



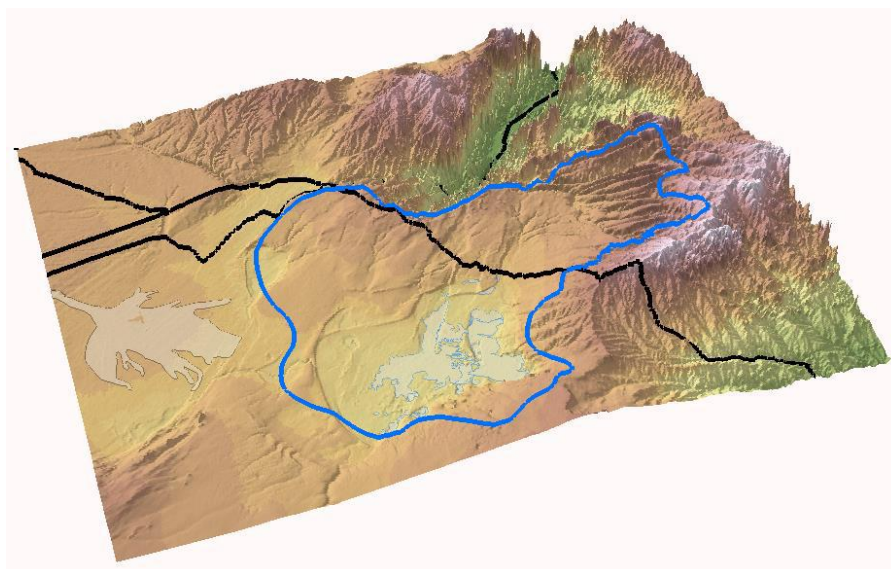
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Hydrogeology of the Eastern Kalahari-Karoo Transboundary Basin Aquifer system (EKK-TBA)

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Hydrogeology of the Eastern Kalahari-Karoo Transboundary Basin Aquifer system (EKK-TBA)

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Abstract

Water insecurity in semi-arid regions of southern Africa provides a major challenge to socio-economic development. The Eastern Kalahari-Karoo Transboundary Basin Aquifer (EKK-TBA), straddling eastern Botswana and western Zimbabwe, faces similar water insecurity challenges and would require effective and sustainable management of groundwater resources which constitute the main source of water. The Basin lies in a semi-arid region receiving mean annual rainfall of 625mm in the north-east to 325mm in the south. The EKK-TBA is generally flat, ranging from about 1 400 to 880m amsl towards the Makgadikgadi Pans in the southern part of the Basin. Perennial rivers in the eastern EKK-TBA drain towards the Zambezi River and few ephemeral rivers drain towards the Makgadikgadi Pans in the southwest.

The EKK-TBA is home to about 600 000 people who, together with the mining sector, agriculture and biodiversity heavily rely on groundwater for their sustenance and yet there is limited data and information on the sustainability of the groundwater resources. Mining accounts for the bulk of the groundwater usage. Potable groundwater occurs within the southern fringes of the EKK-TBA. The main aquifers of the Basin are the Kalahari Group deposits, Ntane/Forest Sandstone and the Mea Arkose/Wankie Sandstone. Faulting and fracturing have compartmentalised certain sections of the aquifers, whilst maintaining a regional discharge of groundwater into the Makgadikgadi Pans. Groundwater salinity, however, increases towards the central portions of the basin and with depth of the aquifers.

Groundwater recharge is estimated at <3% of average annual rainfall and insignificant recharge is expected for annual rainfall <350mm. Current water demand is outstripping supply. Further increase in potable water demand, resulting from exponential population growth of the basin (projected to be about 950 000 by 2050), coupled with future expansion of groundwater irrigated agriculture under changing climatic conditions (decreasing rainfall and increasing temperature) will exert enormous pressure on the available groundwater resources and this calls for innovative approaches to sustainably develop and utilise the

limited groundwater resources of the Basin. Establishing and capacitating a Basin-wide management unit/organisation and a groundwater monitoring network and simultaneously a groundwater model are paramount in balancing demand and supply.

Keywords: Eastern Kalahari-Karoo Transboundary Basin Aquifer, Conceptual model, Groundwater Management, Groundwater monitoring, Sustainable abstraction

Introduction

Groundwater constitutes the main source of water in the mainly semi-arid EKK-TBA and since water demand is outstripping supply, sustainable management of groundwater resources is therefore critical (SADC-GMI, 2020a). This paper looks at salient hydrogeological information and data that can be used by an EKK-TBA management institution to sustainably manage the groundwater resources of the Basin, which is shared between Botswana and Zimbabwe, particularly in light of the water insecurity within the basin. 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 km², of which 65% is in Botswana and 35% is in Zimbabwe (Figure 1). The water availability situation will be worsened by a growing population (projected to reach close to 950 000 in 2020 – SADC-GMI, 2020a) and this comes with increased demand for food, translating to increased irrigation, consequently imposing a higher demand for water resources whose amount and availability will be impacted by climate variability and change.

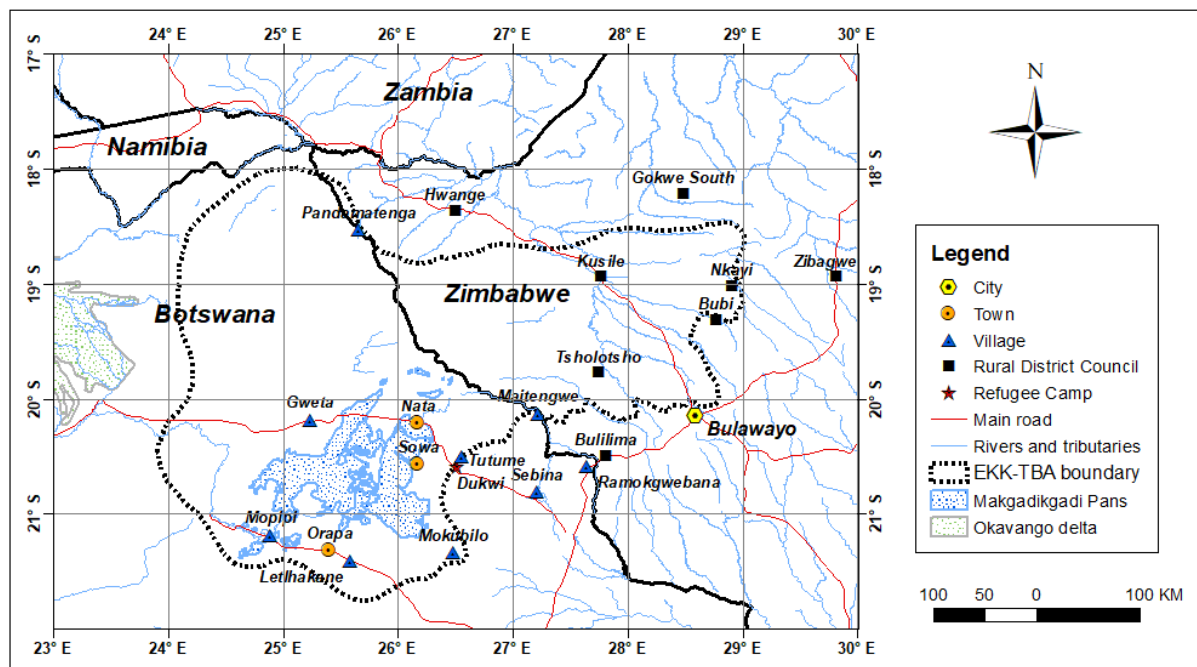


Figure 1: Location of Bulawayo City, towns, villages and Rural District Councils

Source: SADC-GMI (2020a)

