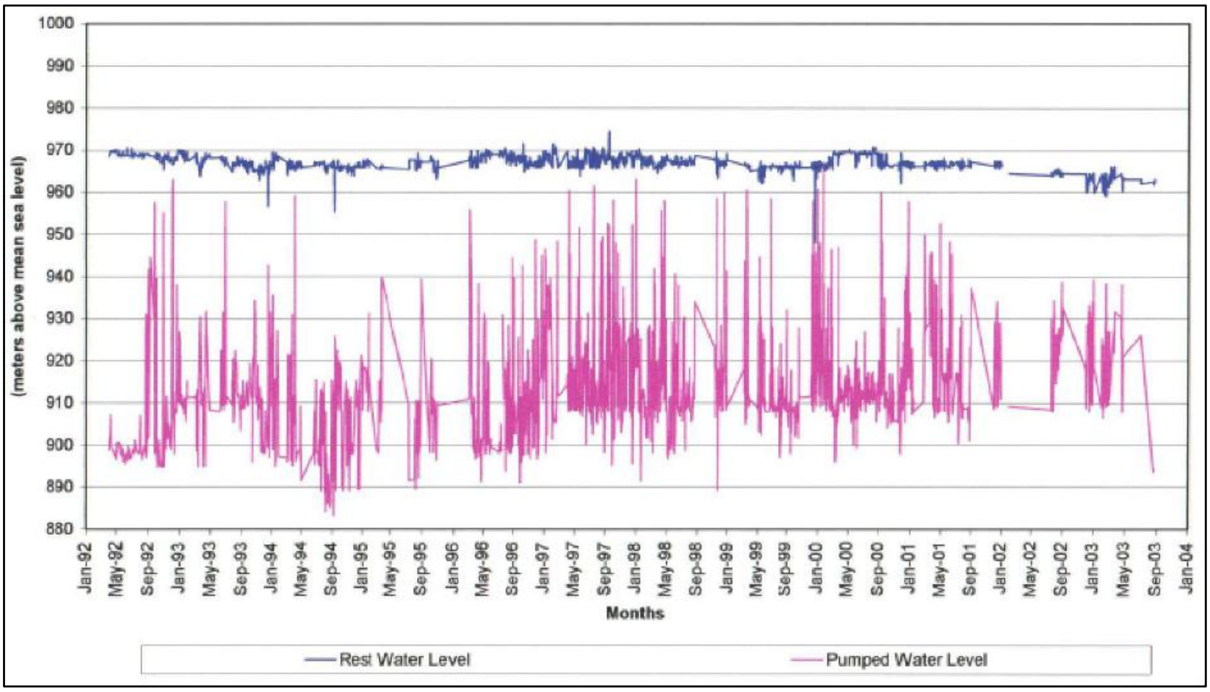


Figure 6.16: Groundwater level fluctuations in production borehole 3613
Source: Geoflux (2005)

Based on the limited measuring points, the groundwater can be considered to flow north to north-west, Figure 6.17, 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 of the groundwater dynamics.

6.7.1.3. Maitengwe Wellfield

The Maitengwe Wellfield comprises 9 production boreholes, ranging in depth from about 110-200m (DWA, 2002), and it lies on the border with Zimbabwe, Figure 6.11. 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*).

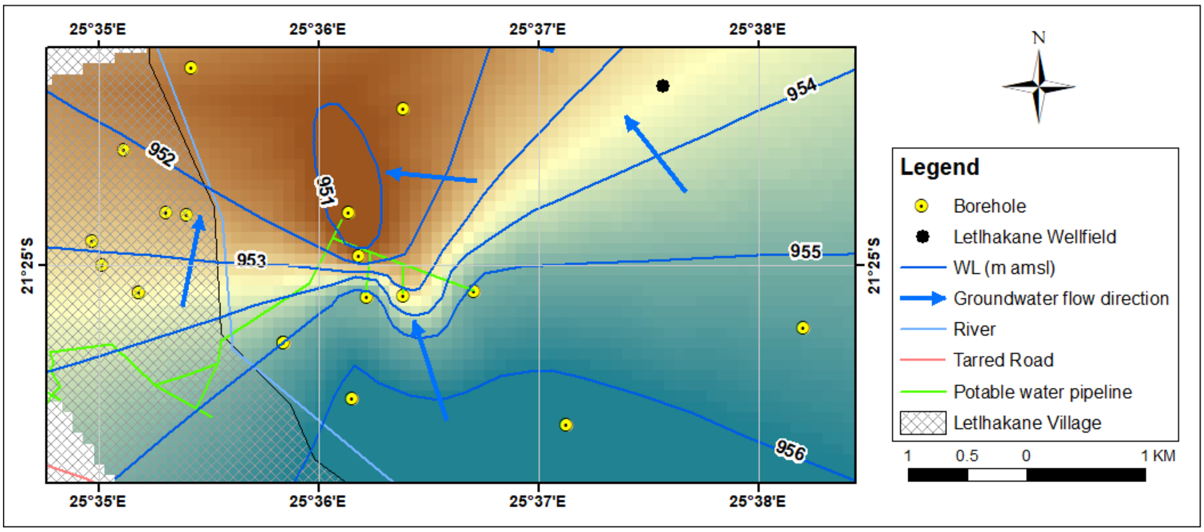


Figure 6.17: Letlhakane Wellfield piezometry and groundwater flow
Source: modified after Geoflux (2005)

The Upper Ntane Sandstone (equivalent to the Forest Sandstone in Zimbabwe) forms the main aquifer and ranges in thickness from 2-76m and has a mean thickness of about 30m, with yields varying from 24-240 m^3/d (DWA, 2002). The basalt overlying the Ntane Sandstone, where it is deeply weathered and fractured, can have localised high yields (200-1 000 m^3/d) (DWA, 2002; United Nations, 1989).

The Upper Ntane Sandstone groundwater demonstrates a progressive deterioration in water quality towards the northwest, in the direction of deepening basin and within a distance of less than 20km along the flow paths (DWA, 2002). The groundwater was classified into five hydrochemical zones based on hydrochemical facies and the Total Dissolved Solids (TDS), Figure 6.18.

CMB methods yielded groundwater recharge rates of 9-14 mm yr^{-1} and 10 mm yr^{-1} was considered reasonable (DWA, 2002). Carbon-14 (^{14}C) dating provided a wide range of recharge rates, varying from 2-37 mm yr^{-1}. The higher recharge rates were attributed to recharge from the Maitengwe River (*ibid*).

Limited groundwater level monitoring was carried out in Maitengwe Wellfield in 1999 (January – March) and a typical hydrograph from one of the 26 network boreholes (BH 9005) monitored is presented in Figure 6.19. BH 9005 clearly shows a declining water level and hence the need for effective groundwater management. 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 6.20.

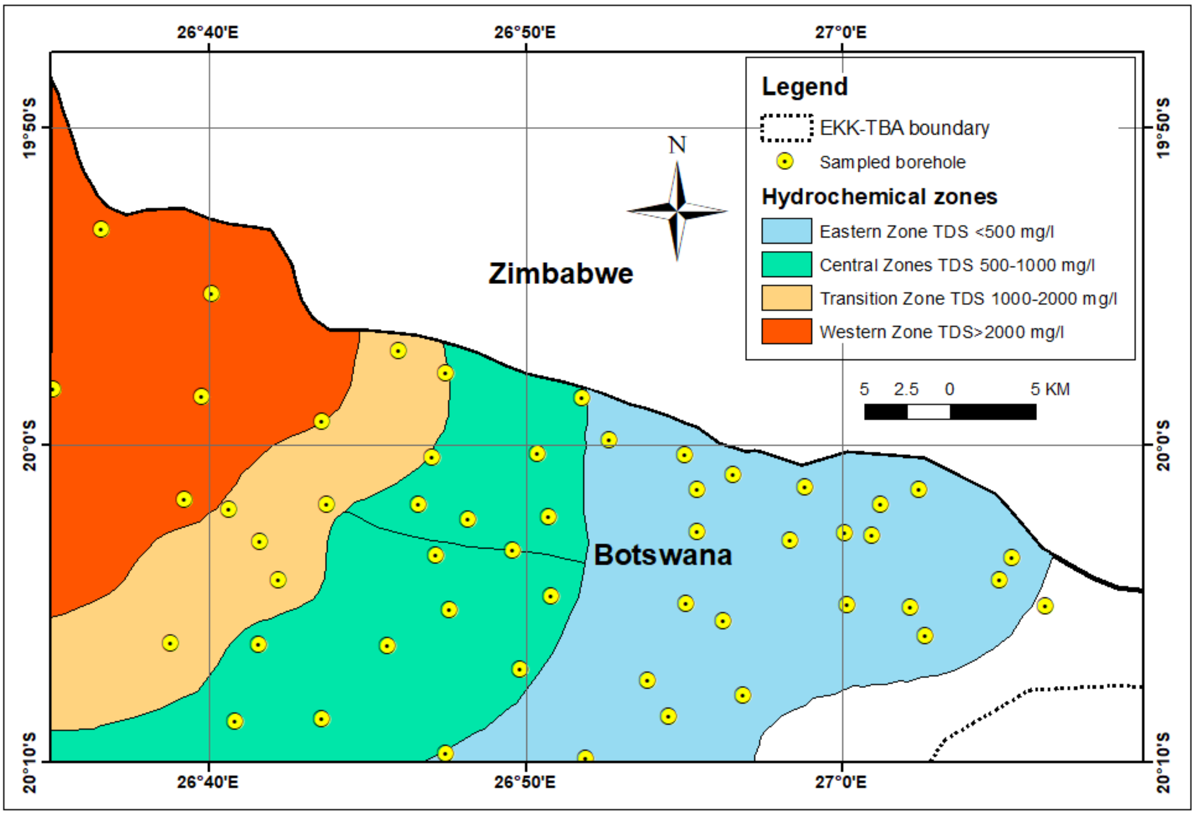


Figure 6.18: Upper Ntane Sandstone hydrochemical zones

Source: modified after DWA (2002)

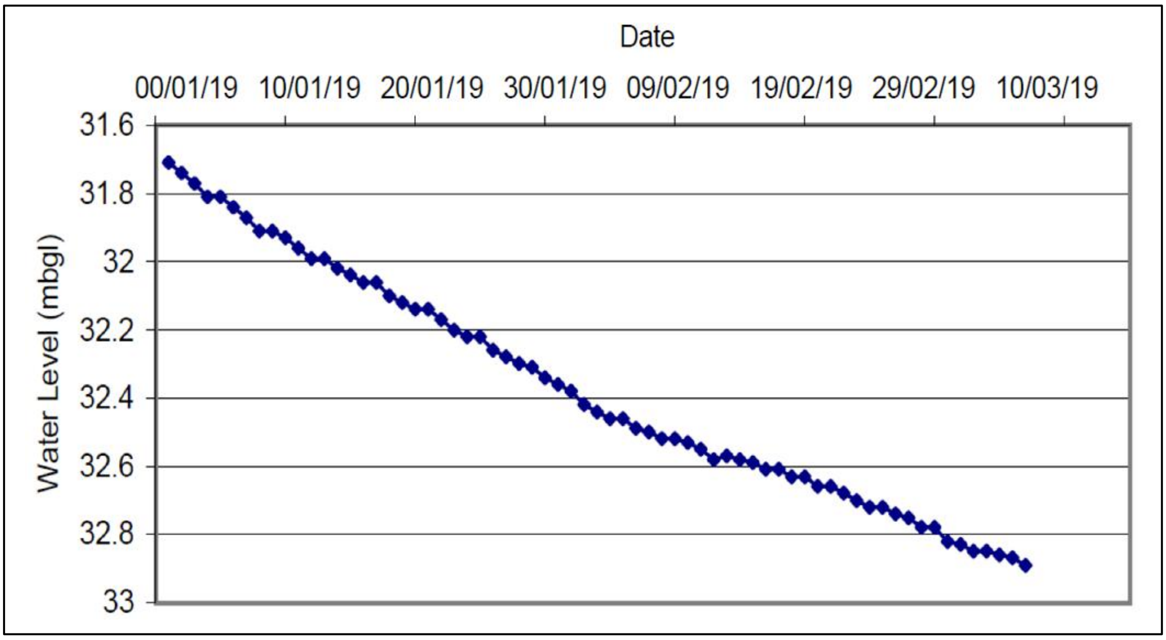


Figure 6.19: Borehole 9005 groundwater hydrograph

Source: DWA (2002)

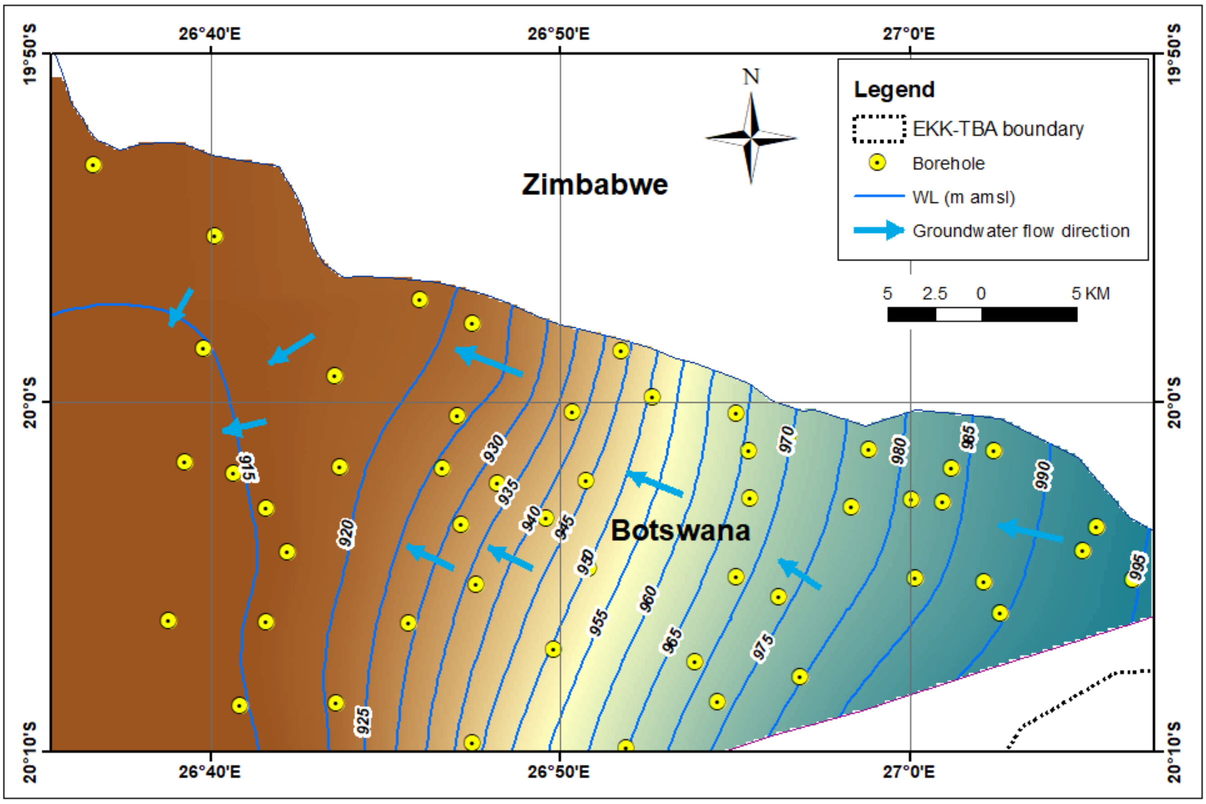


Figure 6.20: Maitengwe Wellfield piezometry and groundwater flow

Source: modified after DWA (2002)

6.7.1.4. Nyamandlovu Wellfield

The Nyamandlovu Wellfield lies towards the south-eastern margin of the EKK-TBA in Zimbabwe, Figure 6.11. 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.

The Forest Sandstone (equivalent to the Ntane Sandstone in Botswana) forms the major aquifer and has an average thickness of 100m, with borehole yields ranging from >10-2 000 m^3/d (Beekman and Sunguro, 2015; Martinelli and Hubert, 1996; Beasley, 1983). Local farmers also rely on groundwater from the aquifer, abstracted through own boreholes, for agricultural purposes (cropping and livestock).

The groundwater quality of the Nyamandlovu Sandstone Aquifer is generally good with total dissolved solids (TDS) concentrations below 1 000 mg/l and electrical conductivity between 300-500 µS/cm (Sunguro, 1991; Interconsult, 1986). Isolated high nitrate levels were recorded in some farmers' boreholes and these were attributed to poorly constructed boreholes that allowed leakage into the aquifer along the borehole casing (Sunguro, 1991).

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. The recharge rates varied from 2-62 mm/yr, with the lower values being the most prevalent (Beekman and Sunguro, 2015). High recharge rates occur along preferential paths such as fracture and fault zones (*ibid*).

A groundwater level monitoring network was setup in 1989 with initially around 79 boreholes and recent communication with ZINWA staff indicates that monitoring has been ceased due to lack of resources. Figure 6.21 shows a hydrograph of one of the monitoring boreholes (4-UMGU-123).

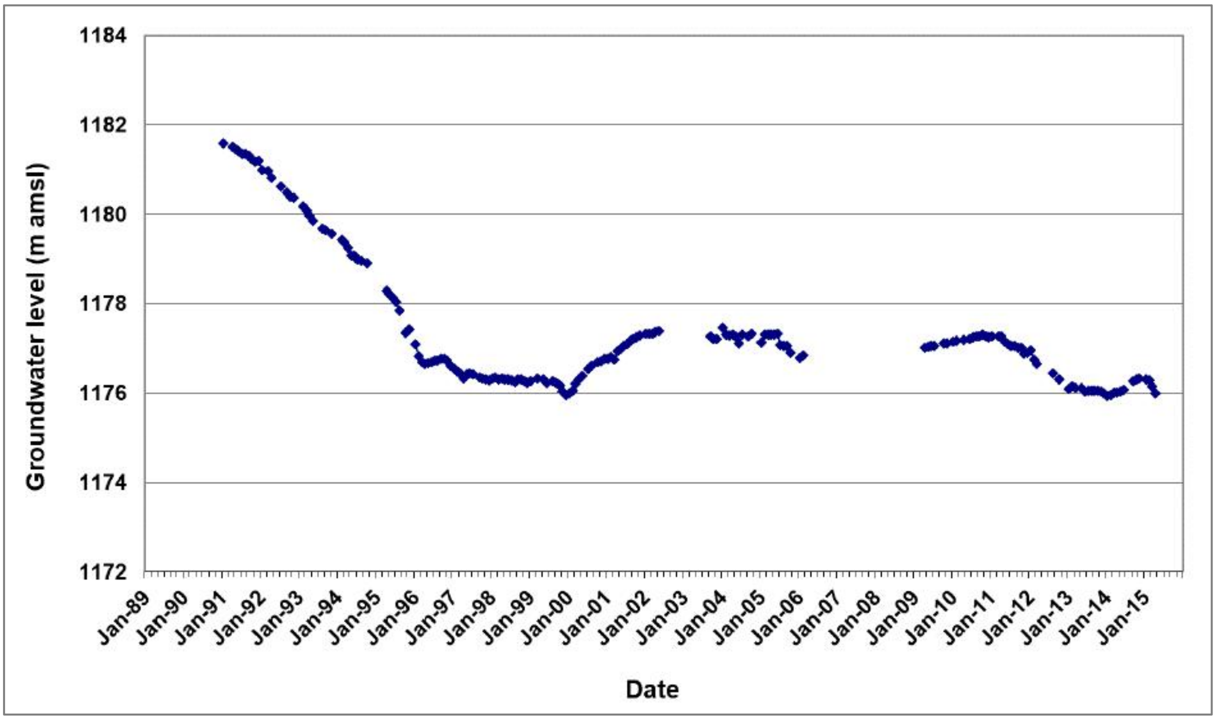


Figure 6.21: Borehole 4-UMGU-123 groundwater hydrograph
Source: Beekman and Sunguro (2015)

Groundwater within the Nyamandlovu area flows in a north-westerly to northerly direction as shown in Figure 6.22.

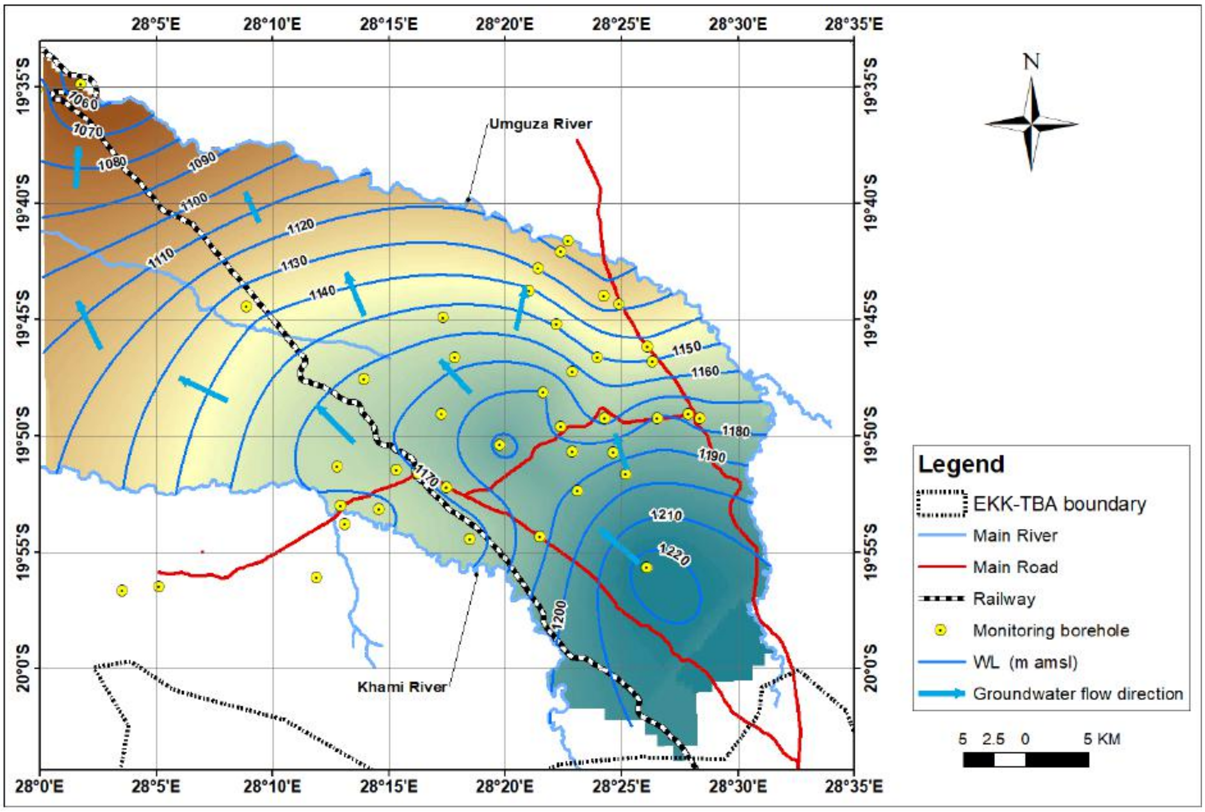


Figure 6.22: Piezometry and groundwater flow directions in the Nyamandlovu area
Source: modified after Beekman and Sunguro (2015)

6.7.2. Private owned and managed wellfields

There are several diamond mines owned wellfields to the south of Makgadikgadi Pans which supply groundwater for mining operations, Figure 6.23. Three Debswana diamond mines within the EKK-TBA, Orapa, Letlhakane and Damtshaa (OLD) 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 6.23) 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 6.7.1.2) which supplies water to the village, Figure 6.23. 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).