Mean maximum temperatures range from around 25 °C in Zimbabwe to around 32 °C in Botswana. Average annual rainfall ranges from 325mm to 625 mm in the southern and northern parts of the Basin respectively. The Basin is underlain by Kalahari Group deposits that are underlain by the Karoo Supergroup (Upper and Lower Karoo Groups) comprising basalt, sandstone, mudstones and shales. The main aquifers are represented by the surficial Kalahari Group deposits and deep seated Ntane/Forest Sst. (Upper Karoo Group) and Mea Arkose Sst. (Lower Karoo Group). Groundwater has been largely developed along the fringes of the Basin and groundwater flows towards and is discharged into the low lying Makgadikgadi Pans in the southern part of the Basin within Botswana. The groundwater quality is generally fresh within the recharge zones in the margins of the Basin and becomes saline with increasing distance from the recharge zones and increasing depths of the aquifers.

The sectoral use of the groundwater is confined to domestic, commercial agriculture (irrigation), mining and the environment including wildlife. The mining sector accounts for 63% of the water use in the Basin, whereas agriculture and domestic use 15% and 22% respectively (SADC-GMI, 2020b). Water utilisation by the environment is not yet quantified.

Groundwater governance and management is restricted to the various institutions within the two countries and there is no basin management institution. The country institutions mandated with groundwater management face a variety of logistical and human resources capacity challenges (SADC-GMI, 2020a and b).

Methodology

Data and information were acquired from available literature (peer reviewed publications and internal organisational reports). Information was also obtained from the SADC-GMI Groundwater Information Portal (GIP). Remotely sensed data was obtained from reputable online sites such as the Climate Research Unit Version 4.04 to complement locally measured data and fill gaps with no data. Field visits could not be conducted due to the constraints imposed by the Covid-19 pandemic.

Data and information availability on a basin-wide scale was very limited, whereas substantial data and information was available on the various wellfields developed within the Basin. The local hydrogeological perspective was first looked at in detail and in combination with sparse spatial data and information of other parts of the Basin as well as inferences from peer reviewed publications, technical reports and authors' expertise of the area, a regional perspective was arrived at. Quality control was conducted on the data before it was analysed. Data and information analysis and interpretation of the wellfields preceded the establishment of a basin-wide hydrogeological perspective.

Results and discussion

Climate

The EKK-TBA lies in a mainly semi-arid region, with the spatial distribution of the mean monthly maximum temperatures from both meteorological stations (5) and the CRU data represented by 79 virtual stations (Figure 2). Temperatures are higher in Botswana compared with Zimbabwe, with the western part of the EKK-TBA displaying high temperatures of more than 30 °C. Note that this spatial trend was also observed for mean monthly minimum temperatures (SADC-GMI-2020a). Furthermore, a statistically significant trend of increasing temperatures in the course time was found (*ibid*).

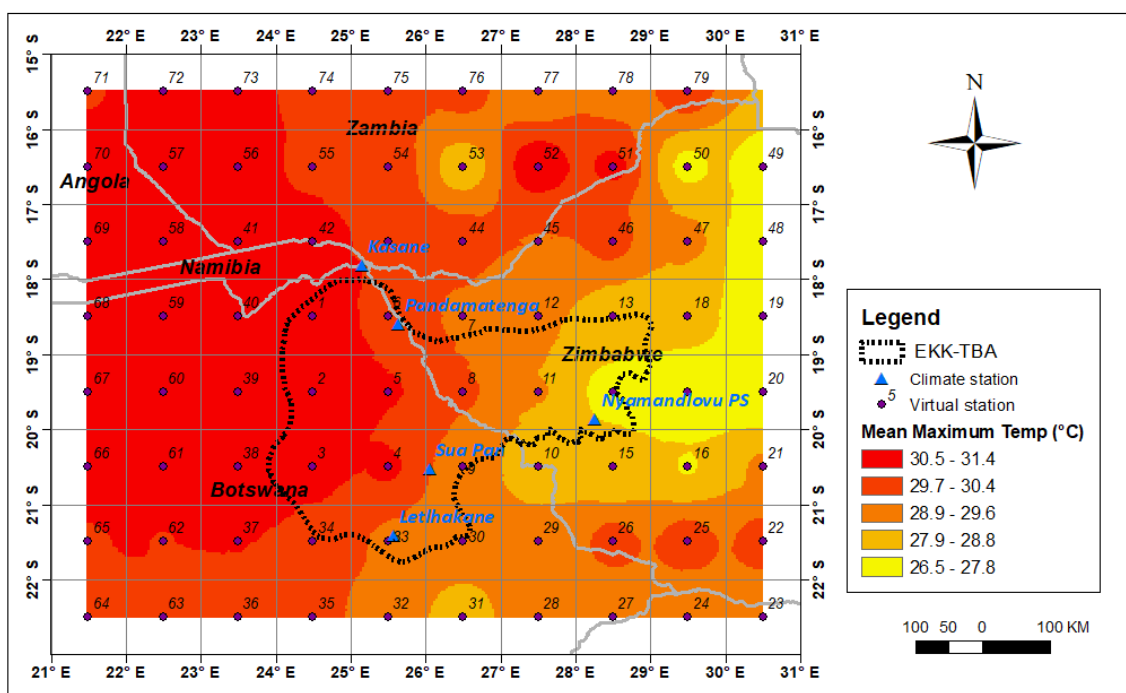


Figure 2: Spatial distribution of mean monthly maximum temperatures

Source: SADC-GMI (2020a and b)

The spatial distribution of rainfall within the EKK-TBA also exhibit an increasing trend from the southern part (325 mm/yr) to the northern part (625 m/yr) of the Basin, Figure 3. There is good correlation between observed rainfall and CRU derived amounts for most of the stations, Figure 4. Nevertheless, there is no statistically significant trend in annual rainfall variation within the Basin.

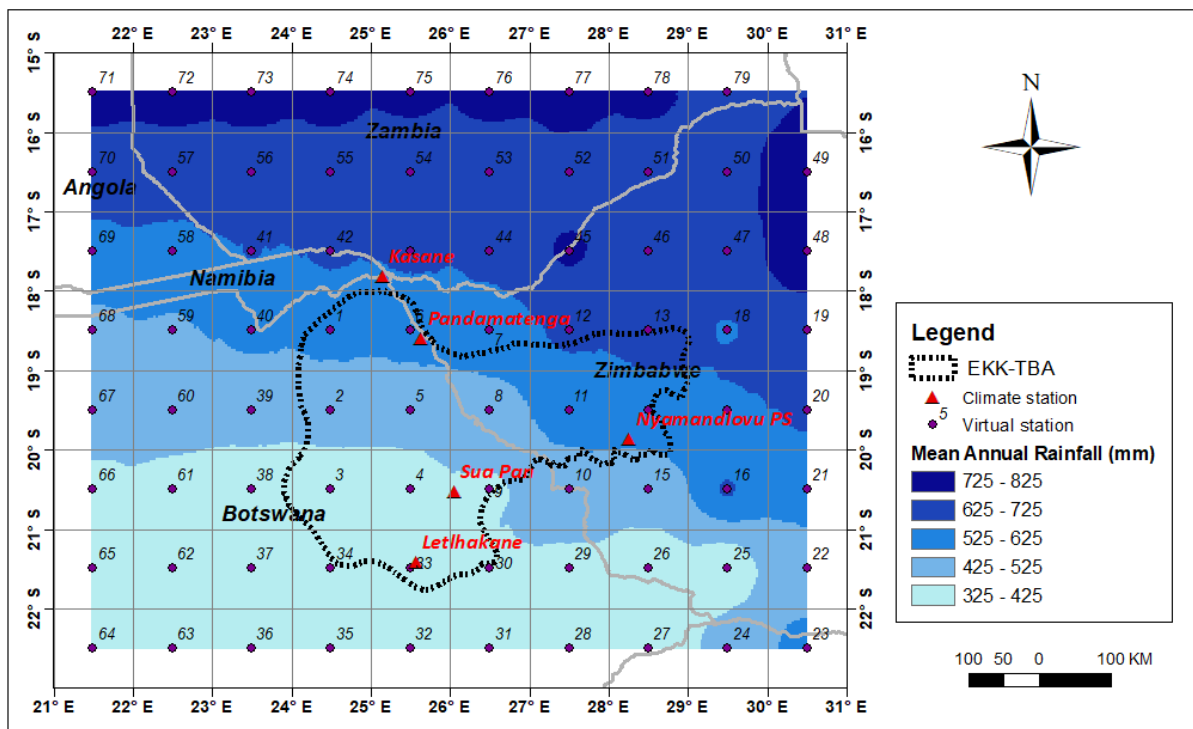


Figure 3: Spatial distribution of mean annual rainfall
Source: SADC-GMI (2020a)

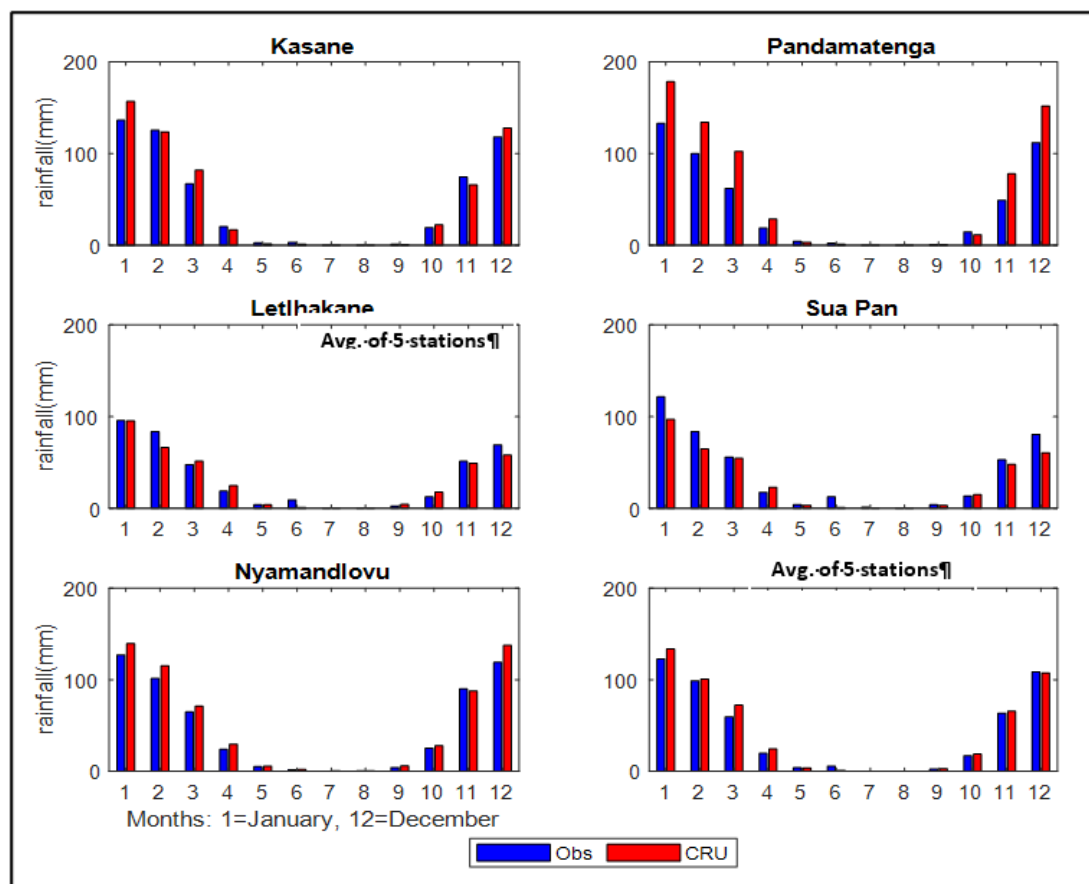


Figure 4: Comparison between observed and CRU derived mean monthly rainfall
Source: SADC-GMI (2020a)

Topography and surface water drainage

The topography of the EKK-TBA is generally flat and ranges between 880 and 1 400 m amsl in the central southern (Makgadikgadi Pans) and eastern (gradient) parts respectively, [Figure 5](#). The eastern topographic gradient is ~ 0.004 and the central southern topographic gradient is ~ 0.0002 (SADC-GMI, 2020b).