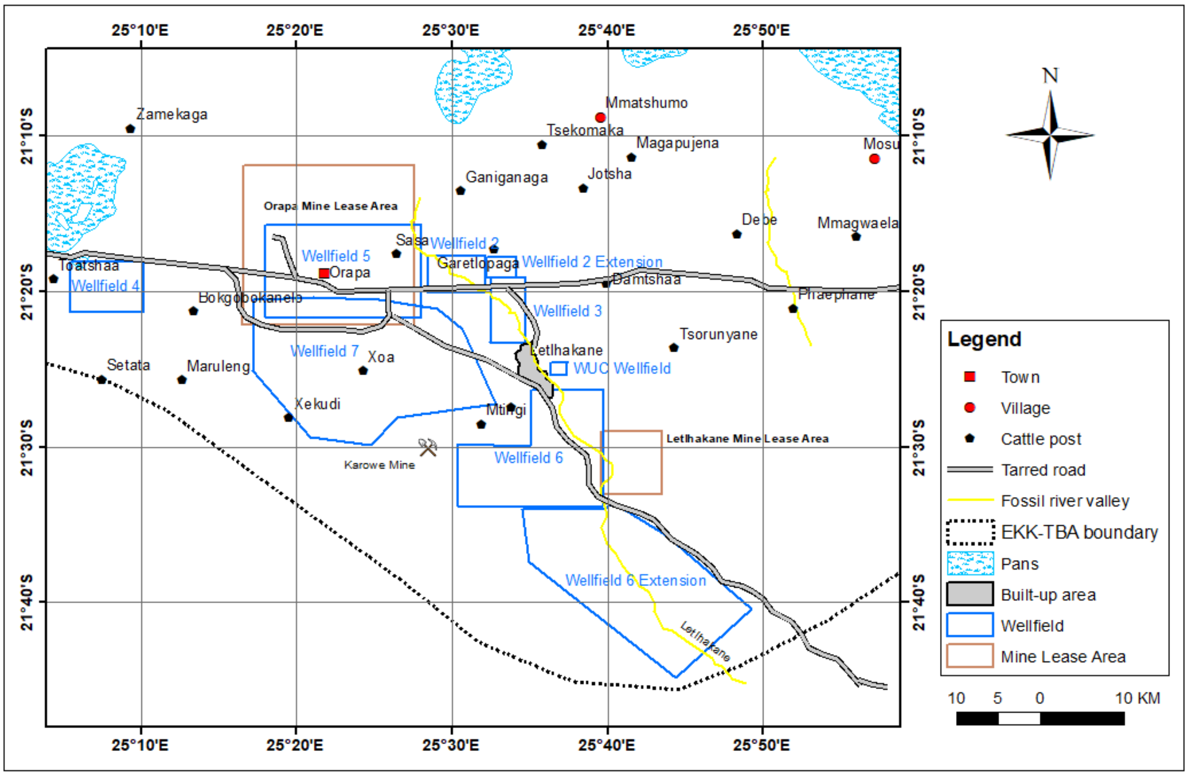


Figure 6.23: OLD mines and wellfields, Karowe mine and WUC Letlhakane Wellfield
Source: modified after Mogami (2013) and Debswana (2015)

The mines' wellfields penetrate three major sedimentary aquifers: the Ntane Sandstone, the Mosolotsane sandstone and mudstones, and the Mea Arkosic sandstone and weathered granite contact zone. 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 lies below the superficial Caenozoic to recent Kalahari Sand deposits (less than 20m thickness) and Stormberg basalts (95-110m 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.

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 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 6.3 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 to the requirements of the BOS 32:2000 guidelines (see Table 6.1).

Table 6.3: 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)

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.

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 to 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 a 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 6.24 (Debswana, 2015).

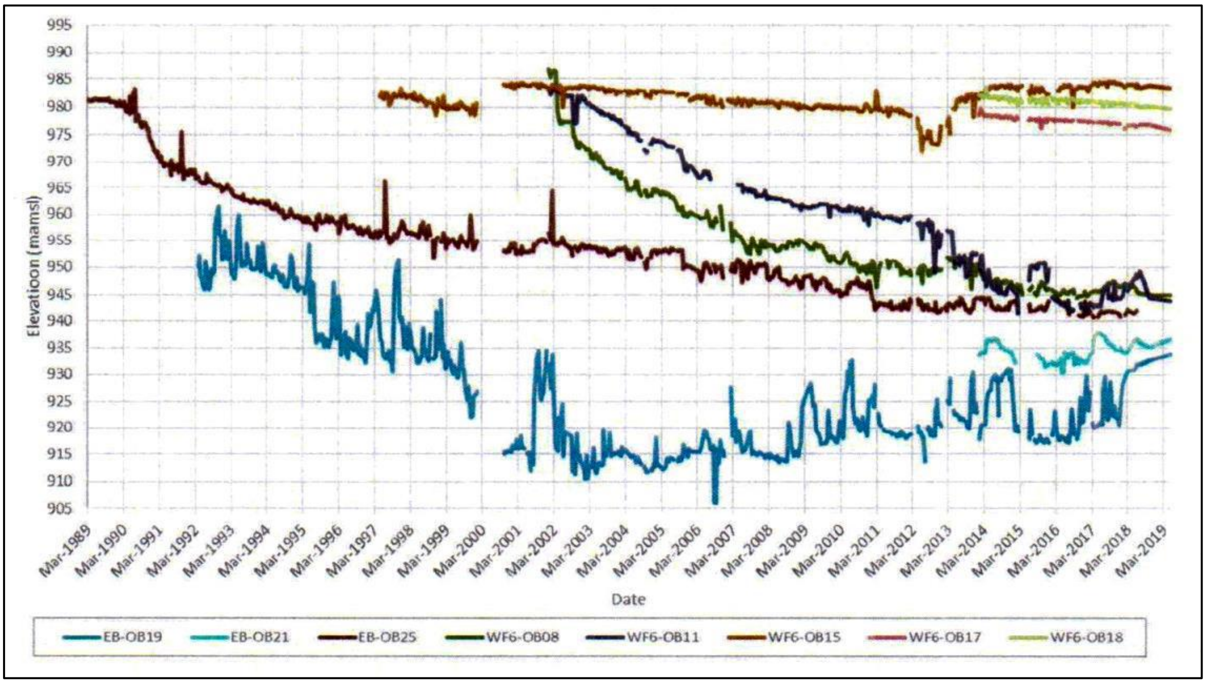


Figure 6.24: Groundwater levels of Wellfield 6 exploitation and observation boreholes
Source: Debswana (2020)

Regional groundwater flow in the Greater Orapa area is from the south and the east towards the Makgadikgadi Pans, with a gradient of about 0.0001 to 0.0002 (Debswana, 2020), Figure 6.25. Locally, groundwater flows towards major pumping centres.

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.

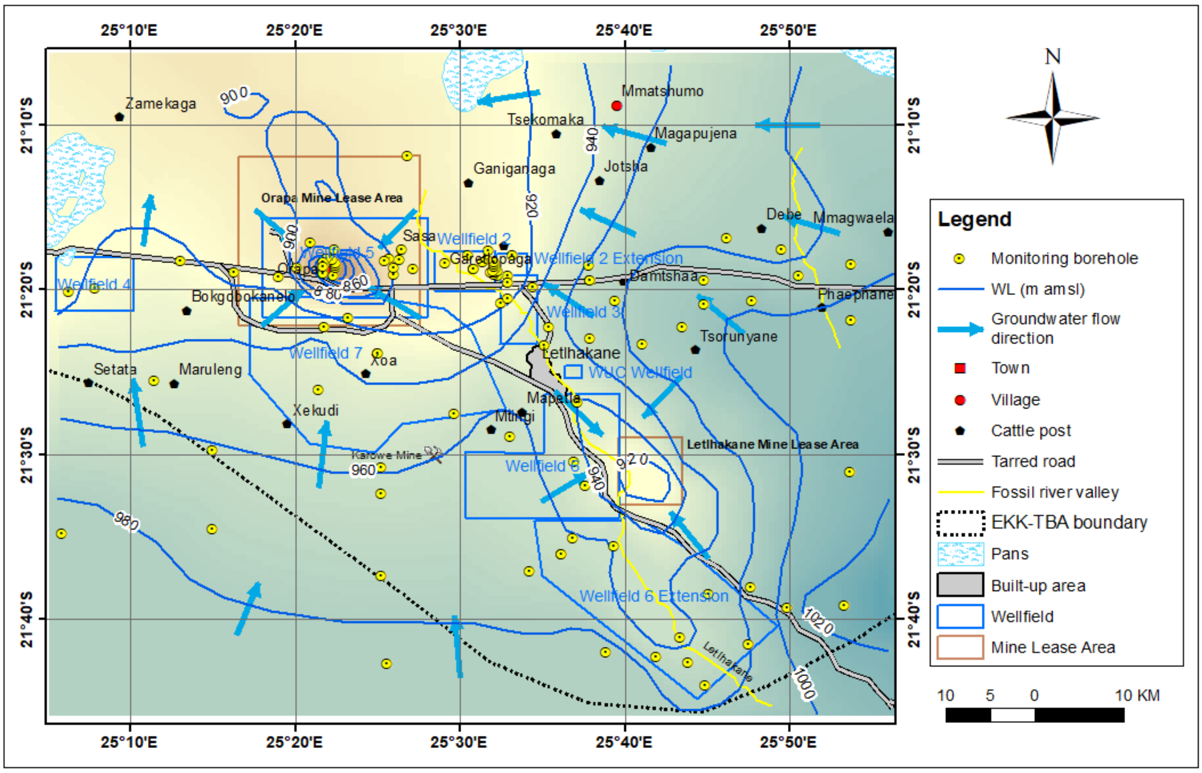


Figure 6.25: Regional groundwater flow in the OLDM area as at 2019
Source: modified after Debswana (2020)

6.8. Key Messages

- Groundwater development within the EKK-TBA is generally localized: It is mostly confined to the southern and south-eastern fringe of the EKK-TBA. There is a lack of comprehensive basin-wide hydrogeological investigations which includes geophysical, groundwater recharge and managed aquifer recharge, and hydrochemical investigations, groundwater modelling, etc.
- Data scarcity: hydrogeological data and information is mostly limited to wellfields on the fringe of the Kalahari-Karoo Basin and is sparse with regards to lithology, tectonics, and hydrogeological data (yields, hydraulic characteristics, chemistry, water levels related to aquifers/aquitards)
- Data quality: the quality of hydrogeological data and information is generally poor. There is also a lack of quality control. The quality of the SADC-HGM database for example differs from country to country – e.g. depth to swl > BH depth or lack of data on BH depth; lack of information on the geology intersected; incomplete chemical analyses, etc.
- Hydrogeological databases: there is lack of good quality hydrogeological databases. There is also the issue of difficulty in accessibility to data and information. Standardisation of the data and information is also lacking, and this complicates harmonisation of the databases.
- 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 in the EKK-TBA and if at all, it is carried out over too short time

periods, infrequently, and mostly for very few parameters. In Botswana, neither the DWS nor the WUC have an effective and efficient groundwater monitoring system in operation, and the collected data is not comprehensive, consistent or stored in a readily useful manner (Farr, 2017). This situation certainly applies to the EKK-TBA. 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*). A comprehensive monitoring programme (groundwater levels, abstractions, water quality and rainfall) need to be urgently instituted to ensure the sustainable development of groundwater. Increased abstractions for the City of Bulawayo and by the local Nyamandlovu farmers in Zimbabwe may result in a drop in the groundwater levels and possibly a deterioration in the groundwater quality. Groundwater monitoring must be strengthened rather than stopped. The density and frequency of monitoring at both local and regional scales will be determined by the objective(s) of the monitoring.

- Localised induced groundwater level depressions: due to the need for pit dewatering, there is localised induced groundwater level depressions around the mines. 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. It is estimated that in the case of the KDM, groundwater levels within a 5 km radius from the mine lease perimeter will be significantly lowered and this will inevitably affect several local farmers who rely on the groundwater for agricultural purposes. The situation is envisaged to worsen when the Ntane Sandstone, which forms the principal regional aquifer, is dewatered for mining operations.
- Unregulated borehole drilling: uncontrolled drilling of private boreholes within the OLDM wellfields over the past 10 years, especially within Wellfields 6 and 7, of which some have breached the minimum allowable borehole spacing (8 km), poses the risk of groundwater overexploitation and unwarranted competition of the groundwater resource.
- Groundwater modelling: groundwater modelling is not periodically conducted
- 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. Lack of more precise information on dewatering presents data gaps for making informed decisions on the impact of the dewatering and the effect of the disposal of the saline groundwater onto the environment.
- Groundwater blending: blending of (hyper) saline and fresh groundwater for mining operations may be an alternative to lessen the pressure on fresh groundwater resources. The Middle Kalahari Group Saline Aquifer to the northwest of Orapa around Phuduhudu and Gweta, is high yielding with groundwater having an average TDS of 108 000 mg/l (hyper saline) which is more than three times the maximum plant operating quality of 30 000 mg/l.

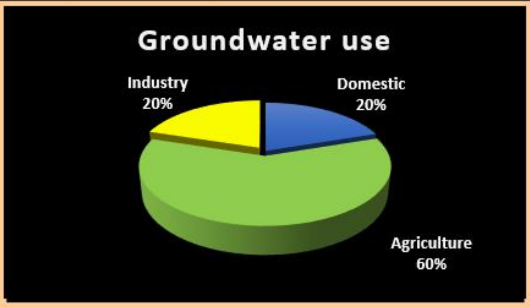
- Water requirements: water supply for mining operations is currently demand driven and this should be critically reviewed by the Water Apportionment Board in terms of setting timely, realistic and sustainable abstraction rates and volumes. Related to this is the mines' projected increasing abstractions from the wellfields and dewatering boreholes which have the potential to derail the objective of sustainable management of groundwater resources.
- Groundwater 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. Alternative data collection techniques need to be explored to avoid data gaps and improve on data quality.

7. WATER USE

This chapter discusses water use in the context of agriculture (crop water use); domestic water supply; mining; and environment, ecosystems, game parks and reserves. 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, agriculture is the sector consuming percentagewise 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. It thus can safely be 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%

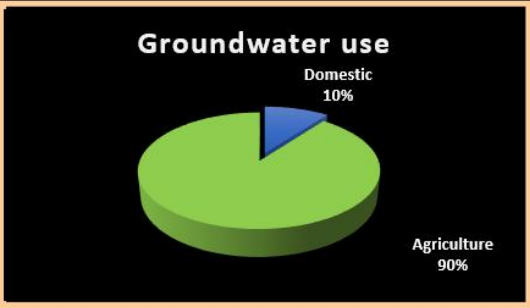


Figure 7.1: Groundwater use in Botswana and Zimbabwe
Source: Beekman (2010) and Pietersen and Beekman (2016)

7.1. Agriculture

Active crop mapping is an important component for agriculture monitoring and determining accurate crop water estimates which is an important part in water resources management. Available season or historical thematic crop maps are useful for stratification purposes in agricultural statistics and more importantly, water resources accounting (Khan et al., 2016). Satellite data provides promising primary data source of information for deriving timely and accurate active crop and crop water use maps at various scales (McNairn et al., 2014; Skakun et al., 2016). This is because of their synoptic abilities of space-borne satellites to acquire timely images in different spectral bands and provide repeatable, continuous measurements for extended territorial extents. It will be demonstrated in this section how the NDVI remote sensing technique is used in estimating active cropping areas that can be compared with physical on-the-ground measurements of cropping areas, and this can be translated into (crop) water use. The Nyamandlovu area in Zimbabwe where historical irrigation data was available and forms part of the EKK-TBA, was selected for piloting the technique.

The Nyamandlovu area is predominantly a semi-arid area situated between the Umguza and Khami Rivers, covering approximately 1680 km^2. Water use in the area is mainly from groundwater from the Nyamandlovu (Forest) Sandstone Aquifer in the south-west and to a lesser extent from the Kalahari Sand Aquifer in the north-west. Crop production (Figure 7.2) is one of the main economic activities sustaining livelihoods in the area. The aquifer supports local irrigation farming (mostly market gardening), various ranching activities and it supports the City of Bulawayo as a supplementary water source (Beekman and Sunguro, 2015).

Proper water resources accounting and management in agriculture requires up to date and spatially explicit information on active cropping areas. Satellite (seasonal) data were acquired and analyzed, and the results compared with the acreage of irrigated cropping areas determined for a groundwater resource assessment and modelling study carried out in 2015 (Beekman and Sunguro, 2015). For known crop water use, the analysis of satellite imagery will provide a timely spatial distribution of active cropping areas and (ground)water use.

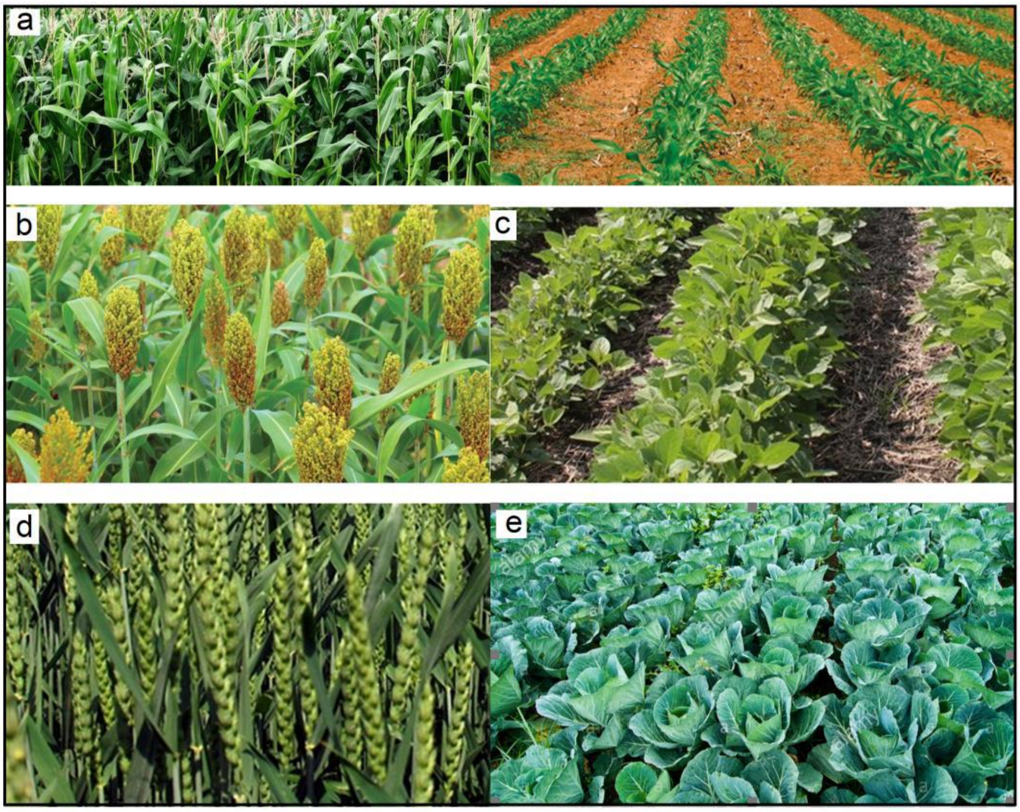


Figure 7.2: Typical crop types in the Nyamandlovu area
a-maize, b-sorghum, c-soya beans, d-wheat and e-vegetables

7.1.1. Satellite data acquisition and calibration

To derive estimates of crop water use in the Nyamandlovu area, Landsat time series data, at 30-m spatial resolution for the period between 1990 and 1999 as well as for the year 2020 were downloaded from the United States Geological Survey (USGS) online spatial data portal (http://earthexplorer.usgs.gov), Table 7.1. The images were converted to spectral radiance ($Wm^{-2}sr^{-1}\mu m^{-1}$), based on an algorithm developed by Chander et al. (2009). The algorithm was also used in correcting for solar angle and earth-sun distance errors as the images were acquired for different time spans and seasons (Li et al., 2013). The algorithm was run using the Landsat calibration coefficients provided in the image metadata files. The calibration procedure was carried out according to equation 7.1. Further, selected Landsat spectral bands were atmospherically corrected and converted to reflectance using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) model (Kaufmann et al., 1997).

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{Q_{cal\,max} - Q_{cal\,min}}\right)(Q_{cal} - Q_{cal\,min}) + LMIN_\lambda \qquad (7.1)$$

where L_λ is the spectral radiance at the sensor's aperture ($Wm^{-2}sr^{-1}\mu m^{-1}$), Q_{cal} is the quantised calibrated pixel value (DN), Q_{calmin} is the minimum quantised calibrated pixel value corresponding to $LMIN_\lambda$ (DN), Q_{calmax} is the maximum quantised calibrated pixel value corresponding to $LMAX_\lambda$ (DN), $LMIN_\lambda$ is the spectral at-sensor radiance scaled to Q_{calmin} ($Wm^{-2}sr^{-1}\,\mu m^{-1}$), and $LMAX_\lambda$ is the spectral at-sensor radiance scaled to Q_{calmax} ($Wm^{-2}sr^{-1}\,\mu m^{-1}$).

Some of these images were L1T products, i.e. they were ortho-rectified and geometrically corrected in the Universal Transverse Mercator projection (UTM) and World Geodetic System 84 (WGS84) ellipsoid. Quantized and calibrated scaled Digital Numbers (DNs) for each Landsat OLI and TM band were converted into Top-Of-Atmosphere (TOA) spectral reflectance and brightness temperature (K) values, using the rescaling coefficients of the metadata file.

7.1.2. Nyamandlovu land use and land cover mapping

For the Nyamandlovu area, a land use/land cover map was generated using a supervised classification algorithm in a GIS environment, Figure 7.3. The classification was implemented using Landsat imagery and Google Earth was used to identify reference points. The crop land cover thematic class was masked out of the derived land use map of the Nyamandlovu area and further used for deriving active crop areas for the period of 1990-1999 and for 2020. The derived land use map for the Nyamandlovu area shows that crop cultivation is indeed a dominant land cover type in the area.

Table 7.1: Summary of the Landsat data series

Image Scene details	Acquisition Date	Pixel size
LC08_L1TP_171074_20200531_20200608_01_T1	2020/05/31	30m x30m
LT05_L1TP_171074_19990709_20161219_01_T1	1999/07/09	30m x30m
LT05_L1TP_171074_19980807_20161223_01_T1	1998/08/07	30m x30m
LT05_L1GS_171074_19981111_20161220_01_T2	1998/11/11	30m x30m
LT05_L1GS_171074_19971023_20161229_01_T2	1997/10/23	30m x30m
LT05_L1TP_171074_19961020_20170103_01_T1	1996/10/20	30m x30m
LT05_L1TP_171074_19960716_20170103_01_T2	1996/07/16	30m x30m
LT05_L1TP_171074_19951002_20170106_01_T1	1995/10/02	30m x30m
LT05_L1TP_171074_19950308_20170109_01_T1	1995/03/08	30m x30m
LT05_L1GS_171074_19940524_20170114_01_T2	1994/05/24	30m x30m
LT05_L1TP_171074_19940812_20170112_01_T1	1994/08/12	30m x30m
LT05_L1TP_171074_19931028_20170116_01_T1	1993/10/28	30m x30m
LT05_L1TP_171074_19930825_20170117_01_T2	1993/08/25	30m x30m
LT05_L1TP_171074_19920416_20170124_01_T1	1992/04/16	30m x30m
LT05_L1TP_171074_19910921_20170125_01_T1	1991/09/21	30m x30m
LT05_L1TP_171074_19910414_20170127_01_T1	1991/04/14	30m x30m
LT05_L1TP_171074_19900817_20170130_01_T1	1990/08/17	30m x30m
LT05_L1TP_171074_19900411_20170131_01_T1	1990/04/11	30m x30m

7.1.3. Seasonal and inter-annual crop area in Nyamandlovu

To derive the area under cropland for the period between 1990 and 1999 and for 2020, the normalised difference vegetation index (NDVI), developed by Tucker (1979), was used. NDVI uses reflectance in the red and Near Infrared (NIR) spectral region to measure the vigor of the plant's health (Xue and Su, 2017). NDVI has been widely used to examine the relationship between spectral variability and changes in vegetation growth rates (Mutanga et al., 2017). It is a useful indicator in determining active crop areas in addition to detecting crop condition and the inherent crop changes or timely growth patterns. NDVI values range between -1 and 1, where -1 depicts water, 0 represents bare surfaces and 1 represents green, healthy vegetation. The NDVI is computed using equation 7.2:

$$\text{NDVI} = \frac{\text{NIR}_{\text{band4}} - R_{\text{band3}}}{\text{NIR}_{\text{band4}} + R_{\text{band3}}} \qquad (7.2)$$

Where $\text{NIR}_{\text{band4}}$ is crop reflectance in the near infra-red wavelength and R_{band3} depicts crop reflectance in the red portion of the electromagnetic spectrum of Landsat satellite imagery.