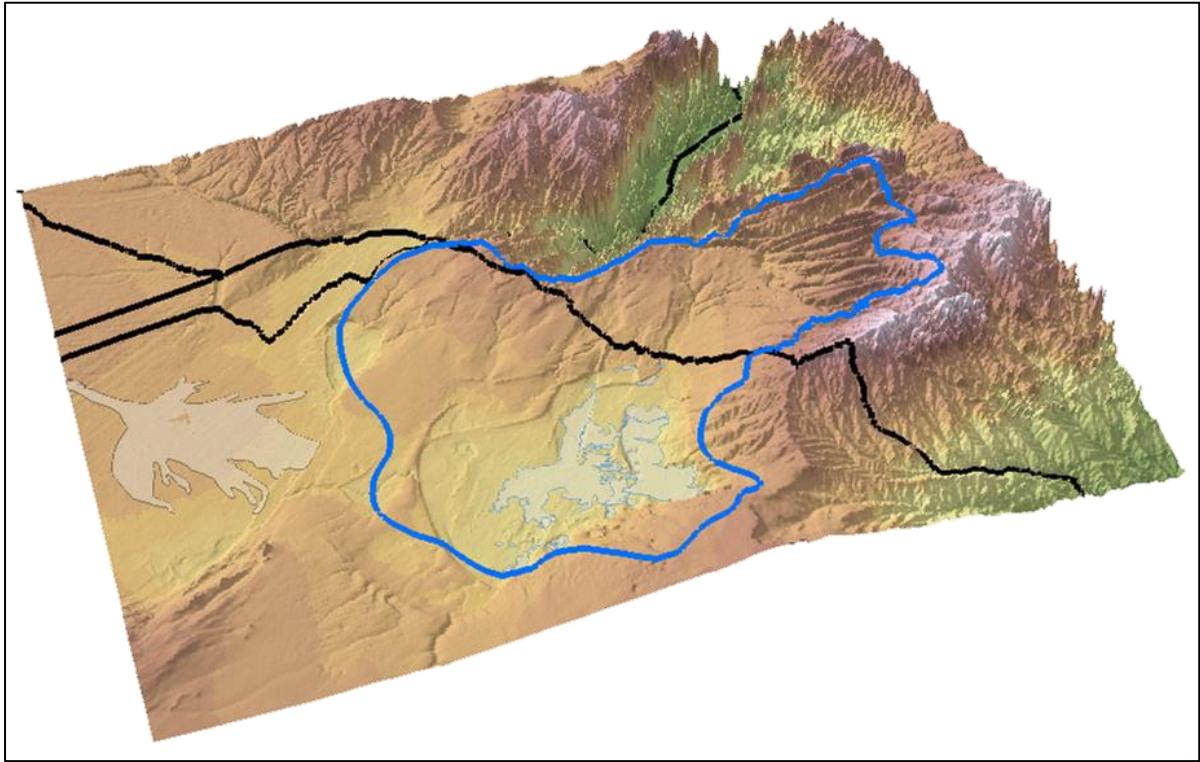


Figure 5: Digital Elevation Model (30m SRTM) topography of the EKK-TBA

Source: SADC-GMI (2020a)

Most of the rivers within the Basin are ephemeral and stop flowing soon after rainfall events. Perennial rivers occur in the eastern part of the Basin and are represented by the Gwayi River system, [Figure 6](#). Consequently, baseflow is negligible and generally represent the release of river bank storage soon after rainfall episodes.

Geology

The Karoo Basin, formed as a result of subduction and orogenesis along the southern border of southern Africa in the then southern Gondwanaland, is an intracratonic basin in which sediments of mainly fluvial origin (Karoo Supergroup) were deposited (Visser, 1995). The stratigraphy of the EKK-TBA is represented by the lithological sequences in NE Kalahari Karoo and Mid Zambezi Basins ([Figure 7](#), [Table 1](#)) and correlate well across all the southern African Basins (Catuneanu et al., 2005).

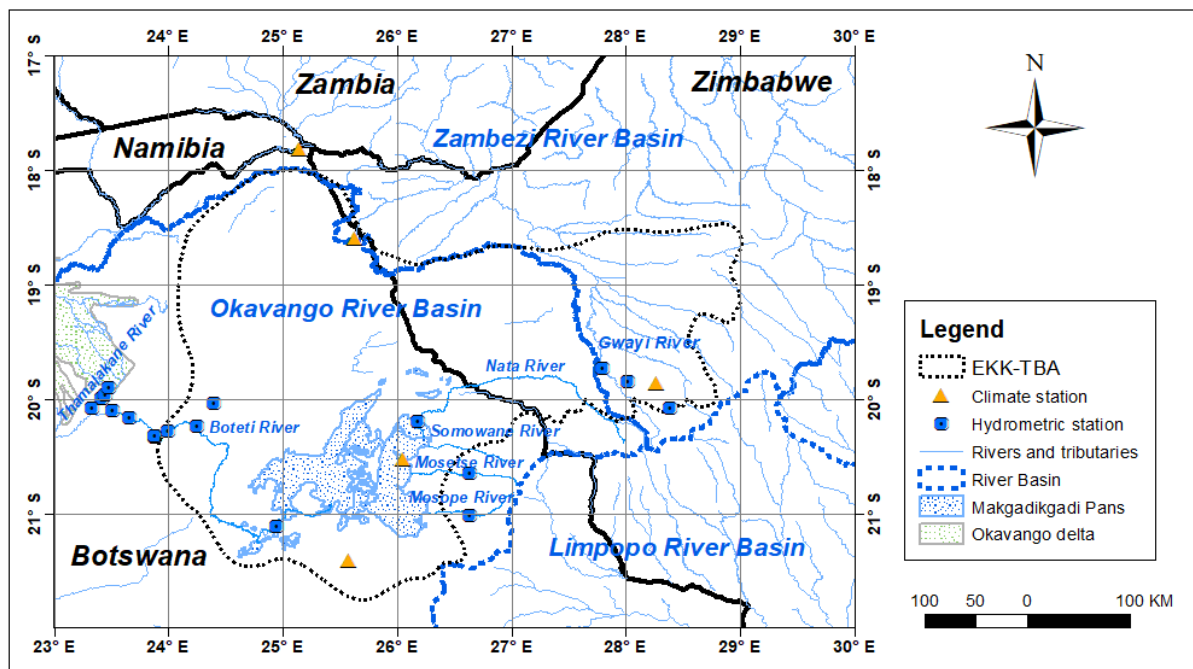


Figure 6: Surface water drainage in the EKK-TBA and climate and hydrometric stations
Source: SADC-GMI (2020a and b)

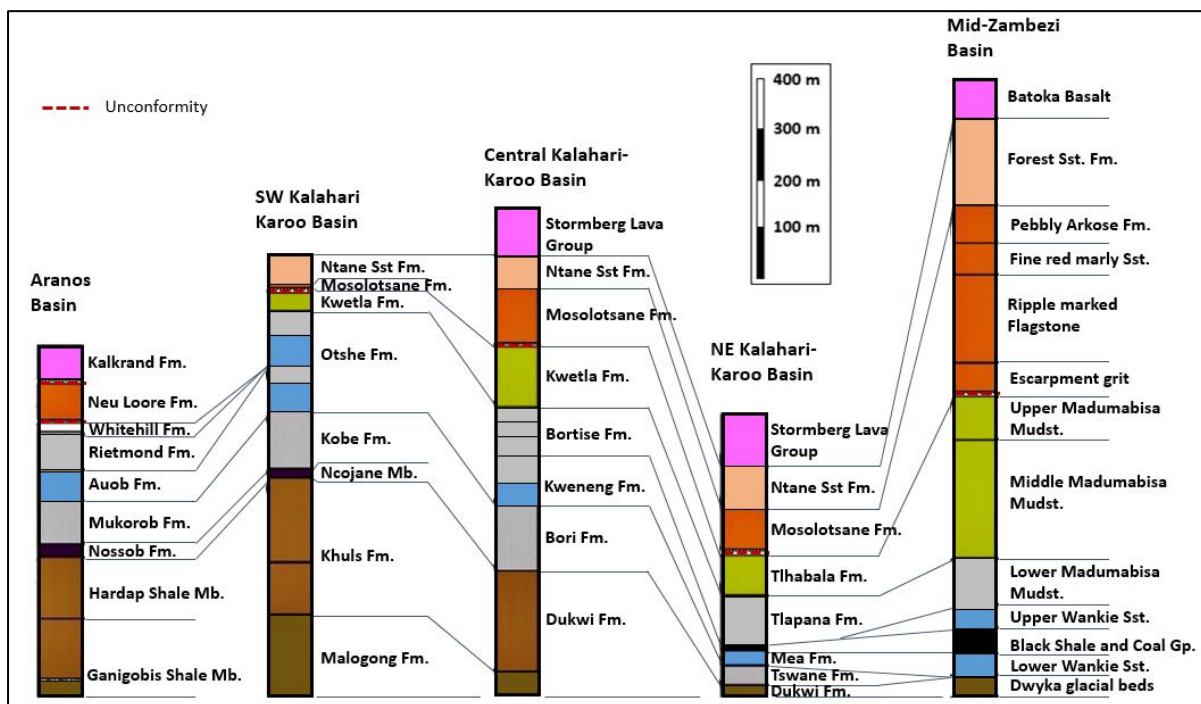


Figure 7: Correlation of Karoo Supergroup lithostratigraphic units
Source: modified after Catuneanu et al. (2005)

Table 1: Stratigraphic sequence of the EKK-TBA

Quaternary sediments; alluvium, sand, gravel, calcrete	
Kalahari Group deposits; Aeolian sand, sandstone, limestone	
Basalt (Stormberg/Batoka)	Upper Karoo
Ntane/Forest Sandstone	
Mosolotsane Equiv. (Escarpment grit to Pebbly Arkose Fms, Error! Reference source not found. mudstones)	
Beaufort Group; mudstone, sandstone	
Ecca Group (incl. Mea Arkose and Wankie Sandstone Fms); shale, mudst., sst., coal	Lower Karoo
Dwyka Group (Dukwi Formation); tillite, mudst., coal, sst.	
Basement complex	

Source: SADC-GMI (2020b)

The surficial geology and structural geology of the EKK-TBA is presented in Figure 8 and shows that the Kalahari Group covers the majority of the Basin, overlies the basalt and is only absent in the eastern, southeastern and southern fringes of the Basin. The Ntane/Forest Sandstone outcrops in the southern, southeastern and eastern parts of the Basin whereas the much deeper Mea Arkose Sandstone outcrops in the southeastern section of the Basin, Figure 9.

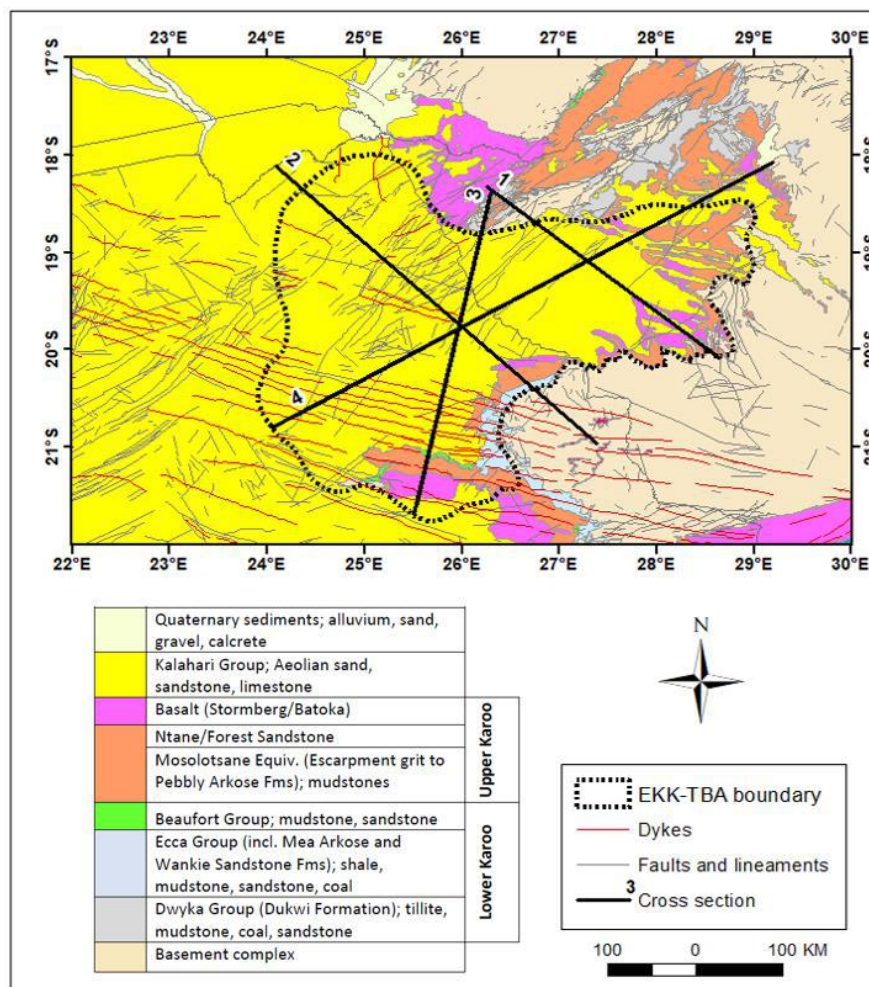


Figure 8: Geology of the EKK-TBA and surroundings

Source: modified after Council for Geoscience (2009)