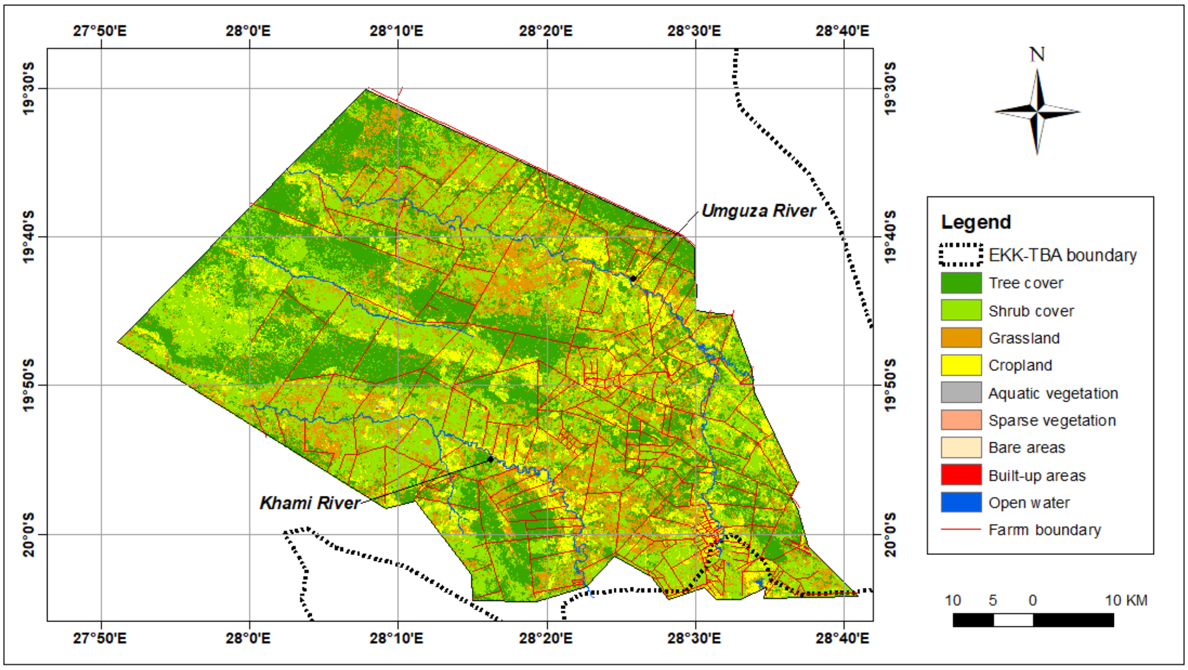


Figure 7.3: Land cover types in the Nyamandlovu area

To determine active (irrigated) cropped area, all farms in the Nyamandlovu area between the Khami and Umguza Rivers were digitized from a high spatial resolution SPOT image, Figure 7.4. The total cropped area was 6 902.75ha. The NDVI for the entire period was computed. A threshold technique was thereafter applied to mask out non-crop areas, e.g. bare surfaces and water bodies. All pixel values with NDVI values ≥ 0.2 were considered active croplands. This assisted in determining the variability in cropping patterns and associated crop coverage within the Nyamandlovu area.

The results indicate that the size in active (irrigated) crop areas (in hectares) varies significantly across seasons and years, Table 7.2. April 1990 and 1992, March 1993, as well as October 1994 and 1997 had the largest area of active crops with NDVI values ≥ 0.2. It is important to note that depicted variations can also be a result of the change in cropping patterns and not necessarily implying that during a particular season less crops were planted. Some crops might have been still young with small canopy cover when the satellite images were acquired, thus the 30-m Landsat image pixel sizes might have masked them; critical crop reflectance will be overshadowed by the background reflectances from non-target features such as the underlying bare surfaces.

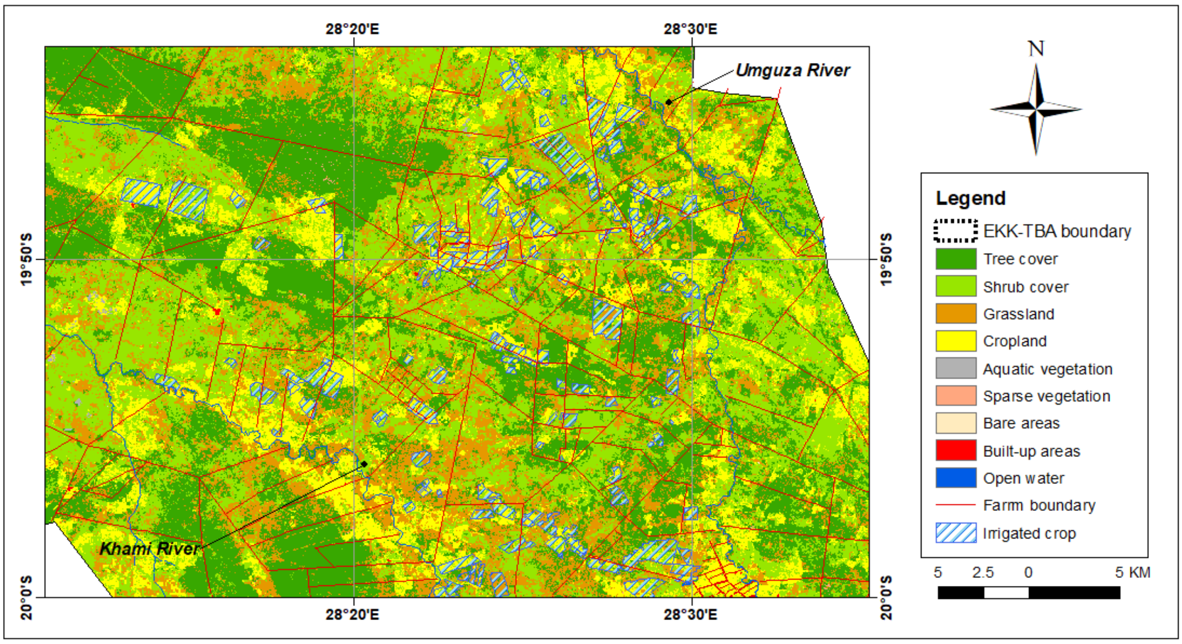


Figure 7.4: Irrigated crop areas in the Nyamandlovu area

Table 7.2: Estimated active cropping area and water use (1990 – 1999 and 2020)

Image Date	NDVI trends	Croplands (Ha)	Crop water use (m^3/day/ha)
05/1990	-0.46 – 0.71	1 232.9	11 219.1
08/1990	-0.28 – 0.78	284.3	2 586.7
04/1991	-0.79 – 0.56	220.0	2 002.0
09/1991	-0.14 – 0.60	202.8	1 845.3
04/1992	-0.21 – 0.70	1 238.1	11 266.4
03/1993	-0.32 – 0.78	98.4	895.7
08/1993	-0.26 – 0.73	189.4	1 723.7
10/1993	-0.74 – 0.28	27.9	253.8
05/1994	-0.33 – 0.73	481.5	4 381.2
10/1994	-0.32 – 0.59	1 159.5	10 551.7
10/1995	-0.18 – 067	230.7	2 099.0
10/1996	-0.23 – 0.73	354.9	3 229.4
10/1997	-0.32 – 0.59	1 159.5	10 551.7
08/1998	-0.40 – 0.76	134.0	1 219.6
11/1998	-0.25 – 0.59	85.9	781.6
07/1999	-045 – 0.78	446.5	4 063.4
05/2020	-0.14 – 0.56	228.6	2 080.0
Average		**443.7**	**3 930.6**

7.1.4. Crop water use estimation

The crop water use was estimated 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 and amounts to 3 332.6 m^3/yr/ha or 9.1 m^3/day/ha.

The largest active crop area was found for particular months of 1990, 1992, 1994 and 1997 and was between 1 159.5 and 1 238.1 ha. For these particular months/years, the active crop area is comparable to the irrigated (active) crop area of 1 200 ha as reported in Beekman and Sunguro (2015).

7.1.5. Remotely sensed crop area validation

The derived active crop areas require validation using field surveys. Intensive field surveys are recommended to determine the accuracy of the NDVI-based estimates. There is need to collect the geographic locations of the satellite mapped cropped areas and subsequently compute the actual individual cropping areas and then compare them with the crop areas derived from satellite data. Furthermore, it is recommended to acquire satellite imagery for the months of August to November to ascertain the actual active and irrigated crop acreage in the area. From the foregoing, it can be concluded that the NDVI remote sensing technique can be used for the Nyamandlovu area as a monitoring tool for determining the acreage of active crops and hence (ground)water use and also that it is a promising tool that can be used for other agricultural areas within the EKK-TBA.

7.2. Domestic water supply and water demand

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 handpump equipped boreholes in the case of Zimbabwe.

7.2.1. 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 (DWA, 2008). Abstractions have been increasing over the years due to increased water demand as a result of increasing population. The water demand stands at more than 6 000 m^3/day against a supply of about 4 000 m^3/day (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 population.

7.2.2. 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.

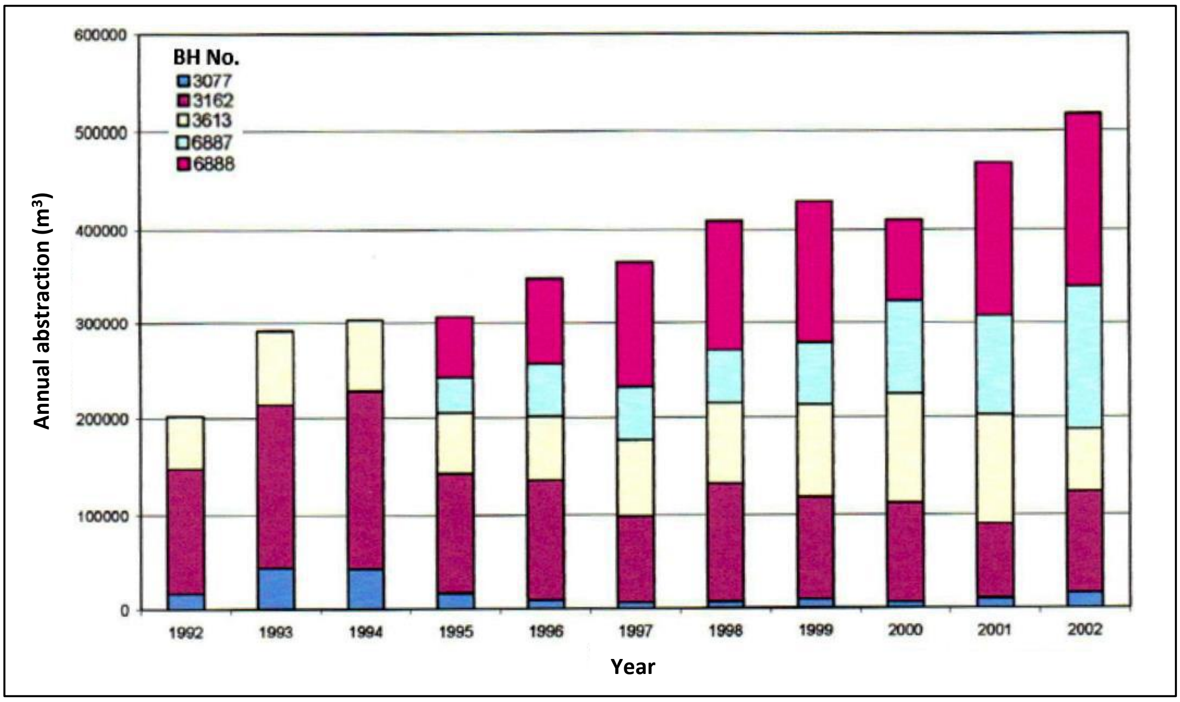


Figure 7.5: Letlhakane Wellfield annual abstractions
Source: Geoflux (2005)

Five new boreholes were drilled and developed in 2005 to give a combined yield of 274 m^3/hr and yet there still is a water supply deficit. Figure 7.6 shows the deficit in potable water supply up to 2020.

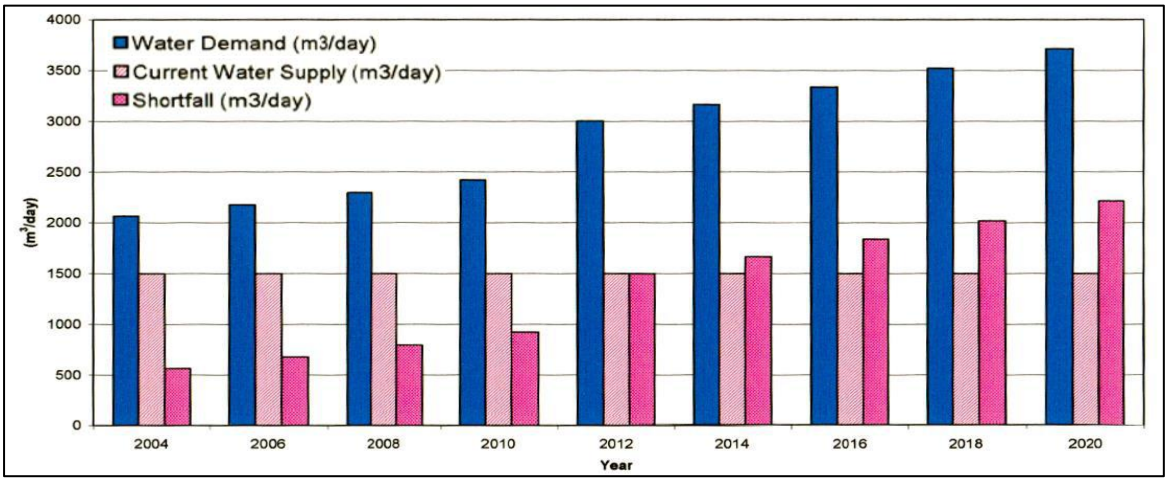


Figure 7.6: Letlhakane Wellfield - Water demand vs water supply
Source: Geoflux (2005)

7.2.3. Maitengwe Wellfield

The water demand in the Northeastern District in Botswana which is supplied by the Maitengwe Wellfield was estimated at around 9 700 m^3/day by 2025 against a supply of around 4 500 m^3/day, leaving a deficit of over 5 000 m^3/day and this calls for very effective and efficient strategies to manage the limited groundwater resources and optimise usage.

7.2.4. Nyamandlovu Wellfield

Groundwater from the Nyamandlovu area is used for agricultural purposes (irrigation and livestock), human consumption by the local population and to augment the City of Bulawayo's surface water supplies. Figure 7.7 shows monthly abstractions from the Nyamandlovu Wellfield for the City of Bulawayo over the period of March 1993 to July 1999. 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 must be developed including innovative water demand management strategies coupled with efficient water utilisation techniques, particularly for agriculture, to meet the ever-increasing demand.

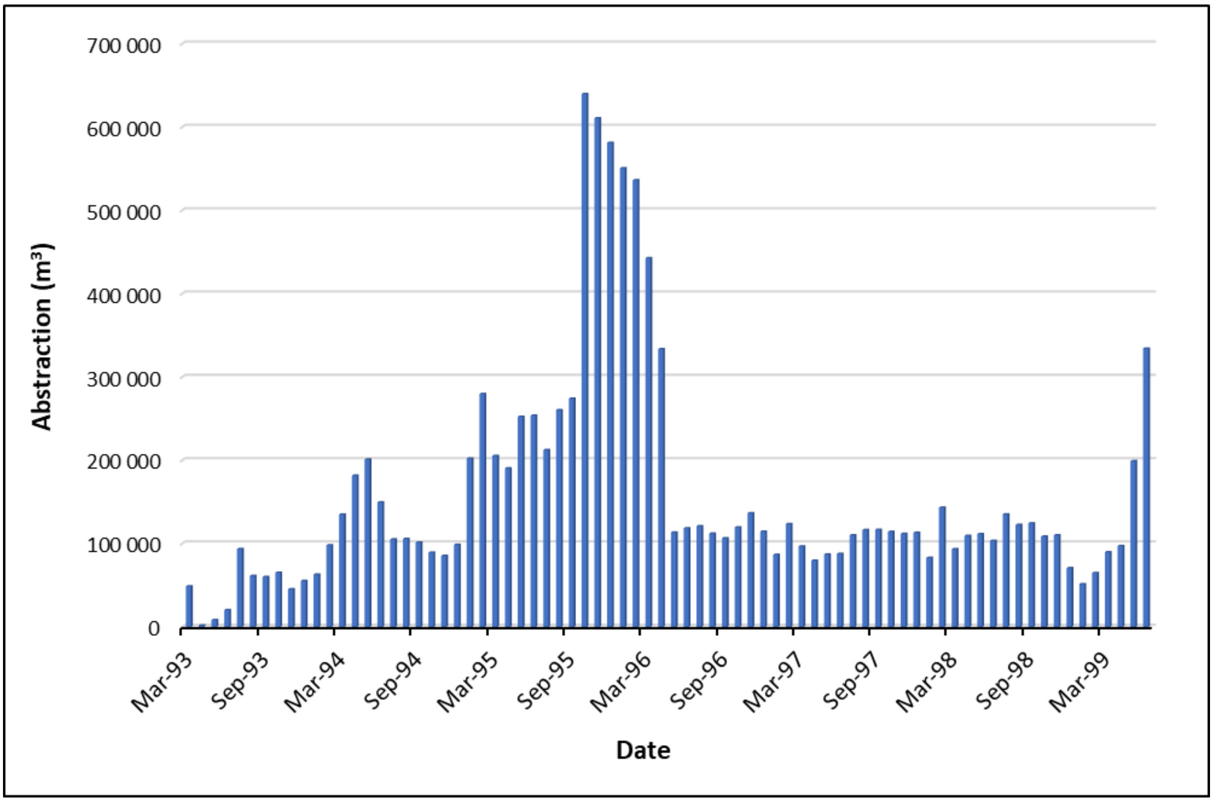


Figure 7.7: Monthly groundwater abstractions from the Nyamandlovu Wellfield
Source: Beekman and Sunguro (2015)

7.3. Mining

Within the EKK-TBA, mining takes place predominantly in the Botswana part (currently mainly diamonds and soda ash) and requires significant volumes of water. The mining sector in Botswana accounts for 10-15% of the total water use (DWA, 2014)[29] and in the EKK-TBA the source of water is almost exclusively groundwater 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.

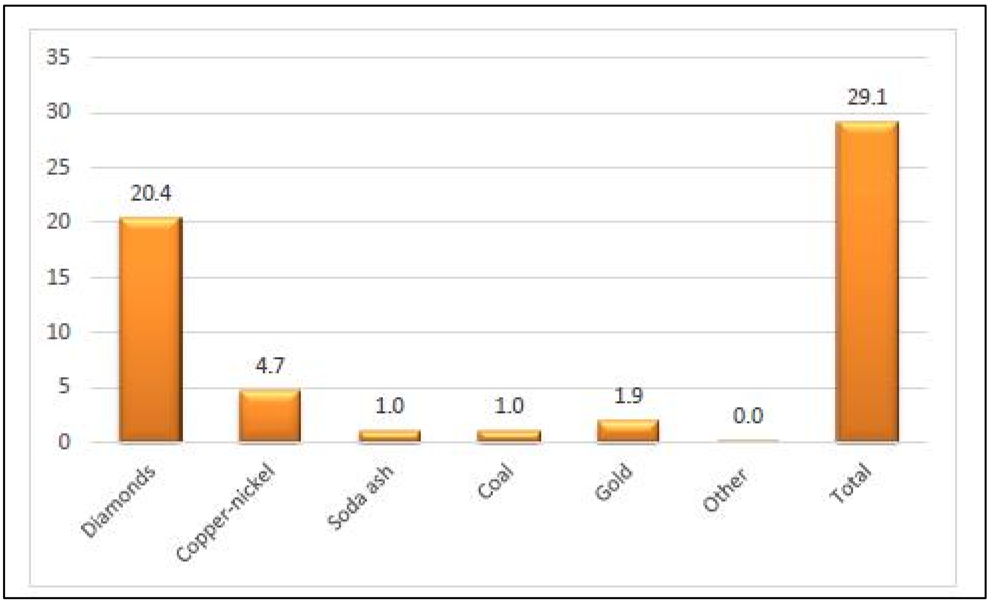


Figure 7.8: Water use in the Botswana mining sector (Mm^3/year)
Source: DWS (2018)

7.3.1. OLMD Wellfields

The Orapa, Letlhakane and Damtshaa diamond mines (OLDM) from Debswana (Figure 6.23) 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.

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

Figure 7.10 shows the water supply vs demand projections of OLDM operations up to 2050 (Debswana, 2015) with the water supply being demand driven which tends to negate the sustainability of supply, a critical consideration in a water stressed country such as Botswana.

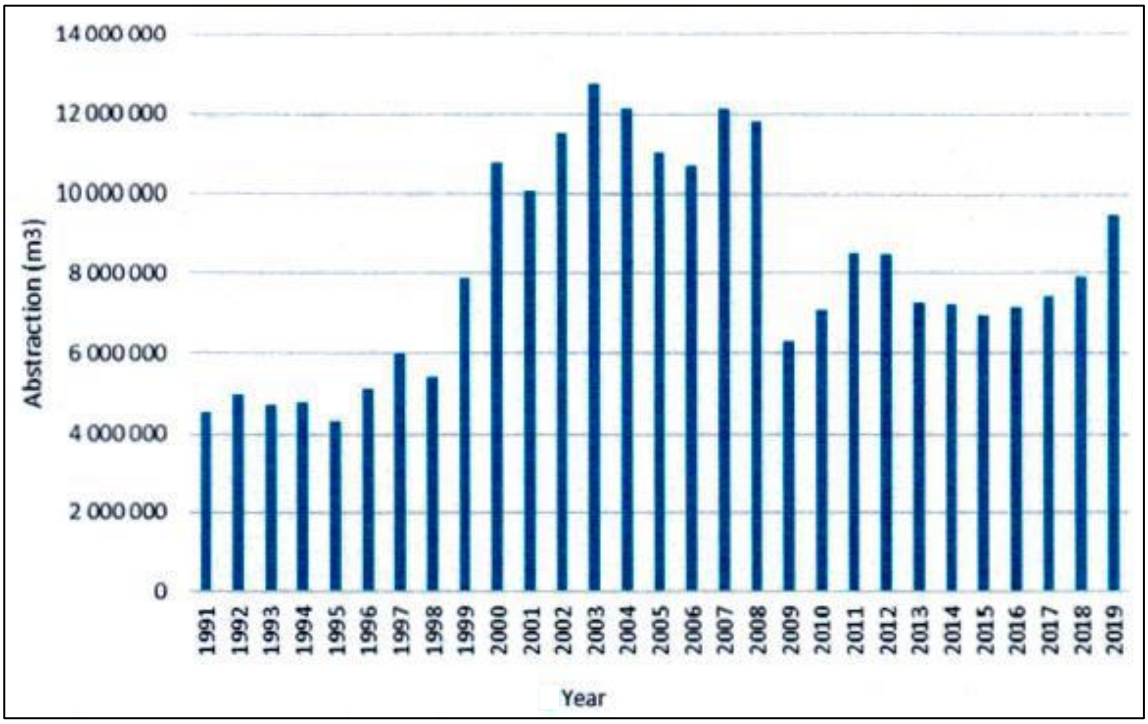


Figure 7.9: Total annual abstraction from OLDM's production boreholes
Source: Debswana (2020)

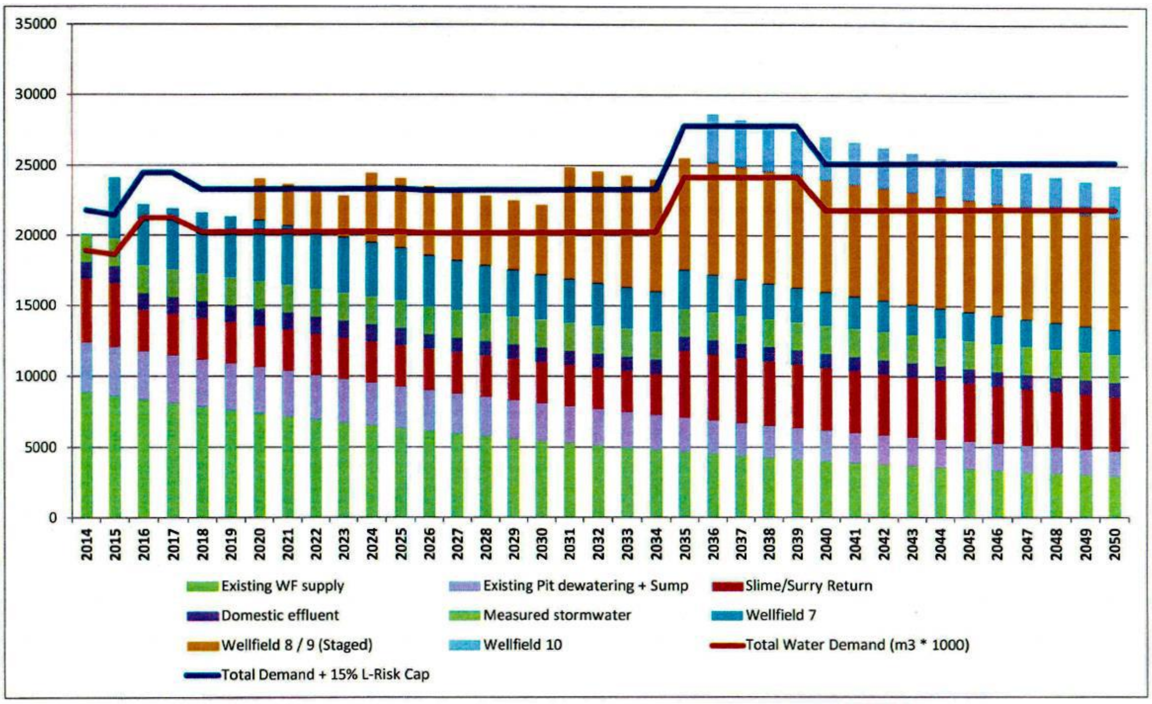


Figure 7.10: OLDM water demand and supply projections (m^3 * 1000)
Source: Debswana (2015)

Groundwater abstractions from Wellfields 2, 3, 5 and 6 are planned to decrease in the course of time; 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.

7.3.2. KDM Wellfield

The Karowe Diamond Mine (KDM) (Figure 6.23), 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 as reported by Royal HaskoningDHV (2017) and this needs to be independently established.

7.4. Environment, ecosystems, game parks and reserves

Water for the environment and ecosystems is an important consideration in water allocation. It sustains plants, animals and micro-organisms which are critical components of ecosystems. Environmental flows describe the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems as well as the livelihoods and well-being of those who depend on them. Sufficient water is also critical to sustaining ecosystems that promote tourism. This section therefore looks at water use in the environment, ecosystems, game parks and game reserves found in the EKK-TBA.

7.4.1. Environment and ecosystems

Water in the EKK-TBA environment, especially within the protected areas, serves as a habitat and breeding grounds for wild animals and birds, and supports plant life and micro-organisms.

Makgadikgadi Pans and Nata Bird Sanctuary

The Nata Bird Sanctuary is found in the corner of the Sowa Pan (part of the Makgadikgadi Pan complex), where the Nata River delta is located, (Figure 5.6). The Sanctuary protects an ecologically sensitive and important natural environment for a range of animals, birds and plants. Over 165 bird species are found in the area, including the greater and lesser flamingos (about 250 000) which appear seasonally to breed, depending on the rains (Figure 7.11). When the rains are abundant, the Makgadikgadi salt Pans are covered in shallow waters, rarely deeper than 50 cm, appearing as an immense blue lake[30]. Besides the birds, the rains which arrive in December to April, render the Makgadikgadi Pans breeding grounds to a wide range of animals including elephants, herds of zebras, springboks, giraffes as well as reptiles and amphibians. The seasonal increase in herbivores in the pans during the rainy season attracts predators such as lions, cheetahs, and hyenas in their hunt for food.

Figure 7.11: Flamingos in the Nata Bird Sanctuary
Source: Nthomiwa (2016)

The Boteti River is the main river that feeds into the Makgadikgadi Pans and is also home to the Bayei, a tribe of fishermen and agriculturalists in Botswana. Fishing is one of the tourism activities, as in the Okavango Panhandle, known for its legendary tiger fish. The Boteti River also provides for some fishing activities sustaining livelihoods of the local communities through the Boteti River Fishery (Mosepele, 2014).

Hwange National Park

The Hwange National Park (HNP) covers large swaths of the basin on the Zimbabwe side of the EKK-TBA. The HNP is surrounded by communal areas where livestock and crop production are practiced by the communal farmers. Domestic and wildlife coexist in the forest reserve

[30] https://www.exploring-africa.com/en/botswana/makgadikgadi-pans/makgadikgadi-pans-climate-and-when-visit

and in the communal area but the HNP is uninhabited apart from a few tourist resorts that rely on groundwater for their needs. The Zimbabwean authorities have pointed out that the elephants have exceeded the carrying capacity of the HNP, which is impacting the ecosystem within and outside the park and causing the destruction of key vegetation. Figure 7.12 shows a typical waterhole supplied by groundwater within the HNP.

Figure 7.12: A typical waterhole in Hwange National Park

Land use is a strong driver of aquatic ecosystems as it determines allochthonous substances and the concentrations that reach water, as well as transportation rates and fluxes between the terrestrial and aquatic habitats (Brendonck et al., 2008; Davis et al., 2015; Nhiwatiwa et al., 2011; Pacheco and Fernandes, 2016; Williams et al., 2016). Land use also drives species diversity and abundance, hence any changes in land use such as deforestation and increased agriculture and urbanisation have profound effects on freshwater ecosystems (Catherine et al., 2008, Kelley et al., 2000, Stomp et al., 2011). Water level fluctuations (WLF) and drying up affect species living in the aquatic–terrestrial transition zones, in particular, littoral helophytes and benthic invertebrates as well as organisms living in the pelagic zone (Teferi et al., 2014).

WLF and water scarcity in arid and semi-arid ecosystems are a major issue for wildlife conservation and domestic herbivores (Epaphras et al., 2008; Fynn et al., 2015; James et al., 1999; Pettit et al., 2012; Wolanski and Gereta, 2001). In addition to drinking water, WLF determine plant zonation in wetlands and, as a result, access to key sources of forage for wild and domestic herbivores during the dry season (Fynn et al., 2015; Pettit et al., 2012). To support pastoralism and conservation objectives, artificial sources of water have been created, by feeding natural waterholes with groundwater. Given that aquatic ecosystems provide valuable water and forage sources in semi-arid regions, it is important to understand their structure and functioning for management and conservation purposes as they are major contributors to regional biodiversity in and around the HNP (Williams, 2005).

Hwange National Park is a typical semi-arid savanna with a surface water deficit for the greater part of the year (Chamaille-Jammes et al., 2007; Msiteli-Shumba et al., 2018). Due to the water deficit, 67 boreholes were installed at some natural waterholes and wetlands, allowing for the artificial pumping of groundwater to ensure water availability throughout the year (Msiteli-Shumba et al., 2018). Without artificial pumping, only 19.6% of the park remains within 5 km of a water source under average climatic conditions. However, Chamaille-Jammes et al. (2007) argue that modifying the hydroperiod of HNP aquatic ecosystems through pumped groundwater might have profound effects on their functioning and might change the driving factors.

It was previously suggested that pumping water into most arid protected areas has produced more negative than positive results (Redfern et al., 2005; Msiteli-Shumba et al., 2018). The argument proffered was that this leads to vegetation trampling throughout the year and increasing predation around waterholes (Illius and O'Connor, 2000). Moreover, pumping may induce the deterioration of water quality through contamination from saltwater intrusion, a major concern in semi-arid and arid environments (Borrok and Engle, 2014).

7.4.2. Game parks and reserves

Orapa Game Park

The Orapa Game Park, one of Botswana's conservation areas, lies within the boundaries of the Orapa mining lease area. The 48 974-hectare Park provides for conservation of biodiversity and promotes scientific research and tourism for the benefit of the Boteti region and the nation at large[31]. In the mostly arid areas of the mine and game park, groundwater is often the only water source (Debswana, 2017). The boreholes (wells and communal standpipes) that supply the villages are owned and operated by the Boteti Sub-District Council and WUC. The mining company Debswana has access to its own wellfields in which the boreholes tap deeper aquifers to supply groundwater to the mines and their residents (*ibid*).

Makgadikgadi National Park

The Makgadikgadi Pans are the world's largest salt pans and are home to the Makgadikgadi National Park. The pans and their surroundings support an array of wildlife (Figure 7.13). The pans are dry for much of the year but during good rains, shallow water collects in the pans, attracting animals and birds including flamingos (Siyabonga Africa, n.d.).

[31] http://www.debswana.com/Careers/4Cs/Connection/Pages/TheEnvironmentAndGameParks.aspx

Figure 7.13: A herd of zebras drinking at the Makgadikgadi Pans
Source: Okavango Expeditions, n.d.

Boteti River

The Boteti River forms a natural boundary between the Makgadikgadi Pans National Park and nearby cattle-ranching villages. The river provides a crucial lifeline for wildlife during the dry season. The Makgadikgadi Pans National Park receives herds of zebras which move in to live along and drink from the Boteti River, during this season. The river becomes the only source of water in the dry season. With the coming of the rains, in early summer, the herds move east to open grassland, where temporary pools filled with water become the watering holes with the margins of the rain-filled salt pans providing nutritious grasses (*ibid*).

In 2007, waterholes were dug by the government authorities and lodge owners to provide water to the wildlife during droughts. The waterholes provide a source of drinking water for wild animals including zebras, elephants, among others. Whilst boreholes were sunk to access water for the animals, a fence was erected to separate the waterholes between park animals and domestic lands (Siyabonga Africa, n.d.).

Hwange National Park

There are various water points in the HNP which consist of pans, seeps, springs and pools, with the majority of these being seasonal and containing water during the rainy season only. Due to perennial water shortages, artificial water points were sunk close to several pans to pump water into them. The north-eastern Kalahari region of HNP consists of 40% of the artificial water points of which there were 13 operational boreholes during the study by Sungirai and Ngwenya (2016).

Sungirai and Ngwenya (2016) found out that water consumption in HNP was dependent upon the seasonal conditions. The study also found out that more animals congregated at the water points as the dry season progressed with a significant drop in the amount of water consumed by wildlife in the month of July which is the coldest month in HNP, hence water demand is expected to be low during this time of the year (*ibid*). The greatest water consumed was in the month of November, which is the hottest period within HNP. As the dry season progresses there are a lot of significant ecological and physiological changes, which occur in the habitats and wildlife respectively (*ibid*). For example, forage availability is low during the dry season such that even the water independent species like the eland, which depend on succulent feeds for their water requirements, are also seen at water points.

Interestingly, the study also found out that vegetation had no effect on the consumption of water by wildlife and that animals congregate on the few water sources available and spread out over a large area during the wet season. This basically means that water availability is a key determinant of the dry season concentration of wildlife around water sources, regardless of the vegetation type in question.

The study also established that HNP had inadequate game water supplies, which was exacerbated by a reduction in the number of functional boreholes, with only 56 out of 80 boreholes being operational. The creation of artificial water sources force wildlife to concentrate at the few watering points which results in habitat destruction. Since its inception, the HNP has been abstracting groundwater, mainly from the Kalahari Sand Aquifer, for wildlife during the dry season. According to a hydrogeological study carried out in the region, groundwater abstraction for wildlife in the long run is not an issue of concern if more boreholes are installed and kept functional (WWF, 2019).

7.5. Key Messages

- The NDVI remote sensing technique has the potential to be used in the timely determination of active crop areas and the crop water requirements in the EKK-TBA and can be used in estimating the amount of groundwater used, which guides decision making in sustainable groundwater resource management.
- Water demand for all sectors (domestic, agriculture, industry including mining, and biodiversity) currently exceeds water availability which is compounded by reduced rainfall as a result of climate variability and change and an increasing population.
- The current installed water supply also exceeds water availability.
- The above calls for immediate measures to balance water demand, water supply and water availability as to ensure sustainable utilisation of water resources, e.g. through innovative water management strategies
- Water supply being demand driven for mining operations tends to negate the sustainability of supply, which needs to be looked into, especially in a water stressed country such as Botswana.
- The generally semi-arid setting of the EKK-TBA is characterised by seasonal water sources such as shallow water pans, seeps, springs, pools and ephemeral rivers (critical water

sources for wildlife), the majority of which dry up during the dry season. The conjunctive use of water resources enables a continuous supply of water to the wildlife and this will increasingly become important with longer term climate change impacts.

- There is limited information available on groundwater dependent ecosystems within the EKK-TBA and this requires further investigation.
- There is a critical need for the assessment and quantification of the sustainability of water resources, together with a sound understanding of current and future water use requirements for the various sectors (domestic, agriculture, industry including mining, and biodiversity). These would enable the development of a sustainable basin level water allocation plan.

8. LAND USE AND LAND COVER

8.1. Land Use

The EKK-TBA, from a land use perspective, is dominated by the presence of national parks, forest reserve areas and wildlife management areas (Figure 8.1). These areas are of significant international and national importance and besides ensuring levels of environmental protection also provide for local and associated socio-economic activities.

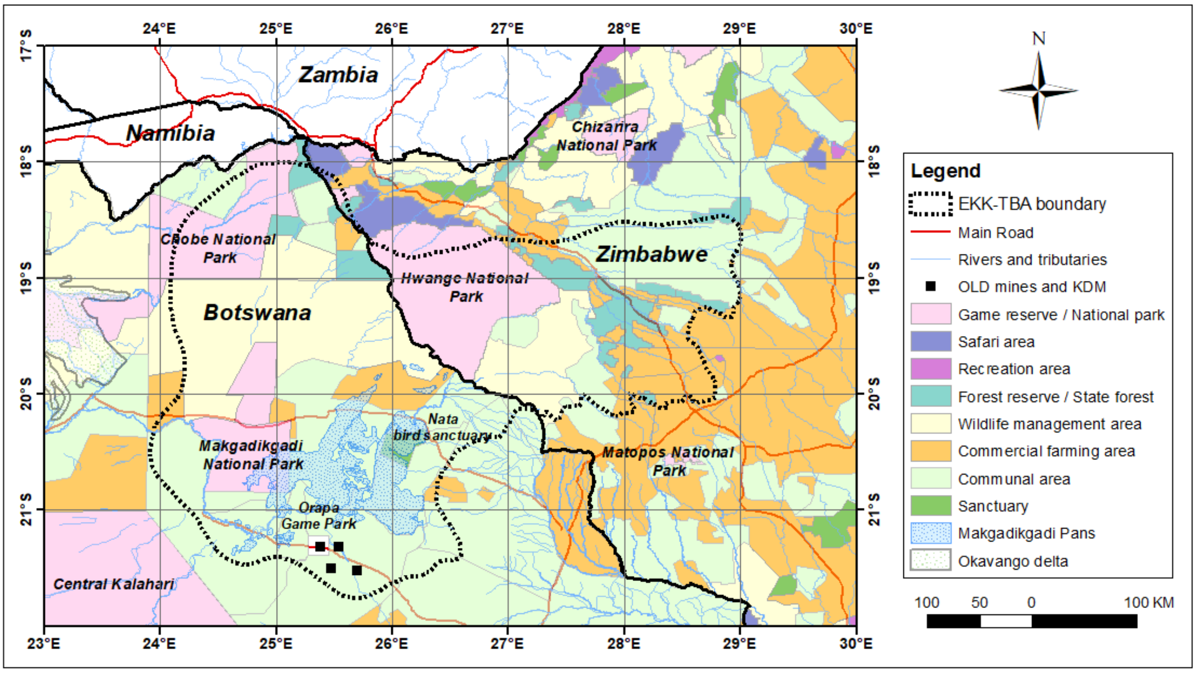


Figure 8.1: EKK-TBA land use map

Other land use activities in the EKK-TBA are mining, agriculture (including cropping, livestock and pastoralism) and human settlements. These can have significant impact on the status of land and water resources (e.g. over-exploitation of (ground)water resources and pollution) in the EKK-TBA. As economies develop, there will be increased pressure to expand such developments, potentially placing areas of environmental importance under pressure. Noting the importance of these land use activities to national and regional economies, there is need to find a balance between these developments and the protection of the environment and biodiversity.

8.1.1. Mining

Mining is an extractive process that consumes land and water resources, often resulting in environmental pollution and degradation (Warhurst and Noronha, 2000).

Diamond and coal mining are key economic activities in the Botswana part of the EKK-TBA and have an environmental impact on the EKK-TBA, specifically around Orapa Town and

Letlhakane Village. In 2016, the Government of Botswana approved a license for the mining of uranium in Letlhakane (Letlhakane Uranium Mine). Uranium mining presents risks of radioactive toxic elements affecting air quality and the land.

The environmental effects associated with coal mining are well researched and have been shown to be largely negative. The biproducts of coal mining operations carry health risks for the human and animal population in the mine-surroundings. The mining operations carry risks of pollution to wetlands and their ecosystems, including surface water and groundwater sources. The significant depths of excavation associated with the mining operations present the risk of groundwater pollution. Coal mining also produces large mountains of solid waste and coal heaps which are prone to spontaneous combustion. Furthermore, leachate from waste heaps is often acidic, thereby aggravating general and large-scale acid mine drainage (AMD) that can pollute both surface water and groundwater.

The anticipated intensification of mining in Botswana, as can be seen from an increased number of existing prospecting mining licences in the country, is likely to have detrimental impacts on the environment, including, increased land pressure, land exposure and deforestation (Engleton et al., 2012). This heightens the potential for conflicts between the major land use sectors such as mining and agriculture.

In Zimbabwe, the Hwange District, which partly overlaps the EKK-TBA, is primarily a mining district. However, within the EKK-TBA there is no major mining activity. The Hwange Coal Mining and the Hwange Coal Power Station for example are located outside the EKK-TBA but the impact of their operations on the EKK-TBA are not known and need to be investigated.

8.1.2. Agriculture

Situated in Botswana's EKK-TBA is Pandamatenga Village where commercial farming is practiced as the main land use activity. The village is considered most suitable for farming due to its characteristic fertile black cotton soils and favourable rainfall conditions averaging 600mm annually. Pandamatenga farms (Figure 8.2) 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.

Figure 8.2: Grain farming in the Pandamatenga area
Source: The Conservation Imperative (2019)

The project involved the allocation of 25 000 hectares of virgin land to pioneering commercial farmers. While undertaking interventions to transform the expansive virgin land into agricultural land, one of the challenges the farmers faced was the interference and destruction of crops by wild animals in the area[32] as there was no fencing to keep them out. In 2002, the government erected an electric fence approximately 160km in length around the farming area enclosing an area of approximately 43 000 hectares of cropping land. The fence keeps most wild animals out of the farms, helping to boost crop production (The Conservation Imperative, 2019).

Livestock and subsistence farming make up the most important part of people's livelihoods in Zimbabwe's part of the EKK-TBA. Major commercial agricultural activities (livestock and irrigated cropping) in Zimbabwe occur in the Nyamandlovu and Umguza areas and provide fresh produce and to the City of Bulawayo and surrounding areas (Figure 8.3).

8.1.3. Eco-Tourism

Wildlife in northern, central and south-western Botswana provides for an important economic resource through eco-tourism (Winterbach, 2014; Winterbach and Somers, 2014). The Orapa Game Park, near the Debswana Orapa mine within Botswana's EKK-TBA, lions, jackals, and springboks are some of the wild animals that may be found. The Nata Bird Sanctuary, at the north-eastern periphery of the Sowa Pan which is part of the Makgadikgadi Pans, is the only bird protected reserve in Botswana and covers an area of approximately 230

[32] https://www.facebook.com/theconservationimperative/videos/1357720404351667 Pandamatenga Farming Project Botswana

km^2. The sanctuary is home to 165 species of birds including flamingos and the great white pelican among others.

Figure 8.3: Commercial agriculture in the Nyamandlovu area

The Makgadikgadi Pans are salt pans comprising wetlands located in the middle of the dry semi-arid areas of northern Botswana and attract tourists. The pans are all that remains of the former Lake Makgadikgadi, which dried up tens of thousands of years ago. The area is of archaeological significance with studies linking the origin of modern Homo sapiens evolution to this region some 200 000 years ago, when it was a vast, exceptionally fertile area of lakes, rivers, marshes, woodlands and grasslands especially favourable for habitation by mammals (Chan, 2019).

The Hwange National Park (HNP) is the largest protected area in Zimbabwe and forms part of the Kavango-Zambezi Transfrontier Conservation Area (Government of Angola, 2011). It covers an area of over 1.4 million hectares and is home to rich biodiversity and adjacent to important land concessions (Loveridge et al., 2007a). There are around 400 bird species and 107 animal types and is mostly known as the habitat for one of the world's largest population of elephants, estimated at around 50 000. Within the park are located key presidential elephant waterholes such as the Kanando Pan and Mpofu Pan (African Conservation Foundation, 2014). Since 2010, holistic management has been implemented in the Hwange Communal Lands (HCLs) with the aim of restoring degraded watersheds and croplands through proper livestock grazing management. The approach involves holistic planned grazing (Chatikobo, 2015).

While tourism is a key economic activity supporting the national economy in general and livelihoods within the area in particular, there are reports of human-wildlife conflicts arising from encroachment of human settlements into the park as they search for pastures for their livestock and farming area. In addition, wildlife occasionally wanders into communities and surrounding villages to the park and destroy crops and livestock and this affects the livelihoods of the communities. Prolonged droughts are reported to worsen the incidence of human-wildlife conflict. For example, in 2019, 311 animal attacks on people and 36 human fatalities were recorded and in 2018, 195 animal attacks on people and 20 human fatalities[33].

8.1.4. Land degradation

Increased land degradation in the North-Eastern District of Botswana, which partly covers the EKK-TBA, has been associated with poor land use practices deployed by communities, such as deforestation and overgrazing. Climate change is likely to exacerbate land degradation – a challenge linked to poor farm practices and exacerbated by occasional intense rains (Sida, 2008).

In Botswana, wood fuel from forests and woodlands accounts for 70% of net energy supply in Botswana (Sida, 2008). Wood fuel is the main source of energy for Botswana's rural households (UNEP, n.d.). High reliance on wood for fuel resulted in significant depletion of trees (deforestation) around towns and major settlements. Several policies were introduced to address land degradation, by advocating for the privatization of land use, which establishes fenced commercial cattle ranches with exclusive grazing rights. The aim was to promote more sustainable land management (Dahlberg, 2000). While the anticipated positive impact of these land privatization policies has not been realized over the last few decades, the official view remains that uncontrolled management of communal grazing is not only unproductive but has led to unprecedented range degradation (Government of Botswana, 1991).

In Zimbabwe, the Hwange District, which partly covers the EKK-TBA, is known for rampant deforestation, resulting from the unquenched demand for wood fuel as the country grapples with lengthy daily power cuts of up to 10 hours in some parts[34]. As wood is fast becoming the main source of heating and cooking, especially for the poor (Figure 8.4), it is leading to the destruction of forests. While concerns have been raised about the massive deforestation for charcoal, weak surveillance and policing regimes against the backdrop for huge demand for charcoal (resulting from electricity shortages and high electricity costs), hinder the cessation of this environmentally harmful activity. Although communities engage in tree cutting for a thriving charcoal business, the business is illegal.