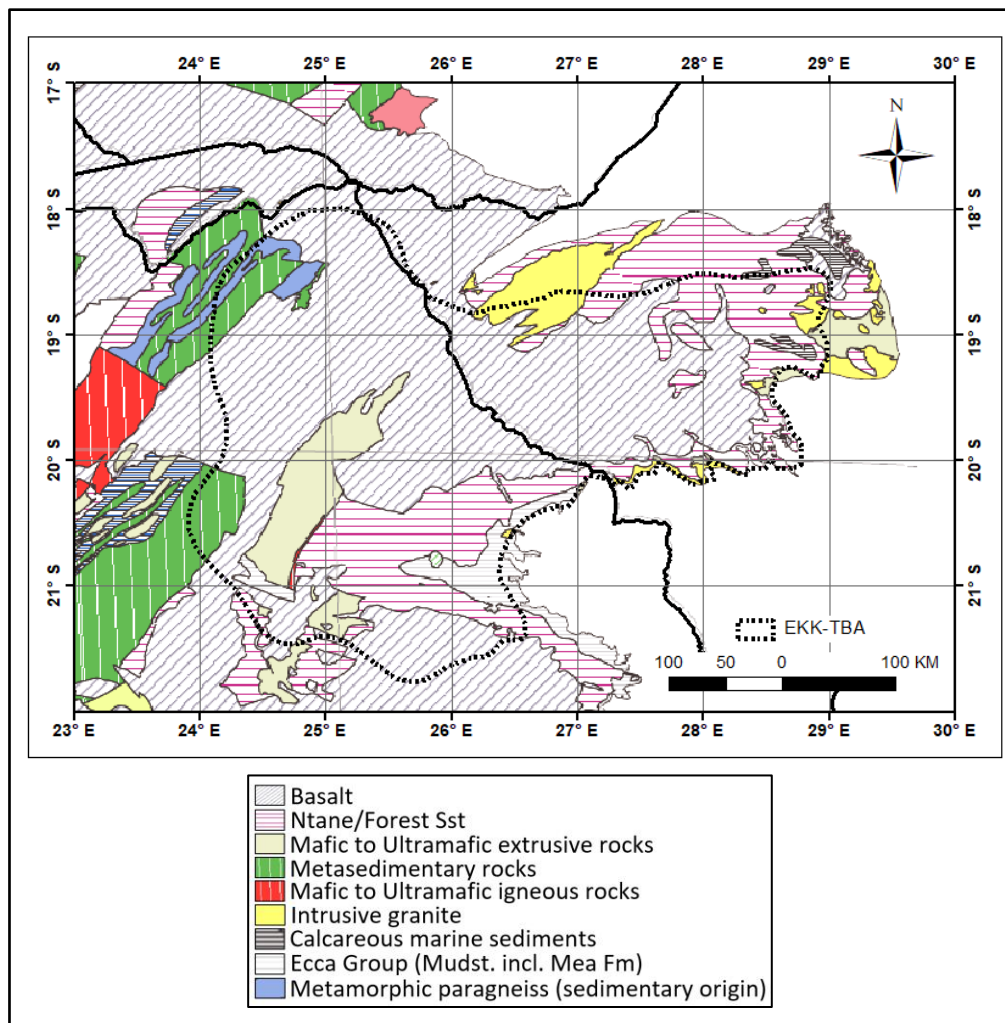


Figure 9: Pre-Kalahari Formations

Source: modified after Council for Geoscience (2009)

Dykes and faults

A tholeiitic Okavango Dyke Swarm striking east-southeast across Botswana and Zimbabwe, cuts through the south-western part of the EKK-TBA and spans a region nearly 2 000 kilometres long and 110 kilometres wide, with a mean dyke thickness of about 17m (Figure 8; SADC-GMI-2020b). NE-SW and NW-SE trending normal faults are predominant in the western section of the Basin. The dykes and faults resulted in extensive block faulting and compartmentalisation of the formations (*ibid*) and this is shown on the cross-sections depicted in Figure 10 and on the geological fence diagram, Figure 11. These were constructed from available lithological data and inferences from the Super Karoo lithostratigraphic units and other geological maps (Figure 7, Figure 8 and Figure 9; SADC-GMI, 2020b). The cross-sections exhibit horst and graben morpho-tectonic features, with the horsts corresponding to uplifted basement complexes and the grabens corresponding to Karoo depressions. The complexity of the faulting is shown for example by the surface geology of the Dukwi area (Figure 12) on the south-eastern margin of the Basin.

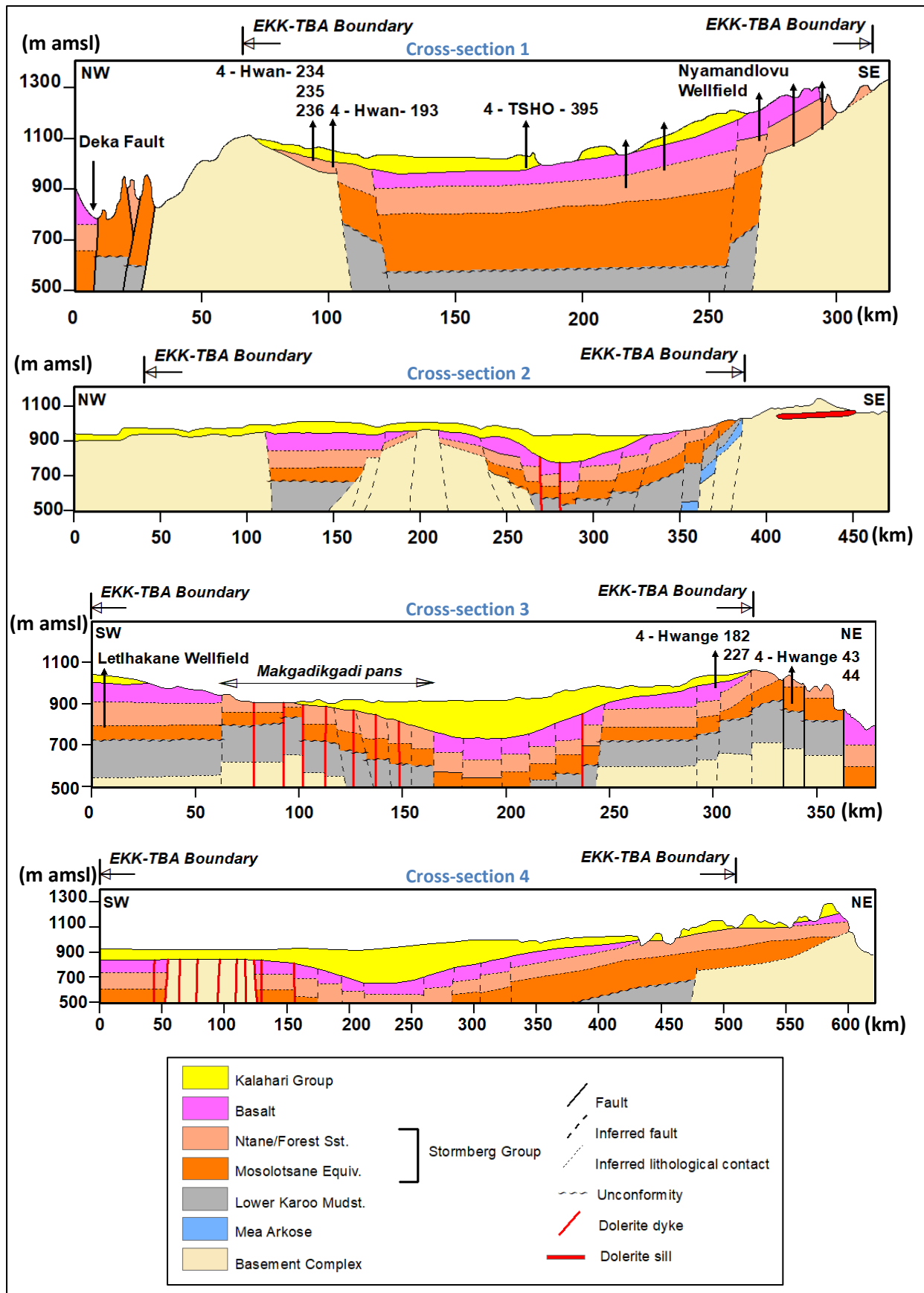


Figure 10: Geological cross sections

Source: SADC-GMI (2020b)