[33] https://www.zimlive.com/2020/01/15/prolonged-drought-re-ignites-human-wildlife-conflict-in-hwange/ MAT NORTH, News

[34] https://allafrica.com/stories/201906280228.html Zimbabwe: Power Cuts Drive Deforestation

Figure 8.4: Wood for firewood collected often by women in households
Photo by Evidence Chenjerai: Global Press Journal (2019)

Whilst policies exist to curb the charcoal business, implementation is hampered by weak enforcement regime, corruption and poorly capacitated institutions. For example, while the Statutory Instrument 112 of 2012 - the Forest Regulations provide for control of firewood, timber and forest produce, their enforcement has proved problematic as the Forestry Commission finds it difficult to prove whether or not the charcoal was produced in Zimbabwe (Nemukuyu, 2019).

8.1.5. Climate variability and change

Brazier (2015) in her report on climate change in Zimbabwe noted the following likely changes between 2050 and the end of the century:

- A modest decrease in total amount of rainfall
- Changes to the onset and end of the season
- More frequent and longer mid-season dry periods
- Erratic rainfall distribution
- More droughts and floods that may recur in successive years
- Temperature increase of between 1°C and 3°C, which is greater than the global average

The abovementioned effects of climate change are also likely to apply to the EKK-TBA (see also Chapter 4). The effects would lead to degradation of natural resources, especially soil, water, natural vegetation, crop, livestock and wildlife species. The future impacts of climate change in the EKK-TBA will exacerbate the harmful effects of poor land-use practices, notably deforestation and overgrazing.

8.2. Land Cover

Figure 8.5 depicts a satellite derived land cover map for the EKK-TBA, specifically showing woodland, shrublands, croplands, grasslands, riparian vegetation, sparse vegetation, bare-lands, built-up areas, and water bodies.

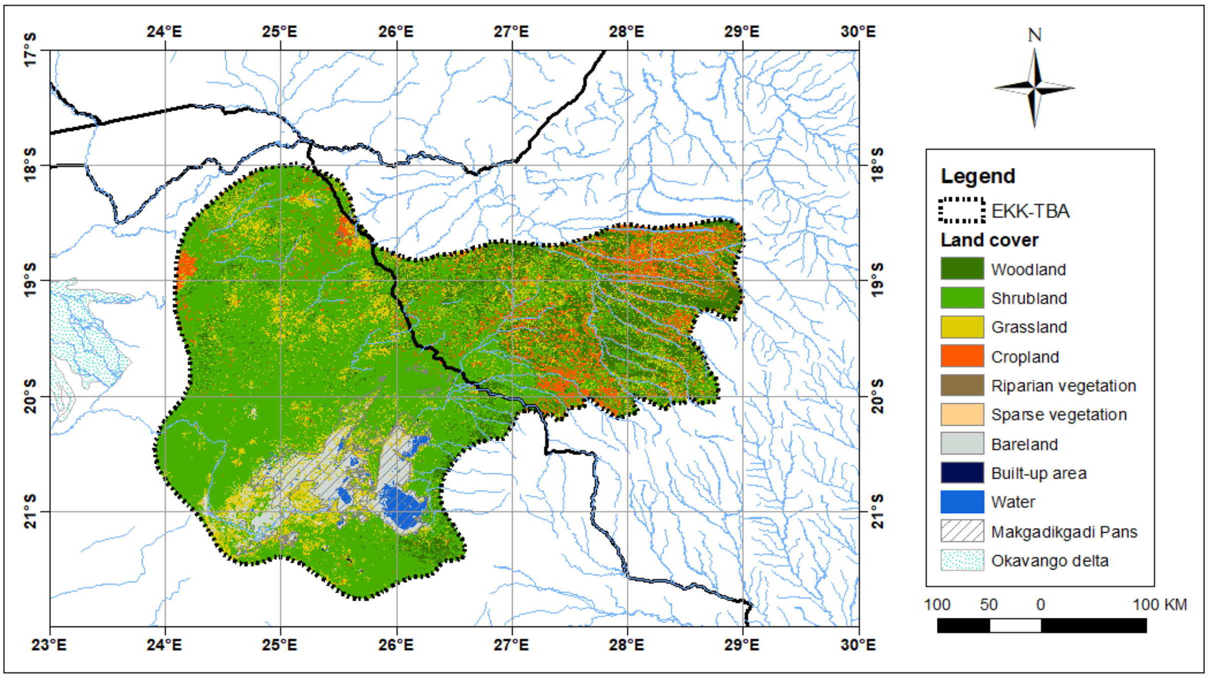


Figure 8.5: EKK-TBA satellite derived land cover map

Linked to Figure 8.5 is Table 8.1 which depicts the percentage area covered by each land cover type in the EKK-TBA. It was calculated using statistical tools in a GIS environment.

Table 8.1: Land cover EKK-TBA

Land cover type	Area (% EKK-TBA)
Woodlands	12,9
Shrublands	58,9
Grasslands	13,8
Croplands	7,7
Riparian vegetation	<0.1
Sparse Vegetation	<0.1
Barelands	5,4
Built-up Areas	<0.1
Water	1,3

Source: ESA (2016)

The vegetation cover in the EKK-TBA is classified as bush and tree savannah, with alternating grassland biomes (see also Jonker, 2016). There is a predominance of Kalahari deciduous Acacia thornveld such as open savannah *erioloba* and *Acacia haematoxylin*, along with desert grasses (*ibid*). The occurrence of these deep root shrubs and trees is telling of the availability of deeper soil moisture and the distribution of rainfall which varies from north (on the average 575 mm/yr) to south (on the average 375 mm/yr) (see Chapter 4). Greater abundance of shrubs and trees occur along river channels and water pans, whereas areas associated with bedrock outcrop have sparse vegetation cover.

In Botswana, the north-east is characteristically covered in tree savannah and woodland, compared to the low shrub savannah vegetation in the southwest. This distinction in vegetation cover can be explained by the higher annual precipitation received in the north-eastern part of Botswana compared to southern part.

Whilst human activity and livestock have had an impact on the vegetation, most indicators of land degradation are absent in the North East District, implying that the land has not lost its productive potential (Dahlberg, 2000). Communal land use practices in the district include alternating cultivation and grazing (*ibid*).

The open-pit mining method used in the mining of diamonds in Orapa and other neighbouring towns and villages in the EKK-TBA has been associated with detrimental effects on the environment and the people both during and after production (Warhurst and Noronha, 2000). Due to a shortage of accommodation in the diamond mining town of Orapa, many of the mine workers reside in neighbouring Letlhakane and Mopipi Villages. The Boteti sub-district suffered severe land degradation due to its mining activities (Warhurst and Noronha, 2000).

Furthermore, with the inception of diamond mining, significant changes were realised in the mix and areal coverage of land use and land cover types. The result has been a decline in vegetation cover and accompanying increased exposure of the land to desiccation and accelerated soil erosion (*ibid*). The mining of diamonds has driven encroachment on agricultural land and the spatial growth of human settlements onto agricultural land (Engleton et al., 2012).

Most of the central and western parts of the Hwange National Park in Zimbabwe's EKK-TBA are covered by Kalahari Sand, with the two main vegetation types predominantly being woodlands and woody scrub. The woody vegetation on Kalahari Sand deposits in the National Park was classified into nine species. The overall vegetation structure is predominantly determined by the depth of sand and soil moisture (Childes and Walker, 1987). The Kalahari woodland is dominated by Zambezi teak, Sand Camwood *(Baphia)* and Kalahari bauhinia (Hyde et al., 2010). Grasslands are formed around seasonal wetlands in this area. In the north and north-west of the park, the Mopani woodland is the predominant land cover (*ibid*). There are over 1 070 plant species in the park which include about 255 trees and shrubs and over

202 grasses (Makaka and Mazire, 2003). The vegetation of Hwange National Park constitutes 64% woodland, 32% scrubland, with only 4% covered in grasslands and savannah (Hwange Management Plan, 2003). Small areas of grasslands grow along drainage lines and on higher ground in the north-west of the park.

Due to the growing elephant numbers in the National Park, reported to be above the park's carrying capacity, there has been observable modification of vegetative cover linked to elephant activity which destroys many trees and plants in the park (Childes and Walker, 1987).

8.3. Land Tenure

Generally, land tenure systems influence land use development (Bassey, n.d.). The resulting land use and level of implementation of regulations/controls may influence the level of protection afforded to eco-systems and water resources and even the extent of land degradation (*ibid*).

At independence in 1966, Botswana inherited three types of tenure: the tribal land, state land and freehold land (Machacha, n.d.). Today, 80% of the country's population resides in the tribal areas. Under tribal (or customary) land tenure, while the owner has a right to perpetual use of the land (which can be transferred and inherited), the land remains the property of the State. The Government of Botswana owns the State land under the State Land Act. In the freehold land tenure system, the land is held in perpetuity and the owner is free to sell, lease and mortgage the property to both citizens and non-citizens subject to the Land Control Act. The freehold land tenure system has presented challenges in the North-East District where most of the land is still held under freehold titles. Before the turn of the century, a large part of the district was managed as private farmland under freehold tenure (Dahlberg, 2000). As a result of colonial rule, communal land decreased giving way to an increase of human and livestock population densities across the remaining communal land. Freehold farms cover more than half of the district (*ibid*). This predominance of the freehold tenure characterized by perpetual and exclusive owner rights to land, has been linked to severe land scarcity, especially for communal use in the district (Manatsha, 2019). To address the challenge, the government purchased 19 freehold farms between 2005 and 2008 for redistribution (*ibid*). However, challenges related to land tenure remain. The district grapples with the contested land reform problems, where politics and elitism have seen the systematic marginalization of communities (*ibid*).

With respect to water rights, land boards allocate parcels (areas) for borehole drilling or dam construction. There are no exclusive rights for owners of water points to the grazing areas around 'their' water sources. As such, most of the grazing land in Botswana is largely communal. However, owners of water sources have de facto rights to grazing areas around the source, specifically in sandvelds where there are no permanent surface water sources (AfDB, 2016).

The land in Hwange National Park and surrounding areas is classified as State land. Illegal land occupation is reported to have affected the Hwange area specifically in Kanondo near Hwange National Park (African Conservation Foundation, 2014). Illegal land occupation threatens the work of conservationists to implement the necessary protection measures in the Park. A weak policy enforcement regime has been viewed by some conservationists as ineffective in addressing the negative effects of the illegal land occupation on preserving the protected area. For example, in 2013, a directive by Zimbabwe's Cabinet for the withdrawal of Land Offer Letters issued to individuals for land in the area was ignored, putting the protection of key elephant waterholes – the Kanondo and Mpofu Pans and the elephants at risk (*ibid*). The EKK-TBA in Zimbabwe remains highly vulnerable as an eco-system and habitat for wildlife and requires measures to enable the effective implementation of conservation efforts.

8.4. Key Messages

- The mostly semi-arid EKK-TBA is significant for its vast economic and natural resources and as such this area provides for socio-economic development linked to biodiversity conservation, agriculture, and industries such as diamond and coal mining. Both Botswana and Zimbabwe derive a significant amount of their energy from coal powered plants, and thus the mining of coal (on the Botswana side of the EKK-TBA) is of strategic importance despite the impacts that it has on the land and local water resources.
- The EKK-TBA faces significant negative environmental threats from poor land use practices and climate variability and change. Owing to the large dependence on mining, Botswana's EKK-TBA faces risks of pollution of rivers, wetlands and in the longer-term, aquifers.
- The EKK-TBA is endowed with various wetlands and protected areas such as the Hwange National Park, the Nata Bird Sanctuary, salt pans, wetlands, and waterholes. The wetlands provide for concentrated human activity and settlement and provide a natural breeding habitat and a drinking place for wild animals. The range of biodiversity and ecosystems in the EKK-TBA, provides the basis for ecotourism as a major contributor to the economies of both countries. However, the travel ban due to the global Covid-19 pandemic has seen a significant impact on both countries' economies as revenues from international tourism has plummeted. The long-term impact on the countries' economies and the basin's communities is yet to be quantified. Communities may be forced to look for alternative income generating activities that may impact on land and water resources.
- Climate change poses a risk to ecosystems. The evidence of the impact of climate change on the basin's wetlands can be seen from the drying up of the Makgadikgadi salt pans in Botswana, which historically, used to be a freshwater body. In the face of envisaged climate change impacts on the already vulnerable ecosystem, the protection of the EKK-TBA is paramount to ensure the preservation of the natural habitats and biodiversity in the basin.

- Large scale deforestation presents a risk to protected areas and requires that regulatory regimes be strengthened with strict enforcement against illegal land degradation and particularly tree cutting to abate the thriving illegal charcoal business. Notably, addressing the energy challenges in Zimbabwe may hold part of the solution to reducing deforestation, as it will reduce the demand for charcoal for heating and wood fuel.
- Land degradation due to poor agricultural practices should be addressed by implementing climate smart agriculture.
- Political will and improved regulation will be needed to ensure the enforcement of government laws, policies, and regulatory instruments towards the necessary protection of this largely vulnerable semi-arid sandveld eco-system.

9. GROUNDWATER GOVERNANCE

9.1. Introduction

Groundwater governance is the framework encompassing the processes, interactions, and institutions, in which actors (i.e. government, private sector, civil society, academia, etc.) participate and decide on management of groundwater within and across multiple geographic (i.e. sub-national, national, transboundary, and global) and institutional/sectoral levels, as applicable (Vilhoth and Conti, 2018). Groundwater management consists of a planned program of actions aiming at pursuing maximum benefit from the local groundwater systems to the human society, in good balance with and between the objectives of meeting vital water demands, making profits, maintaining resource sustainability, allocating benefits equitably, and conserving the groundwater-related environment and ecosystems (Van der Gun et al., 2012). Water management institutions consist of established rules, norms, practices and organizations that provide a structure to human actions related to water management – notably regulation. The established groundwater management organizations are to be considered here as a subset of water resources institutions. Overall, the institutional framework is considered in three broad categories: policies, laws and administration (Bandaragoda, 2000).

In this chapter the governance framework for groundwater management in the EKK-TBA is elaborated. The analysis of institutions, laws, policies and projected investments will be carried out so as to enhance effective and efficient management of the EKK-TBA by both countries based on the following:

- Existence and comprehensiveness of bi- or multi-national level agreements/treaties, specific to the EKK-TBA
- Existence and comprehensiveness of non EKK-TBA specific agreements/treaties, or other non-binding instruments, of relevance to the EKK-TBA

The comprehensiveness of the legal instruments surveyed is assessed in terms of the inclusion of the following:

- Well drilling/abstraction/Water utilisation
- Water pollution control
- Settlement of water disputes
- Institutional arrangements
- Other matters such as environmental protection and preservation, prevention of harmful effects, data exchange, prior notification of planned measures, emergency situations

Aquifer boundaries, in most cases, do not coincide with political or catchment boundaries which implies that the governance of groundwater resources must be dealt with by multiple organisations through systems of 'polycentric governance' at different scales that enables interaction to occur between different institutions (Muller, 2012; Ostrom, 2009). It is important to consider both formal and informal institutions in the EKK-TBA. The analysis will identify where changes in decision-making should be made to address the gaps and barriers.

9.2. International legal framework

In SADC, the Revised Protocol on Shared Watercourses (SADC, 2000), hereafter referred to as the Protocol, is the legal framework governing transboundary water. Both Botswana and Zimbabwe are signatories to the Protocol. The Protocol focus on shared watercourses meaning a watercourse passing through or forming the border between two or more riparian states. The Protocol is based on three core principles: equitable and reasonable utilisation, the prevention of significant (transboundary) harm and the prior notification of planned measures (Baranyai, 2020). The following gaps have been identified in the Protocol for groundwater management (SADC-GMI, 2019c):

- The Protocol focuses on surface waters and effectively restricts consideration to aquifers that are only hydrologically connected to surface water – such as a river or lake. This means that the EKK-TBA is not considered a shared watercourse based on the above definition
- Excludes solitary, non-recharging and fossil transboundary aquifers from consideration

There is no explicit policy guidance on the development or co-management of groundwater resources. Hardly any guidance regarding the interconnectivity between groundwater and ecological infrastructure; and makes no reference to aquifer boundaries or the situation where aquifers boundaries cross surface water basin boundaries. The new EKK-TBA boundary straddles two shared watercourses: the Okavango – Cubango[35] and the Zambezi[36] (Figure 9.1). This boundary asymmetry adds additional complexity to the governance of the EKK-TBA. The misalignment with political boundaries also means that the EKK-TBA hardly encompasses all the physical, social, or economic factors impacting upon the area within its boundary.

[35] The Okavango River Basin is a transboundary basin which serves as an important source of water resources for three riparian Southern African states: Angola, Botswana, and Namibia

[36] The Zambezi River Basin is a transboundary basin and the river plays a central role in the economies of the eight riparian countries: Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe.

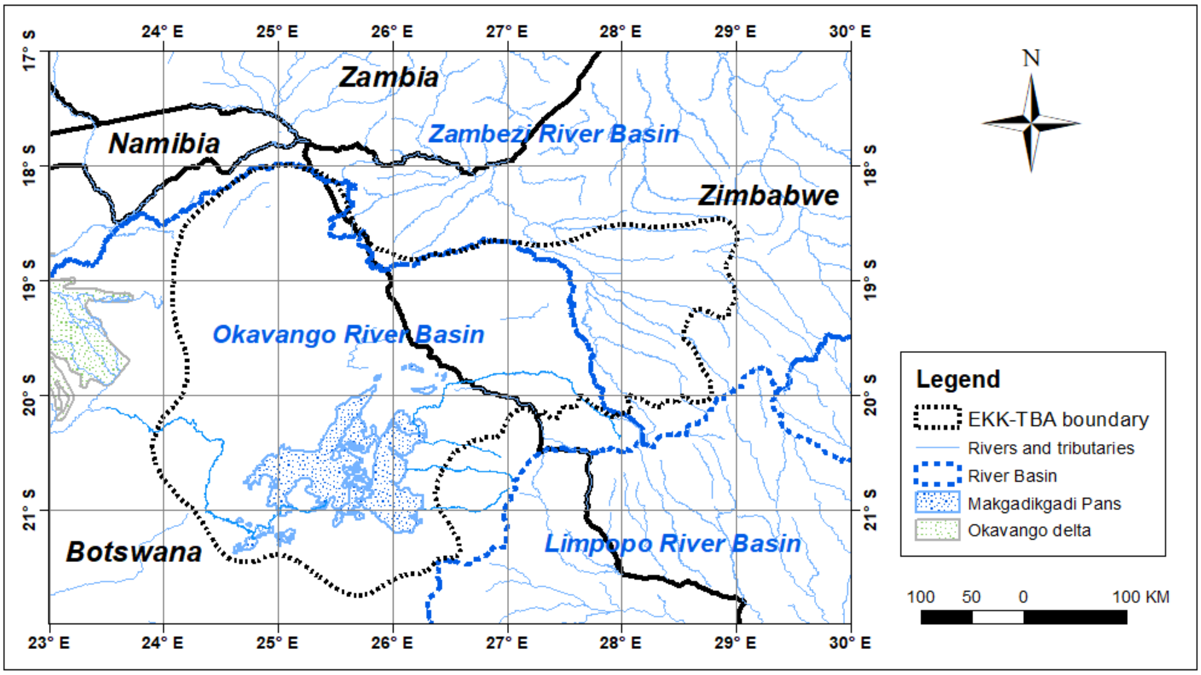


Figure 9.1: The EKK-TBA boundary in relation to shared watercourses

The SADC water institutional framework is given in Figure 9.2. The regional institutional framework does allow for the establishment of bi-lateral or multi-lateral water institutions to support specific purposes (SADC-GMI, 2019c). This provides an opportunity for an EKK-TBA specific policy addendum, memorandum of understanding or agreement around common purpose, e.g. groundwater management including groundwater monitoring, data and information exchange.

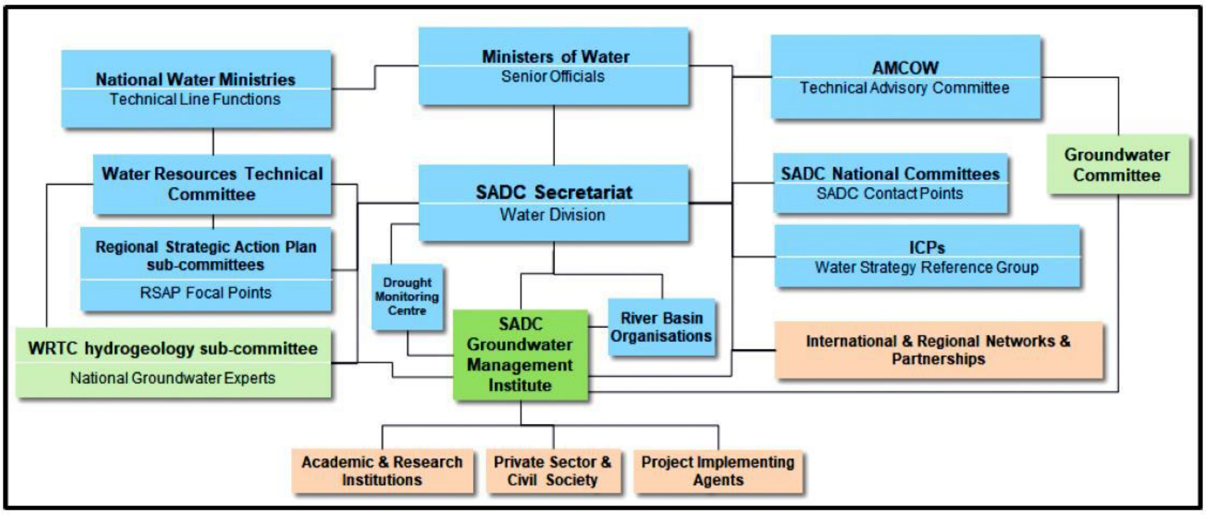


Figure 9.2: SADC water sector institutional framework

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

Source: SADC-GMI (2019c)

9.2.1. UN Draft Articles on the Law of Transboundary Aquifers

From 2002 to 2008, an interdisciplinary team of experts, supported by the International Hydrological Programme of the United Nations Educational, Scientific and Cultural Organization (UNESCO-IHP) developed three reports and three addenda that culminated in the drafting of 19 Articles that were adopted as Resolution 63/124 by the UN General Assembly and commended to governments to take them “into account” in making “appropriate bilateral and multilateral arrangements for the proper management of their transboundary aquifers” (SADC-GMI, 2019c; UNESCO, 2009). This means that the Draft Articles are non-binding. While the major principles outlined in the Draft Articles are already present in the SADC Protocol, many would require further elaboration to meet the needs of a sound shared groundwater governance regime. For example, the obligation not to cause significant harm may require a different threshold for “significance” with respect to an aquifer’s pollution than for surface waters, an area which states might require guidance on (SADC-GMI, 2019c). Further, the Draft Articles appear to endorse an approach based on absolute territorial sovereignty and integrity, which means that states can utilise water resources in their territory as they please without reciprocal consideration for their neighbours (Devlaeminck, 2020). Provisions concerning recharge and discharge zones are particularly challenging because, at least in some respects, they create a second class of state parties who have significant obligations to act but no corresponding rights or benefits (*ibid*). The Draft Articles provide model provisions on which future agreements and arrangements in the EKK-TBA can be formulated.

9.2.2. Other international environmental agreements

In addition to the Protocol and UN Draft Articles, there are emerging practices that can inform the formulation of EKK-TBA specific agreements and arrangements. These include (SADC-GMI, 2019c):

- United Nations Economic Commission for Europe (UNECE) Model Provisions (2012)
- The 1977 Agreement between France and Switzerland on the Genevese Aquifer (re-negotiated in 2007)
- Three agreements on the Nubian Sandstone Aquifer between Chad, Egypt, Libya and Sudan (1992-2000)
- The North-West Sahara Aquifer System consultative arrangement between Algeria, Libya and Tunisia (2002-2008)
- The Memorandum of Understanding between Algerian, Benin, Burkina Faso, Mali, Mauritania, Niger and Nigeria on the Iullemedeen and Taoudeni/Tanezrouft Aquifer System (ITAS) to establish a Consultative Mechanism (2014, replacing an original MoU in 2009)
- The Guarani Aquifer Agreement (2010) between Argentina, Brazil, Uruguay and Paraguay

- The 2015 Al Sag/Al Disi Aquifer Agreement between Jordan and Saudi Arabia

9.3. River Basin Organisations

9.3.1. Permanent Okavango River Basin Commission

The EKK-TBA forms part of the non-active (hydrologically isolated /disconnected) part of the Cubango-Okavango River Basin (CORB) basin. The Permanent Okavango River Basin Water Commission (OKACOM) is a river basin organisation (RBO) established through the OKACOM Agreement of 1994, by three riparian states of Angola, Botswana and Namibia to jointly manage transboundary water resources, of common interest in the Cubango-Okavango River Basin, a basin the countries jointly share (OKACOM, 2020). Zimbabwe does not form part of OKACOM. The structure of OKACOM was established in 2007 and has the following agencies (King and Chonguiça, 2016):

- The Commission: the principal agency, responsible for defining and guiding development and supervision of OKACOM.
- The Okavango Basin Steering Committee (OBSC): the technical advisory body to the Commission, supported by three Task Forces: Biodiversity, Hydrology and Institutional.
- The Secretariat: to provide administrative, financial, and general secretarial services to OKACOM.

Groundwater issues are not formalised in the current institutional setup. This can be formalised through the establishment of a groundwater task force. There is a current project implemented by OKACOM focussing on a groundwater assessment of the CORB and can be tasked to look into the feasibility of setting up of a groundwater task force to manage groundwater resources of the basin including the EKK-TBA.

9.3.2. Zambezi Watercourse Commission

The Zambezi Watercourse Commission (ZAMCOM) is a major river basin organization in Africa. It was established in 2014 as an inter-governmental organisation that brings together eight Riparian states that share the Zambezi River Basin, as stipulated in the 2004 ZAMCOM Agreement and in accordance with the revised SADC Protocol on Shared Watercourses of 2000. The Riparian States to the Zambezi River Basin are the Republic of Angola, the Republic of Botswana, the Republic of Malawi, the Republic of Mozambique, the Republic of Namibia, the Republic of Tanzania , the Republic of Zambia and the Republic of Zimbabwe. ZAMCOM has three main organs (ZAMCOM, 2019):

- The Council of Ministers which is the highest decision-making body
- The Technical Committee (ZAMTEC) which is a technical / advisory body

- The Secretariat (ZAMSEC) which is responsible for the day to day operations of ZAMCOM

Similar to OKACOM, groundwater considerations are not explicitly formalised in the institutional arrangements. In the Zambezi Environment Outlook (2015), groundwater depletion has been identified as a key water issue that requires attention (ZAMCOM et al., 2015).

9.4. National legislation, policies and institutions

The Botswana National Water Policy (MoMEWR, 2012) was drafted in 2012 and adopted in 2016. The current groundwater management legislation, 1956 Botswana Boreholes Act, dates back to more than 60 years ago (Republic of Botswana, 1956), and is supported by an number of other Acts: 1967 Water Works Act (Republic of Botswana, 1968), 1970 Water Utilities Corporations Act (Republic of Botswana, 1970) and 1998 Wastewater Management Act (Republic of Botswana, 1998) and they all do not explicitly address the management of groundwater resources. The legislation does not take into account current water management principles and does not consider transboundary water issues. The Ministry of Land Management, Water and Sanitation Services is responsible for policy formulation and overall management of the water sector. Under the Ministry, the Department of Water and Sanitation (DWS), Botswana Geoscience Institute (BGI) (previously called the Department of Geological Survey), Water Utilities Corporation (WUC), Department of Regional and Town Planning manage water resources at either the district or community level (SADC-GMI, 2019d).

In Zimbabwe, the current Water Policy (2012) was formulated based on the Water Policy of 2004 through an inclusive consultative process and it incorporates policy principles that guide aspects of water resources development and management. Currently, groundwater development, use and management are primarily governed by the Water Act of 1998, Zimbabwe National Water Authority (ZINWA) Act of 1998 and the EMA Act of 2002. The Ministry of Lands, Agriculture, Water and Rural Resettlement through the Department of Water Resources Management develops policies to guide optimum development, utilisation and protection of water resources; ensures availability of water to citizens for primary use and the environment when there are competing demands for water; and ensures equitable and efficient allocation of available water resources for development of rural, urban, industrial, mining and agricultural sectors through ZINWA, Councils and Sub-catchment councils (SADC-GMI, 2019e).

Table 9.1 summarises the policy, legal and institutional issues related to groundwater management in Botswana and Zimbabwe as identified by a Gap Analysis and presented in Action Plans during the SADC Groundwater Governance project (SADC-GMI, 2019d; 2019e).

Note that the coloured cells in the Table represent the status of minimum requirement for a desired future: green for fully achieved; orange for partly achieved; and red for absent/not achieved.

Table 9.1: Governance issues related to groundwater management

Source: SADC-GMI (2019d; 2019e)[37]

Category	Minimum requirement for a desired future	Botswana	Zimbabwe
Policy framework	A long-term policy to protect groundwater by preventing pollution and overuse. This policy is comprehensive, implemented at all appropriate levels, consistent with other water management policies and be duly taken into account in other sectorial policies		
	The social, economic and environmental values of groundwater are all recognised		
	The human right to water is recognized and a rights-based approach to groundwater management is taken, inter alia, through:		
	Prioritization of drinking water/basic human needs in water legislation		
	Ensuring that land-based rights cannot entitle unlimited access/use of freshwater, including groundwater		
	Ensuring groundwater is legally recognized as a public good		
	Recognising the role of groundwater in meeting basic human needs for food security		
	Legal recognition of customary rights to freshwater, including groundwater		
	Legal mechanisms to ensure gender equity in access, use and management of freshwater, including groundwater		
	Provision of pricing mechanisms that incentivize equitable distribution of rights to access and use of groundwater, as well as prioritization of small-scale users' livelihoods and food security needs, especially youth and women		
	Groundwater is recognised as a highly important source of domestic and agricultural water supply and a key resource for poverty alleviation, food security, and the sustainable economic development of rural areas		
	The biophysical and ecological linkages between groundwater and surface water for their use, protection and management are recognised, including land use zoning for groundwater protection and recharge (conjunctive use)		
	The importance of the maintenance of the ecological integrity of wetlands in groundwater management is recognised (recharge zones)		

[37] https://sadc-gmi.org/projects/policy-legal-and-institutional-development-for-groundwater-management-in-sadc-member-states/

Category	Minimum requirement for a desired future	Botswana	Zimbabwe
	Intersectoral collaboration is promoted and facilitated so that the needs and impacts of different sectors (e.g., land, agriculture, mining, municipal, and environment) are taken into account in groundwater management and the impacts of developments in those sectors on groundwater are accounted for		
	The need for adaptive management is recognised due to the inherent limitations in the nature of scientific information in conjunction with the widely occurring dynamic processes of climate, social and institutional change		
	The roles of various stakeholders and water users in groundwater management is recognised and participation of stakeholders in decision-making and groundwater management is promoted and facilitated;		
	An apex body that is responsible explicitly for GW management and playing the role of custodian/trustee on the part of the state is clearly defined;		
	Effective institutional arrangements are coordinated at trans boundary, national and local levels		
	Public access to geo-hydrological data held by the state is promoted and facilitated		
	Additional environmental principles necessary to protect and sustain groundwater are mandated, including: the precautionary principle, the principle of gender equity and social inclusion (GESI), the principle of subsidiarity, and the principle of intergenerational equity.		
Legal framework	All water has a consistent status in law, irrespective of where it occurs		
	Explicit reference to groundwater and conjunctive use management in catchment/water management and development plans and drought/emergency management plans		
	Human right to water recognized in groundwater legislation, facilitating prioritization of drinking water and basic human needs, as well as small-scale users		
	Water use authorizations		
	Legislation must enable the authorisation of groundwater use (with a system that does not discriminate, especially against the rural poor)		
	The permitting of groundwater use should not be tied exclusively to land tenure		
	Legislation should allow for the categorisation of water users		
	Groundwater should be declared a public asset and/or authority vested in government to restrict, in the public interest, the rights accruing from its private ownership to prevent over-abstraction or inequitable access/use by landowners		

Category	Minimum requirement for a desired future	Botswana	Zimbabwe
	New legislation should strive towards changing ownership rights to use (usufruct) rights, subject to a government-controlled, permit system for large scale users with appropriate non-permit systems for addressing the needs of small-scale users		
	The legislation recognises and legalises affordable, small-scale and indigenous solutions		
	The legislation should enable the regulation of borehole drillers, regulation for drilling, control of drillers, information from drillers and standards for borehole drilling		
	Legislation should give water inspectors the right to enter land with the offenses and associated penalties noted in the legislation (this includes appropriate fines and jail time that needs to be adjusted annually)		
	The legislation should enable the regulation of exploration		
	The legislation should allow for zoning for overused/fragile aquifers		
	Groundwater use organizations should be integrated into existing institutional frameworks (e.g., catchment management, customary institutions)		
	The legislation should specify when and how stakeholders, the public and/or other water users are to be engaged in planning, decision making and self-management with regard to groundwater		
	There should be specific mechanisms for directly involving stakeholders in the development of laws and regulations related to groundwater and decisions that may impact the use or quality of groundwater on which they depend for drinking, livelihoods, food security, economic or cultural well-being		
	The legislation should specifically address the issue of the involvement of women and youth in decision-making and the implementation of groundwater supply schemes		
	The legislation should specify the need and parameters for a sustainable system for data collection, management and dissemination, including standardization and harmonization of data. This entails a national monitoring and information system which captures quantity and quality data from key aquifers		
	The legislation should specify the need for drought monitoring systems which extend beyond rainfall, surface water and food security indicators to groundwater and groundwater supply status, including the appropriate prediction of future hydrogeological conditions		
	In transboundary basins, legislation should address the need for standardization and exchange of data as well as the establishment of joint inventories;		
	The legislation should enable access by the public to geohydrological data held by the state		

Category	Minimum requirement for a desired future	Botswana	Zimbabwe
	Legislation should enable regulation to ensure the efficient use of groundwater, such as the use of economic incentives and imposition of technologies		
	Clear mechanisms for promoting compliance with groundwater regulations should be included in the legislation		
	Enforcement provisions should include, inter alia, inspections authority for groundwater management institutions, the ability to impose fines and/or additional administrative penalties and adjust those as necessary, and enumerate criminal offenses associated with failure to comply with the law		
	The legislation must enable the relevant authority (Minister) to make regulations on any relevant matter in the legislation		
	Legislation should provide a clear ability for the government to pass regulatory measures, such as abstraction fees and waste disposal charges, to provide revenue to water management institutions and to incentivise appropriate use of groundwater		
	Legislation should contain provision for its effective implementation, including the mandate, competence and power of the relevant authorities in accordance with uniform governance principles		
Institutional framework	Water authorities or coordinating bodies should have the competence to integrate all aspects of water management and should be rendered competent to arbitrate among various competing demands, and diverging interests regarding groundwater abstraction and use, both in the short-term and in the long-term		
	The authority or body should collaborate with other authorities, competent for public health, land-use planning, soils management, waste management		
	Water user associations and other appropriate forums (such as municipalities) should be utilized to strengthen the user advocacy role and achieve new partnerships and a joint management of the common resource		
Strategy frameworks	Regulating Pollution (Point source and non-point source) i. Water quality targets ii. Regulation of emissions/wastewater discharge/waste storage including the impact of mines on groundwater quality: Permits can be used to regulate the discharge, disposal and possibly the storage of waste should specifically take into account the vulnerability of the aquifer concerned and the provisions necessary for its protection		
	Classification of water bodies		
	Reducing and regulating abstraction		
	Powers of compliance monitoring and enforcement		
	Regulation of abstraction and recharge (usually via permitting)		
	Sustaining wetlands		

Category	Minimum requirement for a desired future	Botswana	Zimbabwe
	Land use zoning – prohibition of abstraction in certain zones; cropping or irrigation practices; protection zones for recharge areas; no surfacing/drainage requirements		
	Legislation must make it mandatory for installation of monitoring equipment of boreholes especially for large-scale users (the information must then be supplied to the state)		
	Powers of compliance monitoring and enforcement		
	The legislation should specify the need for long term plans to ensure the sustainable use of groundwater, including drought management plans and cross-sectorial coordination;		
	Where water legislation provides for catchment level or basin level planning, groundwater should be integrated into those plans (for example through impact assessment requirements)		
	The legislation should specify that groundwater management planning should take into account and be integrated into land use and environmental planning		
	Planning should be cyclical and based on continuous learning from data and stakeholder feedback to ensure adaptive management and effective responses to changing climatic, social, political and institutional contexts/drivers		

9.4.1. Borehole drilling, abstraction and water utilisation

In Botswana, groundwater abstraction for agriculture, mining and domestic purposes is contributing to a decline of groundwater levels (Republic of Botswana, 2013).This is largely, due to lack of or limited monitoring as it is likely that users abstract more than they are legally entitled to and even beyond the rate of recharge for groundwater resources (*ibid*). The Boreholes Act provides for provisions to control the development of boreholes. This requires notification to the Botswana Geoscience Institute and keeping samples and records of the strata drilled through and pumping test results. The person sinking or deepening any borehole shall within 10 days of the completion or abandonment of the work send a complete copy of the record together with adequately labelled samples to the Botswana Geoscience Institute (Republic of Botswana, 1956). The Boreholes Act has a number of provisions to regulate borehole drilling, abstraction and water utilisation (Box 9.1).

Box 9.1: Botswana Boreholes Act for regulating BH, abstraction and use

Source: Republic of Botswana (1956)

- (5) Casual use of water in a public stream, etc.
  - Any person may, without a water right, while he is at any place where he has lawful access to a public stream or to a natural lake, pan or swamp, take and use public water therein for the immediate purpose of (a) watering stock; (b) drinking, washing and cooking; or (c) use in a vehicle, but nothing in this section shall be construed as authorizing the construction of any works.
- (6) Use, etc., of water by owners and occupiers of land
  - (1) Subject to the provisions of this Act and of any other written law, the owner or occupier of any land may, without a water right –

        - (a) sink or deepen any well or borehole thereon and abstract and use water therefrom for domestic purposes, not exceeding such amount per day as may be prescribed in relation to the area where such well or borehole is situated by the Minister after consultation with an advisory board established in pursuance of section 35 in respect of that area. Provided that this paragraph shall not authorize the sinking of any borehole within 236 meters of any other borehole (other than a dry borehole) or authorize the deepening of any borehole which is within this distance of any other borehole.
    - (2) Where any person is authorized under the provisions of subsection (1)(a) to construct or deepen a borehole, he may also construct or deepen stand-by boreholes ancillary thereto: Provided that the total quantity of water which may be abstracted under this section from a borehole and any stand-by borehole ancillary thereto shall not exceed in aggregate the total quantity which may be abstracted from a single borehole under the provisions of that paragraph.
- (7) Right to water for mining purposes
    - (1) The holder of any right under the Mines and Minerals Act to mine any mineral shall have in respect of the land to which his right relates the same rights as are conferred by section 6 on the owner or occupier of any land and may also abstract and use any underground water encountered in any workings and construct any works required for or in connection with these of such water.
    - (2) The holder of any right under the Mines and Minerals Act to prospect may, within the area which he may lawfully so prospect and subject to all rights which others may have to the use of water-
        - (a) abstract and use for prospecting purposes any public water to which he has lawful access.
        - (b) construct or enlarge any well or borehole in any land on which he has a right to explore or prospect, and abstract water therefrom, not exceeding 22,750 liters in any one day; and
        - (c) abstract and use any underground water encountered in any workings and construct any works required for or in connection with the use of such water.
- (8) Right to water for forestry purposes
    - (b) construct or enlarge any well or borehole and abstract water therefrom not exceeding 22,750 liters in any one day.
- (9) Prohibition of use of water except with lawful authority
    - (2) Any person who diverts, dams, stores, abstracts, uses, or discharges any effluent into, public water or who, for any such purpose constructs any works except under and in accordance with the provisions of this Act or of any other written law shall be guilty of an offence and the offender shall be liable to the penalties prescribed in section 37.

In Zimbabwe, groundwater is no longer just supplying water to the rural population but has also become a major source of water in urban areas. Of late, family-based self-supply systems (Manzungu et al., 2016) in the form of boreholes and shallow wells have become an important source of domestic water in peri-urban and urban area (Government of Zimbabwe, 2012). There has been a general decline of irrigated agriculture in all catchments except Runde, whose water is mainly utilized by multi-national companies (Triangle and Hippo Valley). In 2010, 70% of the potential available water was not used and in 2011 80% was not utilized (*ibid*). The decline in water utilization in agriculture has led to a large decline in raw water sales to irrigators, leading to loss of revenue to ZINWA that enables it to carry out the primary functions of planning, development and management of water resources (*ibid*). The Water Act (Government of Zimbabwe, 1998) has several provisions to regulate borehole drilling, abstraction and water utilisation (Box 9.2).

Box 9.2: Zimbabwe Water Act for regulating BH drilling, abstraction and use

Source: Government of Zimbabwe (1998)

- (32) Use of water for primary purposes
  - (1) Subject to section thirty-three and Part IX, any person may abstract water for primary purposes: Provided that this subsection shall not be construed as conferring on any person a right, which he would not otherwise possess, to enter or occupy any land for the purpose of abstracting the water.
- (33) Power of catchment council to limit quantity of water abstracted for primary purposes
  - (1) Notwithstanding anything contained in this Act, a catchment council may, if it thinks it necessary in the public interest to ensure the equitable distribution and use of water, by notice in the Gazette—
    - (a) a limit the quantity of water which may be abstracted for primary purposes by any person or class of persons within any area from any source of water.
    - (b) specify the maximum number of livestock an individual owner is entitled to water for the primary purposes.
- (34) Application for permit
- (35) Authority to sink boreholes for any purpose or wells for purposes other than primary purposes
  - (1) The written authority of the catchment council to sink, alter or deepen
    - (a) a borehole for any primary purposes shall be obtained;
    - (b) a borehole or well for any purposes other than primary purposes shall be obtained before making an application for a permit in terms of subsection (1) of section thirty-four in respect of ground water.
  - (2) Within thirty days of the completion of the sinking, altering or deepening of the borehole or well, the owner or occupier of the land on which the borehole or well has been sunk, altered or deepened shall notify the catchment council in the prescribed manner of the fact and furnish the council such particulars as may be prescribed, and, if ground water has been found, the catchment council shall, in the case where an application is made therefor, issue a permit to the owner or occupier in terms of section thirty-four.
- (43) Records of amount of water abstracted to be maintained
  - (1) A catchment council may require the holder of a permit issued in terms of this Part—
    - (a) to provide and install a meter or other measuring device for measuring and recording the amount of water abstracted; and
    - (b) to submit to the catchment council in the prescribed form at such intervals as the catchment council may require, returns indicating the amount of water abstracted.
  - (2) Any officer or other person authorized by a catchment council may inspect any meter or other measuring device, take readings therefrom and seal such device in order to prevent interference with its working.
- (58) Water development restriction areas
- (59) Investigation of use of water by National Water Authority
- (61) Declaration of water shortage areas
  - (1) If the Minister, acting on the recommendation of the National Water Authority and in consultation with the catchment council concerned, is of the opinion that—
    - (a) the flow of water in any public stream has at any time ceased or if the flow of water or the level of water in the storage works has fallen or is likely to fall below the level of the usual flow or acceptable level of storage works in the public stream; or
    - (b) it appears that the abstraction of water from boreholes and wells in any area is likely to diminish unduly the ground water resources in the area or affect adversely the flow of any surface water in any public stream; he may, by notice in the Gazette, declare any area specified in the notice to be a water shortage area for such period, not exceeding twelve months, as may be specified in the notice.

- (63) Sinking, deepening or altering of boreholes and wells in water shortage areas restricted
    - (1) No person shall, in a water shortage area, commence to sink, deepen or alter a borehole or well for any purpose otherwise than in accordance with a permit issued by the catchment council, and the provisions of Part IV relating to boreholes and wells shall apply, mutatis mutandis.
- (64) Maximum volume and rate of abstraction of water in water shortage areas

9.4.2. Water pollution control

Uncontrolled land uses impact on groundwater recharge and water quality.

In Botswana, water quality is threatened by intensive irrigation, pollution from mines, cities and industries, including leaching from landfills, and poor sanitation facilities. Siltation of rivers also occurs as a result of deforestation (Department of Water Affairs, 2013). The lack of compliance monitoring and enforcement is contributing to water pollution. The Water Act (Republic of Botswana, 1968) has several provisions for regulating water pollution (Box 9.3).

Box 9.3: Botswana Water Act for regulating water pollution

Source: Republic of Botswana (1968)

- (9) Prohibition of use of water except with lawful authority
    - (2) Any person who diverts, dams, stores, abstracts, uses, or discharges any effluent into, public water or who, for any such purpose constructs any works except under and in accordance with the provisions of this Act or of any other written law shall be guilty of an offence and the offender shall be liable to the penalties prescribed in section 37.
- (36) Pollution of public water, etc.
    - (1) Any person who-
        - (a) except under the authority of this Act or any other written law interferes with or alters the flow of or pollutes or fouls any public water; or
        - (b) without the permission of the Water Registrar places any poison in any public water or water in any work to which any member of the public or domestic animal may reasonably be expected to obtain access, whether lawfully or unlawfully, shall be guilty of an offence and shall be liable to the penalties prescribed in section 37.
    - 2) For the purposes of this section the polluting or fouling of public water shall include the discharge into, or in the vicinity of, any public water, or in a place where public water is likely to flow, of any matter or substance likely to cause injury whether directly or indirectly to public health, livestock, animal life, fish, crops, orchards or gardens which are irrigated by such water or any product in the processing of which such water is used or which occasions, or which is likely to occasion, a nuisance.

Pollution of Zimbabwe's water sources from point and non-point sources is increasing at an alarming rate, despite the existence of regulations and penalties for offences. There is limited coordination of key institutions that include Urban Councils, ZINWA, Environmental Management Agency (EMA), Department of Irrigation (DOI), and Ministry of Mines and Mining Development (MMMD) related to water pollution at the operational level. The Water Act requires permits for discharge or disposal into water (Government of Zimbabwe, 2012).

9.4.3. Settlement of water disputes

The Botswana Water Act has provisions for settlement of disputes through lodging appeals directly to the Minister whose decision in the matter is final (Republic of Botswana, 1968), whereas the Zimbabwe The Water Act makes provisions for settlement of disputes through the Administrative Court.

9.4.4. Institutional arrangements

In Botswana, the Department of Water and Sanitation is the primary institution responsible for water management in Botswana supported by the Botswana Geoscience Institute which is responsible for groundwater exploration and monitoring. The granting and administration of water rights is done by the Water Apportionment Board (WAB), a body that draws its powers from the Water Act 1968 (ORASECOM, 2008) (Table 9.2).

Table 9.2: Overview of the institutional framework of the Botswana water sector

Source: Republic of Botswana (2013)

Institution	Functions
Department of Water and Sanitation	• Water resource management and planning • Planning and construction of strategic water infrastructure
Botswana Geoscience Institute	• Administration of the Boreholes Act of 1956 • Investigates and monitors major groundwater systems in the country • Maintains the National Borehole Archive for the assessment of groundwater potential
Water Utilities Corporation (WUC)	• Water supply to human settlements • Bulk water supply to industries • Management of raw water reservoirs and water treatment • Operation and maintenance of water supply infrastructure • Wastewater management and treatment
Department of Waste Management and Pollution Control	• Coordination and monitoring of sanitation and waste management • Administration of policy, legislation and programmes regarding waste management and pollution control • Planning and development of wastewater treatment works
Water Apportionment Board (WAB); the secretariat is located at DWA	• Granting and administration of water rights. The WAB will be abolished after the water sector reforms have been concluded
Ministry of Agriculture (Water Development division)	• Development of small agricultural dams • Development of groundwater resources for irrigation

In Zimbabwe, the Ministry of Lands, Agriculture, Water and Rural Resettlement (MLAWRR) is the primary institution responsible for water resources and delegates most of the management responsibilities to the Zimbabwe National Water Authority (ZINWA) (Table 9.3).