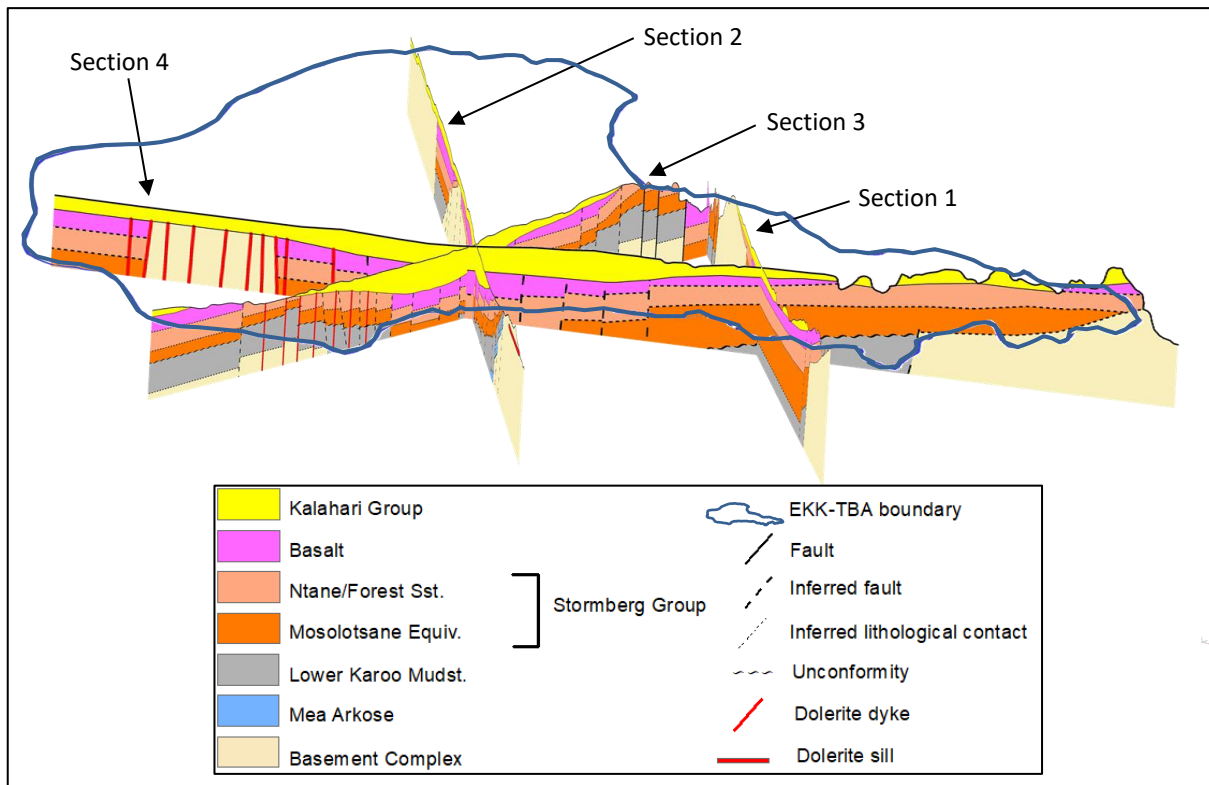


Figure 11: Geological fence diagram
Source: SADC-GMI (2020b)

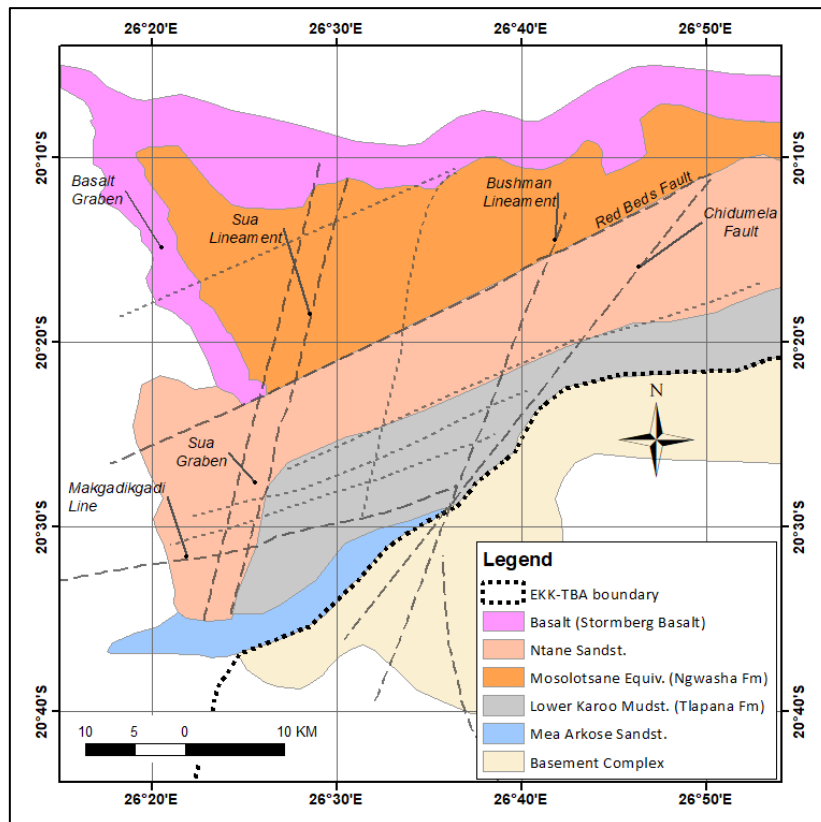


Figure 12: Geology of the Dukwi area showing the effect of tectonics on the stratigraphy
Source: SADC-GMI (2020b)

Local hydrogeological perspective

Hydrogeological data is available on the wellfields developed along the southern to the eastern fringes of the EKK-TBA (Figure 13) and it is scanty for the rest of the Basin. It is for this reason that the hydrogeological assessment was designed to start from the local perspective of wellfields before inferring on the regional hydrogeological perspective. The main aquifers for the wellfields are either the Ntane/Forest Sst. or the Mea Arkose Sst. which are essentially confined deep aquifer systems. The Kalahari Group deposits form the unconfined to semi-confined shallow aquifer.