Table 9.3: Overview of the institutional framework of the Zimbabwe water sector

Source: Government of Zimbabwe (2012)

Institution	Function
Ministry of Lands, Agriculture, Water and Rural Resettlement (MLAWRR)	The overall planning, development and management of water resources in Zimbabwe is presided over by the MLAWRR, supported by ZINWA, Catchment Councils and Sub-Catchment Councils.
National Action Committee on Water Supply and Sanitation (NAC)	Coordination in the water sector is undertaken by the NAC, Chaired by MLAWRR and supported by a National Coordinating Unit. It is the apex inter-ministerial body that was formed to coordinate all aspects of water development and management in Zimbabwe. It comprises 3 sub-committees; the Water Resources Management, Urban and Rural Sub-committees, responsible for sub-sector coordination.
Ministry of Health and Child Care (MHCC)	The MHCC is a key player in the Rural WASH sub-sector responsible for water quality monitoring, promoting safe water supply and household sanitation. MHCC is responsible for promoting improvements in domestic hygiene, specifically through adoption of safe self-supply drinking water systems, such as covered family wells and rainwater harvesting, and house-hold investments in improving excreta disposal and safe sanitation. MHCW has the lead role in promoting health and hygiene education and encouraging healthy sanitation and hygiene
Ministry of Transport, Communications and Infrastructure Development (MTCID)	In the MTCID, the Department of Infrastructure Development (DID) in MTCID hosts a unit to ap-praise and manage infrastructure projects funded from the Rural Capital Development Fund (RCDF). A specific component of this fund is dedicated to financing rural WASH activities. The MTCID chairs the Rural NAC sub-committee and is responsible for sector coordination. MTCID also hosts the District Development Fund (DDF) which maintains a small unit for back-up borehole drilling, deep well-sinking and pump repair and rehabilitation in each RDC. The DDF provides technical guidance and expertise to RDCs in planning and supervising rural WASH development, in addition to advising District Water and Sanitation Committees on borehole drilling and pump maintenance.
The Ministry of Environment, Climate, Tourism and Hospitality (MECTH)	The MECTH, through EMA, is responsible for environmental issues as a regulatory institution on all issues, including water and water issues such as water pollution control, water source protection and

Institution	Function
	water allocation for the environment. It is also responsible for coordination on climate change.
Ministry of Local Government and Public Works (MLGPW)	The MLGPW through Urban and Rural Councils, are responsible for water use and therefore management at consumer level. They represent different constituencies of water users.
Ministry of Finance (MoF) MEPD	The MoF, the MEPD, Development Partners, and the Private sectors are major players with respect to financing of WSS.
Ministry of Women Affairs, Community, Small and Medium Enterprises Development (MWACSMED)	MWACSMED create a conducive and enabling environment that promotes the development and growth of Micro, Small and Medium Enterprises and Cooperatives. Women groups are encouraged to form farming cooperatives and these utilize water
Zimbabwe National Water Authority (ZINWA)	The ZINWA was established through the ZINWA Act of 1998 as a self-financing institution whose key mandate is to plan, develop and manage Zimbabwe's water resources on a sustainable and environmentally friendly basis. It is responsible for the provision of raw water services, sale of agreement water, groundwater investigation and service provision, from which it generates revenues to finance its operations. In terms of the ZINWA Act, ZINWA is also mandated to provide potable water supply services to local authorities and government institutions that are not yet in a position to take on this responsibility themselves. Therefore, ZINWA has 2 distinct functions, the first being that of water resources development and management, and the second being a limited potable water supply function.

9.4.5. Provision for other matters

Other matters include environmental protection and preservation, prevention of harmful effects, data exchange, prior notification of planned measures and emergency situations. In Botswana, the Water Act (Republic of Botswana, 1968) makes no provision for other matters, whereas in Zimbabwe, the Water Act has provisions to regulate for other matters such as environmental protection and preservation, prevention of harmful effects, data exchange, prior notification of planned measures, and emergency situations (Government of Zimbabwe, 1998) (Box 9.4).

Box 9.4: Zimbabwe Water Act provisions to regulate other matters

Source: Government of Zimbabwe (1968)

- (67) Water resource management to be consistent with environmental approaches Without in any way limiting the generality paragraph (b) of subsection (2) of section six, in considering, formulating and implementing any proposal for the use, management or exploitation of water resources, due consideration shall be given to—
  - (a) the protection, conservation and sustenance of the environment; and
  - (b) the right of access by members of the public to places of leisure or natural beauty related to water or water bodies.

9.5. Key Messages

- The EKK-TBA boundary straddles two shared watercourses; the Okavango – Cubango and the Zambezi. The boundary asymmetry adds additional complexity to the governance challenges.
- There is need for a bilateral agreement or arrangements to manage the EKK-TBA.
- The legislative frameworks in both countries do not address issues of transboundary aquifers and international obligations per se. However, the Zimbabwe legislation gives the Minister the function "to give effect to any international agreement, to which Zimbabwe is a party, on shared water course systems in a spirit of mutual co-operation."
- Water reforms in Botswana which are currently taking place need to take account of the key issues identified during the TDA.

10. KEY ISSUES

Key issues were derived through combining shared water risks and key messages, which were obtained from the TDA.

10.1. Shared water risks

In a virtual workshop at the beginning of the project, that included staff from SADC-GMI, representatives from the two countries and the consultants, the following very high shared water risks of the EKK-TBA were identified (Annex 2):

- Insufficient potable water for human consumption
- Groundwater over-exploitation
- Contamination of groundwater
- Competing demand for domestic/agricultural/mining/industrial/tourism water
- Climate variability and climate change
- Data and knowledge gaps
- Institutional gaps and barriers
- Inadequate groundwater monitoring systems
- Lack of joint groundwater management of the EKK-TBA

10.2. Key messages

The TDA established the following key messages (Chapters 3 to 9):

Demographics and Socio-economics (Chapter 3)

- Need for proper quantification of the basin population
- Impact of mining and mining pollution has the potential to affect rural and vulnerable communities
- Severe losses in revenue generated from foreign tourists due to the Covid-19 pandemic impacted both economies, in particular, the livelihoods of communities dependent on tourism

Climate (Chapter 4)

- Access to climate data is a challenge particularly from the Zimbabwean side of the EKK-TBA
- Trends: decline in rainfall, high interannual rainfall variability and increasing temperature
- Need to establish resilient and adaptation strategies to mitigate impact of climate variability and change on water resources

Surface water (Chapter 5)

- Data quality in terms of its accuracy, gaps and accessibility, is again a major issue that need addressing
- EKK-TBA falls within the Okavango and Zambezi River Basins
- There is clear evidence of groundwater and surface water interaction

Groundwater (Chapter 6)

- Groundwater development is localized, hence also data and information (mostly confined to wellfields in the fringe of the basin)
- Data quality of hydro(geo)logical data and information is generally poor and there is a lack of quality control
- Lack of good quality hydro(geo)logical databases; difficulty in accessibility to data and information; and limited standardisation of data and information
- Inadequate (integrated and automated) monitoring
- Localised induced groundwater level depressions
- Uncontrolled drilling of private boreholes within the OLDM wellfields over the past 10 years
- Potential water related conflicts between different abstractors
- Groundwater modelling is not periodically conducted
- Potential upconing of saline groundwater and intrusion into shallower and lower salinity aquifers
- Blending of (hyper) saline and fresh groundwater for mining operations could be an option to lessen the pressure on fresh groundwater resources
- Water supply for mining operations is demand driven and this should be critically reviewed by the Water Apportionment Board
- Groundwater management institutions in both countries lack adequate resources to carry out effective and efficient groundwater monitoring

Water Use (Chapter 7)

- Vast majority of water use in the EKK-TBA is from groundwater
- NDVI RS has the potential to be used in timely determination of crop areas and crop water requirements
- Water demand for domestic use currently exceeds water supply
- Water supply in mining is demand driven and tends to negate sustainability of supply
- Conjunctive use of water resources is advocated for continuous supply to wildlife
- Need for a sound understanding and projection of water requirements

Land Use and Land Cover (Chapter 8)

- EKK-TBA faces negative environmental threats from poor land use practices and climate variability and change
- The EKK-TBA is endowed with various wetlands and protected areas
- Large scale deforestation is a risk to protected areas and requires that regulatory regimes be strengthened and enforced
- Protection of the EKK-TBA is paramount to ensure the preservation of the natural habitats and biodiversity

Groundwater Governance (Chapter 9)

- The EKK-TBA boundary straddles two shared watercourses: the Okavango – Cubango and the Zambezi. The boundary asymmetry adds additional complexity to the governance challenges.
- There is need for a bilateral agreement or arrangements to manage the EKK-TBA
- The legislative frameworks in both countries do not address issues of transboundary aquifers and international obligations per se
- The interrelationship of OKACOM and ZAMCOM with regard to water governance in the EKK-TBA needs to be looked into (e.g. hydrogeological subcommittee)

10.3. Key issues

Key issues emanating from the shared water risks and the key messages include:

- Data and databases:
  - Data unavailability/scarcity and inaccessibility (especially from Zimbabwe) and poor quality (accuracy and gaps)
  - Lack of good quality hydro(geo)logical databases and limited standardisation of data and information
- Water insecurity:
  - Projected decline in rainfall, high interannual rainfall variability and increasing temperature
  - Upconing of saline groundwater and intrusion into shallower and lower salinity aquifers
  - Potential water related conflicts could ensue in the EKK-TBA: between the mining companies and local farmers in the Botswana side of the EKK-TBA and in the Zimbabwe part of the EKK-TBA in the Nyamandlovu area between local farmers and ZINWA (abstracting groundwater for the City of Bulawayo)
- Groundwater management:
  - Lack of adequate resources to carry out effective and efficient groundwater management (e.g. monitoring, uncontrolled drilling, etc.)

  - Groundwater over-exploitation: water demand for domestic water use currently exceeds supply; water supply in mining is demand driven and negates sustainability of supply
  - Unregulated borehole drilling posing a risk to groundwater overexploitation and unwarranted competition of the groundwater resource.
  - Inadequate use of innovative technologies: remote sensing has been proven to be an alternative tool that can be used in the timely determination of active crop areas and the crop water requirements in the EKK-TBA and consequently, the amount of groundwater used.
- Biodiversity: the EKK-TBA is endowed with a rich biodiversity which is critical to the countries' economies and the livelihoods of the basin communities and needs to be better protected
- Deforestation and poor agricultural practices are resulting in rapid land degradation
- The EKK-TBA boundary asymmetry adds additional complexity to the governance challenges (OKACOM and ZAMCOM)
- Lack of political will and improved regulation hampering enforcement of government laws, policies, and regulatory instruments
- The EKK-TBA population needs to be properly quantified in order to determine the risks and opportunities that arise from the available natural resources

Subsequent to the identification of key issues, a gap and barrier analysis was carried out to obtain a broader perspective of the water related issues (Annex 3).

10.4. Causal chain analysis

A causal chain analysis of the EKK-TBA key transboundary water issues was carried out accordingly to understand immediate and underlying causes per sector, root causes, environmental impacts and socio-economic impacts (Table 10.1). Note that interventions that are designed to remedy one root cause might also apply to other root causes and in such a case, it will be most cost effective to address them all (ASCLME/SWIOFP, 2012).

A number of mitigation options to address the key issues were put forward and quick-win measures (QWMs) were formulated to address the issues (Annex 2). For both countries, the most preferred QWMs were institutional mapping followed by the designing and implementing a (pilot) groundwater monitoring network for the EKK-TBA.

The key issues, gap and barrier analysis, causal chain analysis and the mitigation and QWMs all form part of the Strategic Action Planning process.

Table 10.1: Causal chain analysis applied to EKK-TBA water resources

EKK-TBA key water issues	**Socioeconomic consequences/ Environmental impacts**	**Immediate causes**	**Underlying resource uses and practices that contribute to the immediate causes**	**Underlying social, economic, legal and political causes of each immediate cause**	**Root causes**
Water insecurity: • Insufficient potable water for human consumption • Climate variability and change Groundwater over-exploitation Pollution and contamination of water Competing demand for domestic / agricultural / mining/ industrial / tourism water Inadequate protection of biodiversity Land degradation Data and knowledge gaps Institutional gaps and barriers Inadequate groundwater monitoring systems Inadequate use of innovative technologies Lack of joint groundwater management of the EKK-TBA	Socioeconomic consequences • Reduction in livelihoods • Increased risk of water related diseases • Malnutrition • Increase in poverty levels • Migration and resulting conflicts Environmental impacts • Water scarcity • Change in water quality • Reduction in water quantity • Impact on groundwater dependent ecosystems (GDEs)	• Poor water supply coverage • Uncontrolled/ unmanaged groundwater drilling and abstraction • Localized induced groundwater level depressions • Groundwater quality deterioration • Pollution of groundwater from various land-use activities • Overgrazing • Reactive water resource planning	• Demand for groundwater resources for domestic use (including livestock watering) • Limited data collection and quality of data • Cumulative impact of groundwater resources not considered • No comprehensive basin-wide hydrogeological investigations which includes geophysical, groundwater recharge and managed aquifer recharge, and hydrochemical investigations, groundwater modelling, etc. • Lack of good quality hydrogeological databases • Unregulated groundwater use • Deforestation • Poor land-use practices	• Subsistence economy. Few sources of income leading to lack of financing • Weak institutional capacity • Insufficient and inefficient use of funds • Insufficient human and institutional capacity in the different spheres of government • Low profile of operation and maintenance • Inadequate knowledge and awareness • Inadequate and outdated legislative frameworks • Lack of capacity for monitoring and enforcement • No EKK-TBA specific agreements and arrangements	• Semi-arid environment – climate variability and change • Seasonal water sources such as shallow water pans, seeps, springs and pools, majority of which dry up during the dry season • Poor natural groundwater quality • Groundwater governance challenges • Extreme poverty • High rainfall and evaporation intensity • Onset of shorter drought duration Reduced runoff • Rainfall variability

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ANNEX 1: OVERVIEW OF SOURCES OF DATA AND INFORMATION

Demographics and Socio-Economics				
	Possible data sources/institution in Botswana		Possible data sources/institution in Zimbabwe	
Data requirement	**Physical**	**Other data sources/web/Internet /gridded**	**Physical**	**Other data sources/web/Internet /gridded**
Population	Statistics Botswana	http://www.statsbots.org.bw /	ZimStat - Census Report	www.zimstat.co.zw
Gender composition	Statistics Botswana; Gender Affairs Department	CGIAR/Waternet Reports; Regional Programme Reports (CRIDF; OKASEC; FAO) Civil society reports; ZimVac reports; DHS reports	Ministry of Women Affairs, Community, Small and Medium Enterprises Development (MWACSMED)	CGIAR/Waternet Reports; Regional Programme Reports (CRIDF; ZRBF, FAO) Civil society reports; ZimVac reports; DHS reports
Age structure	Statistics Botswana	CGIAR/Waternet Reports; OKASEC reports; Civil society reports	ZimStat - Census Report	CGIAR/Waternet Reports; Civil society reports; ZimVac reports; DHS reports
Education and literacy	Statistics Botswana; Ministry of Education and Skills Development	CGIAR/Waternet Reports; Civil society reports	ZimStat - Census Report; Ministry of Primary and Secondary Education; CBO reports	CGIAR/Waternet Reports; Civil society reports; ZimVac reports; DHS reports
Human health	Statistics Botswana; Ministry of Health and Wellness	CGIAR/Waternet Reports; Civil society reports	ZimStat - Census Report; Ministry of Health and Childcare (national and district levels)	CGIAR/Waternet Reports; Civil society reports; ZimVac reports; DHS reports
Poverty status	Statistics Botswana; Minister of Finance and Economic Development	CGIAR/Waternet Reports; Civil society reports	ZimStat - Census Report; Ministry of Public Service, Labour and Social Welfare	CGIAR/Waternet Reports; Civil society reports; ZimVac reports; DHS reports
Employment	Statistics Botswana; Minister of Finance and Economic Development	CGIAR/Waternet Reports; Civil society reports	ZimStat - Census Report; Ministry of Public Service, Labour and Social Welfare; Ministry of Finance and Economic Development	CGIAR/Waternet Reports; Civil society reports; ZimVac reports; DHS reports
Livelihoods	Statistics Botswana; Minister of Finance and Economic Development	CGIAR/Waternet Reports; Civil society reports	ZimStat - Census Report; Ministry of Finance and Economic Development	ZINWA and Catchment Councils; CGIAR/Waternet Reports; Civil society reports; ZimVac reports; DHS reports

Institutions and governance				
	Possible data sources/institution in Botswana		**Possible data sources/institution in Zimbabwe**	
Data requirement	**Physical**	**Other data sources/web/Internet /gridded**	**Physical**	**Other data sources/web/Internet /gridded**
Key national water and water related institutions and functions	Ministry of Land Management, Water and Sanitation Services (DWS); Ministry of Agricultural Development and Food Security; Management Office Ministry of Environment and Natural Resources (Department of Meteorological services); Water apportionment Board Botswana, Department of Water and Sanitation; Water Utilities Corporation	http://www.statsbots.org.bw /	Ministry of Lands, Agriculture, Water and Rural Resettlement; Zimbabwe National Water Authority (ZINWA); Catchment Councils and Sub Catchment Councils; District Development Fund (DDF)	
Transboundary agreements (for the Aquifer)	OKACOM	https://www.okacom.org /	Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA; ZAMCOM	
Land tenure and customary institutions	Land boards; Department of Town and Country Planning		Ministry of Lands, Agriculture, Water and Rural Resettlement; Land Commission; Ministry of Local Government and Public Works	
Gender equity and land access and use	Department of Gender Affairs		Ministry of Women Affairs, Community, Small and Medium Enterprises Development (MWACSMED)	
Water legislation incl. regulations			Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA; ZAMCOM	

Climate data				
	Possible data sources/institution in Botswana		**Possible data sources/institution in Zimbabwe**	
Data requirement	**Physical**	**Other data sources/web/Internet /gridded**	**Physical**	**Other data sources/web/Internet /gridded**
Rainfall and temperature time series (daily)	Department of Meteorological Services (DMS)	Temperature (CRU datasets) https://crudata.uea.ac.uk/cru/data/hrg/	Meteorological Services Department	Temperature (CRU datasets) https://crudata.uea.ac.uk/cru/data/hrg/
		Daily rainfall (GPCC data) https://rda.ucar.edu/datasets/ds497.0/		Daily rainfall (GPCC data) https://rda.ucar.edu/datasets/ds497.0/
Evaporation time series (monthly)	Botswana Water Accounting Reports - The Department of Water And Sanitation	https://www.gleam.eu/	Meteorological Services Department	https://www.gleam.eu/
Other metrological parameters such as Relative humidity, sunshine hours, solar radiation and wind speed	Department of Meteorological Services (DMS); Statistics Botswana	https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5	Meteorological Services Department	https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5
Past flood and drought occurrence	Statistics Botswana	http://www.statsbots.org.bw/	Meteorological Services Department; ZINWA	
Geographic location of climate and stream flow gauging stations	Department of Meteorological Services (DMS); Department of Water and Sanitation		ZINWA (Hydrology Section), Meteorological Services department	
Climate projection and scenarios	Department of Water and Sanitation	IPCC reports	Climate Change Management Department in Ministry of Environment, Climate, Tourism and Hospitality Industry	IPCC reports

Groundwater and surface water data				
	Possible data sources/institution in Botswana		**Possible data sources/institution in Zimbabwe**	
Data requirement	**Physical**	**Other data sources/web/Internet /gridded**	**Physical**	**Other data sources/web/Internet /gridded**
Geological maps (1:250,000 scale)	Botswana Geoscience Institute (BGI)		Geological Survey (Ministry of Mines and Mining Development)	
Geological maps (1:1000,000 scale)	Botswana Geoscience Institute (BGI)			
Aeromagnetic map	Botswana Geoscience Institute (BGI)		Geological Survey (Ministry of Mines and Mining Development)	
Soil maps	Ministry of Agriculture, Food and Agricultural Organisation (FAO)		Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA	
Basin maps (GIS format)	Botswana Geoscience Institute (BGI)		Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA	
Hydrogeological maps	SADC Groundwater Management Institute, Department of Water and Sanitation		ZINWA	
Geophysical data (Aeromag/Gravity)	Botswana Geoscience Institute, Department of Water and Sanitation		Geological Survey (Ministry of Mines and Mining Development); ZINWA (Groundwater Department)	
Lineaments map(GIS format)	Botswana Geoscience Institute, Department of Surveys and Mapping		Department of the Surveyor General	
Borehole database and associated data (e.g. geological profiles)	Department of Water and Sanitation		ZINWA (Groundwater Department)	
Borehole completion certificates	Department of Water and Sanitation		ZINWA (Groundwater Department); DDF	
Consultancy Reports on kalahari karoo aquifers esp around Makgadikgadi/ Gweta/Nata/Dukwi/Maitengwe /Sowa town	Department of Water and Sanitation, Botswana Geoscience Institute		ZINWA (Groundwater Department)	

Groundwater and surface water data				
	Possible data sources/institution in Botswana		**Possible data sources/institution in Zimbabwe**	
Data requirement	**Physical**	**Other data sources/web/Internet /gridded**	**Physical**	**Other data sources/web/Internet /gridded**
Consultancy Reports on kalahari karoo aquifers esp around Nyamandlovu and Epping Forest and Hwange National Park			ZINWA (Groundwater Department), GIZ, WWF, UZ	
Groundwater levels (monitoring)	Department of Water and Sanitation, Botswana Geoscience Institute		ZINWA (Groundwater Department)	
Pumping test reports on above areas	Department of Water and Sanitation, Botswana Geoscience Institute		ZINWA (Groundwater Department)	
Groundwater use and abstraction data	Department of Water and Sanitation, Water Utilities Corporation		ZINWA (Groundwater Department)	
Surface water use and abstraction	Department of Water and Sanitation, Water Utilities Corporation		ZINWA (Hydrology Department)	
Rainfall chemistry and isotope data and reports	Department of Water and Sanitation, Water Utilities Corporation		ZINWA (Groundwater Department)	
Groundwater quality (geochemistry) data or reports	Department of Water and Sanitation, Botswana Geoscience Institute, Water Utilities Corporation		ZINWA (Hydrology and Groundwater Department)	
Surface water quality (chemistry) data or reports	Department of Water and Sanitation, Botswana Geoscience Institute, Water Utilities Corporation		ZINWA (Groundwater Department)	
Groundwater isotope data	Department of Water and Sanitation, Botswana Geoscience Institute		ZINWA (Groundwater Department)	
Surface water isotope data	Department of Water and Sanitation, Botswana Geoscience Institute		ZINWA (Hydrology and Groundwater Departments)	
Spatial or point rainfall data	Department of Meteorological Services		Meteorological Services Department	
River flow data (gauging station)	Department of Water and Sanitation		ZINWA (Hydrology Department)	
Discharge data	Department of Water and Sanitation		ZINWA (Hydrology Section)	
Groundwater infiltration/recharge rate data	Department of Water and Sanitation, Botswana Geoscience Institute		ZINWA (Hydrology and Groundwater Departments)	

Groundwater and surface water data				
	Possible data sources/institution in Botswana		**Possible data sources/institution in Zimbabwe**	
Data requirement	**Physical**	**Other data sources/web/Internet /gridded**	**Physical**	**Other data sources/web/Internet /gridded**
Policies (or reports) on Managed Aquifer Recharge	Department of Water and Sanitation		Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA	
Flooding reports (historical)	Department of Water and Sanitation; Department of Meteorological Services		Meteorological Services, ZINWA (Hydrology Department)	
Flooding locality data (maps)	Department of Water and Sanitation; Global flood map		Meteorological Services, ZINWA (Hydrology Department)	
Strategic investment/masterplans	Ministry of Land Management, Water and Sanitation Services (DWS); Ministry of Minerals Resources, Green Technology and Energy Security		Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA	
Digital elevation model data,DEM(varying resolutions if possible), mainly 30 or 90m	Mapping for Sustainable development-RCMRD; Earth Explorer USGS (web portals); Shuttle Radar Topography Mission (SRTM); Department of Surveys and Mapping		Mapping for Sustainable development-RCMRD; Earth Explorer USGS (web portals); Shuttle Radar Topography Mission (SRTM); Department of the Surveyor General	

Sectoral water use data				
	Possible data sources/institution in Botswana		**Possible data sources/institution in Zimbabwe**	
Data requirement	**Physical**	**Other data sources/web/Internet /gridded**	**Physical**	**Other data sources/web/Internet /gridded**
Crop and livestock	Ministry of Agriculture, Department of Crop Production, Department of Animal Production), Statistics Botswana, Botswana University of Agriculture and Natural Resources		Ministry of Lands, Agriculture, Water and Rural Resettlement	
Hydropower	Ministry of Minerals Resources, Green Technology and Energy		Ministry of Energy and Power Development	
Domestic water supply and sanitation	Department of Water and Sanitation, Water Utilities Corporation		Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA	
Mining	Ministry of Minerals Resources, Green Technology and Energy, Debswana, Water Utilities Corporation		Ministry of Mines and Mining Development	
Industry	Water Utilities Cooperation, Ministry of Mineral Resources, Green Technology and Energy Security		Ministry of Industry and Commerce	
Environment and ecosystems	Ministry of Environment, Natural Resources, Conservation and Tourism		Environment Management Agency (EMA) in Ministry of Environment, Climate,Tourism and Hospitality Industry Zimbabwe; Ministry of Lands, Agriculture, Water and Rural Resettlement	
Riparian habitat for key surface water resources	Ministry of Environment, Natural Resources, Conservation and Tourism		Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA	
Key biomes	Ministry of Environment, Natural Resources, Conservation and Tourism (Department of Environmental Affairs)		Ministry of Lands, Agriculture, Water and Rural Resettlement	
Aquatic ecosystem health status (anything available)	Ministry of Environment, Natural Resources, Conservation and Tourism(Department of Environmental Affairs)		Ministry of Lands, Agriculture, Water and Rural Resettlement	

Sectoral water use data				
	Possible data sources/institution in Botswana		**Possible data sources/institution in Zimbabwe**	
Data requirement	**Physical**	**Other data sources/web/Internet /gridded**	**Physical**	**Other data sources/web/Internet /gridded**
Environmental flows info (if any)	Ministry of Environment, Natural Resources, Conservation and Tourism/Ministry of Land Management Water and Sanitation Services		Ministry of Lands, Agriculture, Water and Rural Resettlement; ZINWA	
Biodiversity (especially any key indicator species or anything endangered)	Ministry of Environment, Natural Resources, Conservation and Tourism(Department of Environmental Affairs)		Ministry of Lands, Agriculture, Water and Rural Resettlement	
Wetlands (key goods and services & possible GW-SW interfaces)	Ministry of Environment, Natural Resources, Conservation and Tourism/Ministry of Land Management Water and Sanitation Services		Environment Management Agency (EMA) in Ministry of Environment, Climate,Tourism and Hospitality Industry Zimbabwe	
Games and parks	Ministry of Environment, Natural Resources, Conservation and Tourism(Department of Environmental Affairs)		Zimbabwe National Parks (ZIMPARKS) in Ministry of Environment, Climate,Tourism and Hospitality Industry Zimbabwe	
Land use and land cover change map(gis format)	Department of Surveys and Mapping		Ministry of Lands, Agriculture, Water and Rural Resettlement	
Landfill waste sites(if any)	Ministry of Environment, Natural Resources, Conservation and Tourism, Department of Waste Management and Pollution Control		Environment Management Agency (EMA) in Ministry of Environment, Climate,Tourism and Hospitality Industry Zimbabwe	
Africa/SADC Groundwater (Grey) Literature Archive		https://www.bgs.ac.uk/sadc/about.cfm https://www.bgs.ac.uk/africagroundwateratlas/archive.cfm		https://www.bgs.ac.uk/sadc/about.cfm https://www.bgs.ac.uk/africagroundwateratlas/archive.cfm

ANNEX 2: SHARED WATER RISKS, MITIGATION AND QWMS

The shared water risks (Section 10.1) were categorised using a qualitative risk assessment method (Figure 1). This involved an analysis of the likelihood of a hazard occurring and the consequence or impact of the hazardous event. In decision-making, low-consequence / low-probability risks (green) are typically perceived as acceptable and therefore only require monitoring (DEFRA, 2011). In contrast, high-consequence / high-probability risks (red) are perceived as unacceptable and a strategy is required to manage the risk. Other risks (amber) may require structured risk assessment to better understand the features that contribute most to the risk (DEFRA, 2011). In the workshop, all the issues were given a very high risk (Table 1).

A number of mitigation options to address the very high water risks were put forward and quick-win measures (QWMs) were formulated to address very high risks (Table 1). QWMs are short-term interventions (less than a year); highly visible; having an immediate impact; and contribute to longer term mitigation measures in addressing high to very high-water risks.

Five (5) QWMs were selected and prioritised using a Multi-Criteria Decision Analysis (MCDA) approach:

- QWM-1: Mapping land use to identify pollution sources
- QWM-2: Stakeholder mapping focusing on water use
- QWM-3: Hydrocensus of the EKK-TBA
- QWM-4: Institutional mapping
- QWM-5: Design and implement a (pilot) groundwater monitoring network

MCDA has the goal of providing an overall ordering of measures, from the most preferred to the least preferred measure (Dodgson et al., 2009). The process can be divided into six steps:

STEP 1:Identify objectives
STEP 2:Identify measures for achieving the objectives
STEP 3:Identify criteria to compare the measures
STEP 4:Assign weights to the criteria
STEP 5:Analysis of the measures, and
STEP 6:Comparative analysis and making the choices

Risk = Likelihood x consequence or impact

Qualitative measures of likelihood

Level	Descriptor	Example description
A	Rare	May occur only in exceptional circumstances. May occur once in 100 years
B	Unlikely	Could occur within 20 years or in unusual circumstances
C	Possible	Might occur or should be expected to occur within a 5 – 10-year period
D	Likely	Will probably occur within 1 – 5-year period
E	Almost certain	Is expected to occur with a probability of multiple occurrences within year

Qualitative measures of consequence or impact

Level	Descriptor	Example description
A	Insignificant	Insignificant impact or not detectable
B	Minor	Health – minor impact for small population Environment – Potentially harmful to local ecosystems with local impacts contained to site
C	Moderate	Health – minor impact for small population Environment – Potentially harmful to regional ecosystem with local impacts primarily contained to site
D	Major	Health – major impact for small population Environment – Potentially lethal to local ecosystems, predominantly local impact, but potential for offsite impact
E	Catastrophic	Health – major impact for large population Environment – Potentially lethal to regional ecosystems or threatened species; widespread onsite and offsite impacts

Qualitative Risk assessment

Likelihood	Consequence / Impact				
	Insignificant	Minor	Moderate	Major	Catastrophic
Rare	Low	Low	Low	High	High
Unlikely	Low	Low	Moderate	High	High
Possible	Low	Moderate	High	Very High	Very High
Likely	Low	Moderate	High	Very High	Very High
Almost Certain	Low	Moderate	High	Very High	Very High

Figure 1: Methodology for qualitative risk assessment

Source: DEFRA (2011)

Table 1: Risk assessment and mitigation measures for the EKK-TBA (incl. QWMs)

No.	Water risks	Likelihood	Consequence / Impact	Risk	Mitigation measures	Quick-Win measures
1	**Insufficient potable water for human consumption**	Almost Certain	Major	Very High	• Evaluate water demand management • Formulate groundwater resource plan for groundwater exploration, planning and development • Water conservation and water harvesting (MAR)	
2	**Groundwater over-exploitation**	Almost Certain	Major	Very High	• Conjunctive water use	• Data collection
3	**Contamination of groundwater**	Likely	Major	Very High	• Determine diffuse and point sources of pollution • Identify recharge and discharge zones • Groundwater vulnerability mapping • Awareness raising campaigns	• Mapping land use for identifying sources of pollution
4	**Competing demand for domestic/agricultural/mining/industrial/tourism water**	Almost Certain	Major	Very High	• Assess water use • Water conservation initiatives (innovative techniques in agriculture) • Awareness raising campaigns	• Mapping stakeholder's water use
5	**Climate variability and climate change**	Almost Certain	Catastrophic	Very High	• Conjunctive water use • Managed Aquifer Recharge	
6	**Data and knowledge gaps**	Almost Certain	Catastrophic	Very High	• Improve data collection, sharing, processing, reporting • Data standardisation, common metrics and terminologies	• Establish groundwater dictionary across the region • Conduct hydro-census of EKK-TBA
7	**Institutional gaps and barriers**	Almost Certain	Catastrophic	Very High	• Identify skills gaps and human capacity requirements • Capacity building (workplace skills development)	• Institutional mapping (incl. SWOT)
8	**Inadequate groundwater monitoring systems**	Almost Certain	Catastrophic	Very High	• Identify needs for groundwater monitoring • Setting objectives of monitoring; ground-water monitoring network design and implementation	• Set up and implement pilot groundwater monitoring network including capacity building
9	**Lack of joint groundwater management of the EKK-TBA**	Almost Certain	Catastrophic	Very High	• Enhance joint understanding of the EKK-TBA	• Agreed conceptual groundwater model of the EKK-TBA

Note that the objectives for the MCDA and the identification of mitigation measures and formulation of quick-win measures (STEP 1 and STEP 2) have already been described above. Criteria are used to assess the consequence of each measure. The idea is to construct scales representing preferences for the consequences, to assign weighted scales based on their relative importance, and then calculate weighted averages across the preference scales (STEPs 3 - 5) (Dodgson et al., 2009). In this analysis, relative preference scales were used, which are simply scales that consider the most and least preferred options. The most preferred option is assigned a preference score of 100, and the least preferred a score of 0. A gradational scaling method is used to assign a score to the various options (Dodgson et al., 2009). Most proponents of MCDA use the method of swing weighting to elicit weights for the criteria.

The scoring and weighting options for both countries are given in Table 2 and Table 3. The scores of each QWM were then multiplied by the normalised weights to determine the priority of the measure from highest to lowest for future action (Table 4 and Table 5).

For both countries, the most preferred measures were institutional mapping followed by the designing and implementing a (pilot) groundwater monitoring network for the EKK-TBA.

Table 2: Scoring and weighting of the options for EKK-TBA Botswana

Criteria	**Weight (0-100)**	**QWM (0-100)**				
		1	**2**	**3**	**4**	**5**
Institutional capacity	75	60	50	65	100	80
Water security (quantity and quality)	90	75	80	60	50	85
Data availability	80	50	70	65	95	90
Linkage of QWM with existing transboundary/national programmes	85	60	60	70	100	70
Cost of intervention	100	70	50	70	90	75

Table 3: Scoring and weighting of the options for EKK-TBA Zimbabwe

Criteria	**Weight (0-100)**	**QWM (0-100)**				
		1	**2**	**3**	**4**	**5**
Institutional capacity	75	60	50	65	100	80
Water security (quantity and quality)	90	80	70	65	60	90
Data availability	80	60	65	70	90	95
Linkage of QWM with existing transboundary/national programmes	85	65	55	75	100	85
Cost of intervention	100	60	40	80	85	90

Table 4: Calculating overall scores of the QWMs for EKK-Botswana

Criteria	Normalised Weight (%)	QWM (0-100)				
		1	**2**	**3**	**4**	**5**
Institutional capacity	17%	10	9	11	17	14
Water security (quantity and quality)	21%	16	17	13	10	18
Data availability	19%	9	13	12	18	17
Linkage of QWM with existing transboundary/national programmes	20%	12	12	14	20	14
Cost of intervention	23%	16	12	16	21	17
Total	**100%**	**64**	**62**	**66**	**86**	**80**

Table 5: Calculating overall scores of the QWMs for EKK-Zimbabwe

Criteria	Normalised Weight (%)	QWM (0-100)				
		1	**2**	**3**	**4**	**5**
Institutional capacity	17%	10	9	11	17	14
Water security (quantity and quality)	21%	17	15	14	13	19
Data availability	19%	11	12	13	17	18
Linkage of QWM with existing transboundary/national programmes	20%	13	11	15	20	17
Cost of intervention	23%	14	9	19	20	21
Total	**100%**	**65**	**56**	**71**	**86**	**88**

ANNEX 3: GAP AND BARRIER ANALYSIS

A gap analysis is a way to compare current conditions and practices in order to identify gaps and areas in need of improvement with regards to compliance to relevant standards. A barrier analysis will assist in understanding both why a problem happened and how it can be prevented.

In addition to the TDA, we carried out a gap and barrier analysis for the EKK-TBA to obtain a broader perspective of water related issues and combined with the TDA, the gap and barrier analysis forms part of the Strategic Action Planning process. An analysis framework was adopted from water risk assessment studies conducted elsewhere (see e.g. Pietersen et al., 2011; Beekman, 2016; Beekman et al., 2016, Gain et al., 2016; Pietersen and Beekman, 2016; Beekman et al., 2019). The Table below summarizes gaps and barriers according to various generalized water related themes. The coloured cells in the Table represent the status of the gaps and institutional barriers/capacity: green for fully achieved/implemented; orange for partly achieved/implemented; and red for absent/not achieved/not implemented.

The gap and barrier analysis revealed several areas where interventions are needed to improve the water security in the EKK-TBA.

Theme	Sub-theme	Criterion	Context	Gap	Institutional barriers / capacity
Policy, legal and institutional framework for TBA management	Policy and legal arrangements	Existence of legislation	legislative framework in place		
		Implementation of legislation	level of implementation		
	Institutional arrangements	Existence and functioning of institutions	institutions in place to implement legislation		
	Sectorial collaboration	Cooperation mechanisms among water users	to foster cooperation between stakeholders and various levels of government		
	Capacity of stakeholders	Mechanisms to deal with capacity gaps of stakeholders	effectiveness of stakeholders to address challenges in WSS		
Culture and water security	Household water security	Quantity of water per capita	availability of water		
		Quality of water	potability of water		
		Type and reliability of water infrastructure	water infrastructure adapted to local circumstances		
		Conflicts and emotional stress	accessibility to water (proximity, conflicts)		
		Cost of water services	affordability		

Theme	Sub-theme	Criterion	Context	Gap	Institutional barriers / capacity
	Collective management	Operation and Maintenance	functioning of water supply system(s)		
	Illegal discharge	Pollution	unauthorised disposal of effluent		
Groundwater quantity	Sustainable yield	Existence of hydrogeological maps	for identification of groundwater resources		
		Groundwater level fluctuations	to determine groundwater replenishment/depletion		
		Baseline studies to delineate aquifer(s); geology, geophysics, isotopes, chemistry, hydraulics (pumping tests)	classification of groundwater resources		
		Previous groundwater recharge estimations	to determine renewable groundwater resources		
		Groundwater modelling	to determine sustainable yields		
	Current abstractions	Groundwater monitoring network (incl. rainfall and piezometry)	to establish resource status		
		Groundwater abstraction	to determine resource use		
	Future abstractions	Population growth and development plans	to determine future groundwater use and developing new wellfields		
	Recharge areas and rates	Change in pre-abstraction recharge	sustainable groundwater use		
	Groundwater quantity hazards	Groundwater quantity hazard assessment	for identifying risks related to groundwater depletion		
	Policy, Legal and Institutional arrangements	Groundwater within overall water policy	sustainability in quantity		
			efficiency in use and allocation between sectors		
			equity by ensuring fair access and protection of water rights		
		IWRM planning function	to ensure fair water allocation		
		Availability of groundwater regulations	regulations in place		
	Management interventions	Incentive framework (pricing, subsidies etc.)	instruments to control groundwater use		
		Water well closure/constraint in critical areas			

Theme	Sub-theme	Criterion	Context	Gap	Institutional barriers / capacity
		Instruments to prevent water well construction	in overexploited areas		
		Water well/BH drilling permits & groundwater use rights	for large users, with interests of small users noted		
		Availability of aquifer numerical management models	at least preliminary for strategic critical aquifers		
		Sanction for illegal water well operation	penalizing excessive pumping beyond permit		
Groundwater quality	Groundwater quality status	Groundwater quality monitoring	to detect groundwater pollution		
	Groundwater quality hazards	Groundwater pollution hazard assessment	for identifying risks related to quality degradation		
	Aquifer vulnerabilities	Existence of aquifer vulnerability maps	to determine classes of aquifer vulnerability		
	Policy, Legal and Institutional arrangements	Groundwater policies within overall water policy	to determine sustainability in groundwater quality		
	Management interventions	Instruments to prevent water well construction	in polluted areas		
		Land-use control on potentially polluting areas	prohibition or restriction of groundwater use		
		Activities	hazard mitigation		
		Levies on generation/discharge of potential pollutants	providing incentive for pollution prevention		
Surface water quantity	Historical and current flows	Rivers and Lake monitoring networks in place	to establish resource status		
		Percentage deviation from the natural river flow	to determine resource availability for water supply		
	Future flows	Population growth and development plans	to alleviate future water pressures		
		Climate change (incl. trends in rainfall)	to understand implications for river flows and future resource availability		
	River quantity hazards	River sediment	silting of rivers and tributaries		
		Solid waste disposal	clogging of rivers and tributaries		
	River vulnerabilities	Over-abstraction	total abstraction and sectoral water-use		
		Regulation of rivers	over-development of rivers leading to degradation		
		Disconnection from wetlands	watershed disturbance		

Theme	Sub-theme	Criterion	Context	Gap	Institutional barriers / capacity
	Policy, Legal and Institutional arrangements	River basin and catchment planning	to ensure integrated planning		
	Management interventions	Water pricing	to control or reduce water use		
		Managing flood and drought risks	resulting in optimal planning		
Surface water quality	Status of river quality	Ecosystem health	to determine river and wet land health		
	River quality hazards	Source of contamination (point and diffuse sources)	to identify potential pollutant loads to rivers and wetlands		
	River and Lake vulnerability and exposure pathways	Changes in the hydrological regime	impact on downstream users		
	Policy, Legal and Institutional arrangements	Environmental flow requirements in policy and legislation	to ensure river water quality		
	Management interventions	Exceedance of environmental standards	to regulate hazardous substances		
Water supply and sanitation services and access	Access to water and sanitation	Water supply governed directly by public agencies	Water supply		
		Wells governed by local choice	private wells		
		Water coverage	measuring access to water		
		Sanitation coverage	access to proper sanitation		
	Status of waste management	Waste disposal practices	waste recycling in place		
		Waste collection capacity	ability to collect waste		
	Threats to water supply	Microbial risks	to determine infectious diseases		
		Chemical risks	to avoid chemical contamination of drinking-water		
		Non-revenue water (incl. leakage, illegal use, etc.)	to determine state of infrastructure and water revenue		
	Vulnerabilities	Flood risks	implications for humans		
		Drought risks	implications for humans		
		Health risks	implications for humans		
	Management interventions	Exceedance of standards for drinking water	to determine the potability of water		

ANNEX 4: STAKEHOLDER CONSULTATIONS

Due to the COVID-19 pandemic, fieldwork could not be planned and neither could face to face stakeholder engagement take place. Ministry officials, country representatives, OKACOM and ZAMCOM representatives, SADC-GMI staff, and the Consultant used the following on-line communication/collaboration platforms: Microsoft (MS) Teams for video conferencing and collaboration in projects[38,39] and ZOOM for video-conferencing[40,41]. Several workshops and consultations with stakeholders took place during the development of the TDA.

Workshop to identify and prioritise shared water risks

An online workshop was held on 27 May 2020 with the SADC-GMI staff, focal persons and representatives of relevant ministries from Botswana and Zimbabwe and the Consultant to identify and prioritise shared water risks. The following delegates participated in the workshop:

Botswana

- Keetile Keodumetse, Department of Water and Sanitation and SADC-GMI Focal person for Botswana
- Moses Moehadu, Water Utilities Corporation, Botswana and alternate for Botswana
- Thato Setloboko, Department of Water and Sanitation

Zimbabwe

- Zibusiso Mangwangwa, Hydrogeologist, Ministry of Lands, Agriculture, Water and Rural Resettlement from Zimbabwe
- Percy Mugwangwavari, Planning Engineer, Ministry of Lands, Agriculture, Water and Rural Resettlement and alternate for Zimbabwe

SADC-GMI

- Thokozani Dlamini, Communication and Knowledge Management Specialist
- Brighton Munyai, Chairperson and Senior Groundwater Specialist
- James Sauramba, Executive Director

Consultant

- Hans Beekman, Regional Coordinator, AquaHA B.V.
- Luc Chevallier, Private Consultant
- Piet Kenabatho, Botswana Coordinator, Private Consultant
- Kevin Pietersen, Team Leader, L2K2 Consultants (Pty) Ltd

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- Tracy Reddy, Pegasys (Pty) Ltd
- Pinnie Sithole, Pegasys (Pty) Ltd
- Sam Sunguro, Zimbabwe Coordinator, Private Consultant

Workshop to validate aquifer system boundary

An on-line workshop was held on 25 June 2020 to discuss and validate the boundary of the EKK-TBA. Present at the workshop were:

Botswana

- Moses Moehadu, Water Utilities Corporation and alternate Focal Person for Botswana

Zimbabwe

- Takudza Makwangudze, Director - Engineering and Hydrological Services, Zimbabwe National Water Authority

SADC-GMI

- Thokozani Dlamini, Communication and Knowledge Management Specialist
- Brighton Munyai, Chairperson and Senior Groundwater Specialist
- James Sauramba, Executive Director

Consultant

- Hans Beekman, Regional Coordinator, AquaHA B.V.
- Susan Byakika, Pegasys (Pty) Ltd
- Luc Chevallier, Private Consultant
- Piet Kenabatho, Botswana Coordinator, Private Consultant
- Kevin Pietersen, Team Leader, L2K2 Consultants (Pty) Ltd
- Pinnie Sithole, Pegasys (Pty) Ltd
- Sam Sunguro, Zimbabwe Coordinator, Private Consultant
- Derek Weston, Pegasys (Pty) Ltd

Workshop on causal chain analysis of key water-related issues

An online causal chain analysis workshop was held on 17 August 2020 with the objective to understand immediate and underlying causes per sector, root causes, environmental impacts and socio-economic impacts. The following delegates participated in the workshop:

Botswana

- Thato Setloboko, Department of Water and Sanitation

Zimbabwe:

Due to connectivity challenges representatives failed to participate and were given an opportunity to provide input after the workshop.

SADC-GMI

- Thokozani Dlamini, Communication and Knowledge Management Specialist
- Micah Majiwa, Governance and Institutional Consultant
- Brighton Munyai, Chairperson and Senior Groundwater Specialist

OKACOM

- Casper Bonyongo, Scientific Officer
- Tracy Molefi, Programme Coordinator
- Phera Ramoeli, Executive Director

ZAMCOM

- Michael Mutale, Executive Director Zambezi River Basin Commission

Universities

- Modreck Gomo, University of the Free State

Consultant

- Hans Beekman, Regional Coordinator, AquaHA B.V.
- Susan Byakika, Pegasys
- Piet Kenabatho, Botswana Coordinator, Private Consultant
- Kevin Pietersen, Team Leader, L2K2 Consultants (Pty) Ltd
- Pinnie Sithole, Pegasys (Pty) Ltd
- Sam Sunguro, Zimbabwe Coordinator, Private Consultant
- Derek Weston, Pegasys (Pty) Ltd