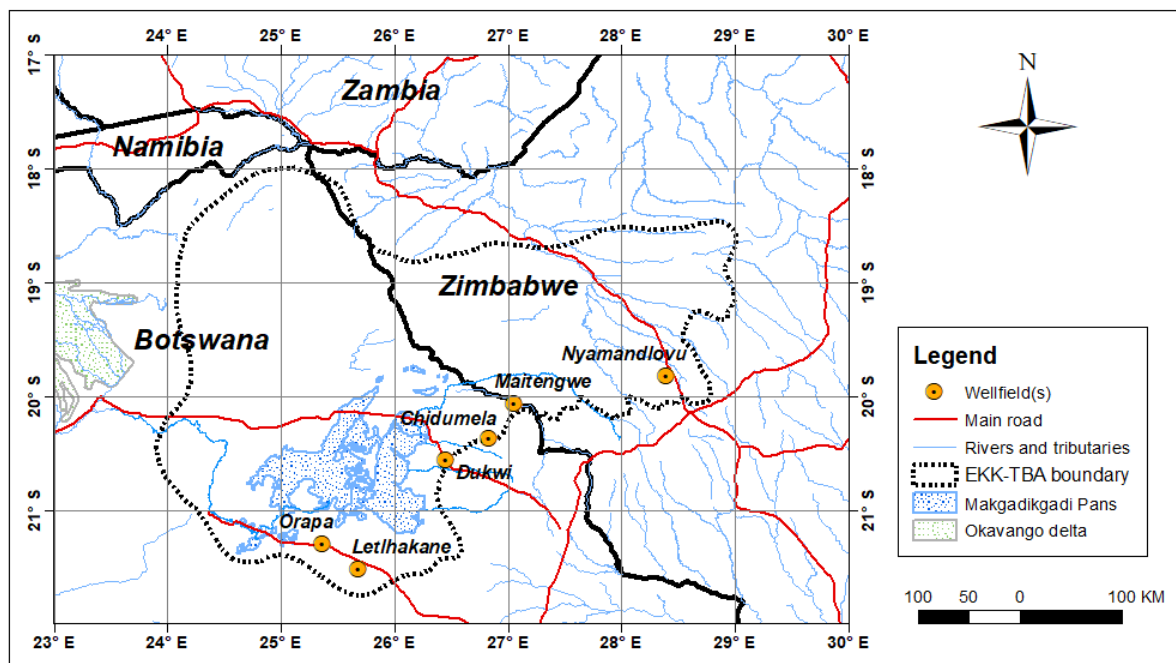


Figure 13: Location of EKK-TBA Wellfields

Source: SADC-GMI (2020b)

Groundwater in all the wellfields ultimately flows towards the Makgadikgadi Pans, which are the discharge area. The groundwater is fresh on the fringes where recharge takes place and rapidly salinizes with distance from the recharge zones and with increasing depth of the aquifers. The rapid change in groundwater quality is typified by the Maitengwe area, Figure 14. Salinisation of the groundwater adds to the water insecurity of the Basin as this water will not be available for domestic use unless treated at a cost which the member states can ill afford. Relatively high nitrate concentrations have found locally from agricultural practices (cropping and livestock) and from blasting in (diamond) mining operations (SADC-GMI, 2020b). Although nitrate does not pose a significant health risk it serves the purpose of an indicator of the vulnerability of an aquifer to pollution.

Groundwater recharge from rainfall occurs directly through diffuse percolation and indirectly through faults, contact zones and fractures. Recharge in the wellfields was estimated from a variety of techniques which included the Chloride Mass Balance (CMB), Water Table

Fluctuation (WTF), Cumulative Rainfall Departure (CRD), Environmental Isotopes, Groundwater Modelling, etc. Recharge rates varied from 2-37 mm/yr in the Botswana wellfields and 2-62 mm/yr in the Nyamandlovu Wellfield in Zimbabwe. Average annual groundwater recharge in the EKK-TBA is generally less than 3% of the average annual rainfall and is similar to what can be found in other semi-arid regions (Beekman et al., 1996; Xu and Beekman, 2019).

Analysis of radiocarbon (^{14}C or C-14) results confirmed the zonation of recharge areas in which 0-10 percent modern carbon (pmC) with lighter oxygen-18 (^{18}O or O-18) values represents older groundwater, recharged under cooler conditions, whereas 50-85 pmC with heavier ^{18}O values represents younger groundwater recharged under evaporative conditions. The radiocarbon content rapidly decreases from 85 pmC in the recharge areas to less than 10 pmC in less than 20 km away from the recharge zone (SADC-GMI, 2020 a and b).

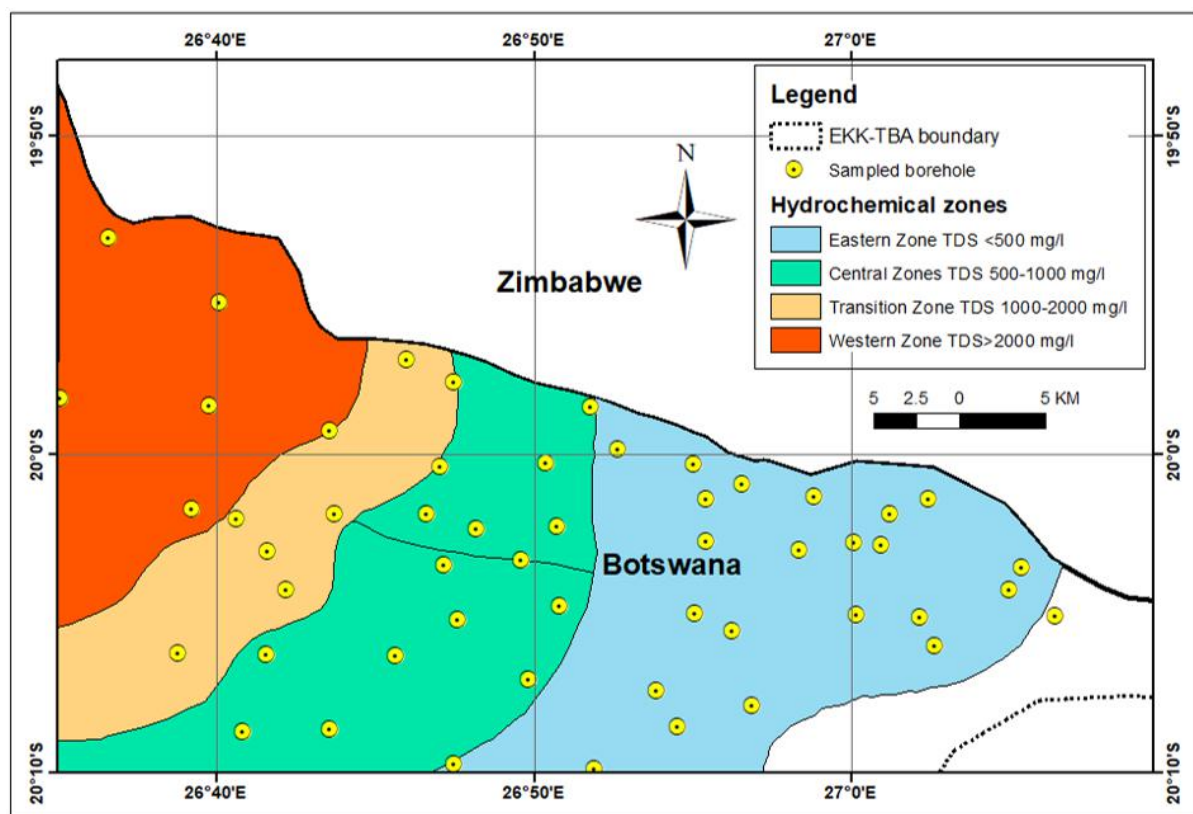


Figure 14: Upper Ntane Sandstone hydrochemical zones in the Maitengwe area

Source: SADC-GMI (2020a and b)

Regional hydrogeological perspective

The main aquifers for the Basin are the deep seated and confined Ntane/Forest Sst., the Mea Arkose/Wankie Sst., and the shallow unconfined to semi-confined Kalahari Group deposits. The Kalahari Group aquifer is not very prolific within Botswana's EKK-TBA (DWA, 2002) but is highly yielding within the Hwange National Park, in the Zimbabwean side of the EKK-TBA (WWF, 2019).

Groundwater flow

Groundwater flow in the Kalahari Group aquifer flows towards the Makgadikgadi Pans, conforming with that of the wellfields, [Figure 15](#).

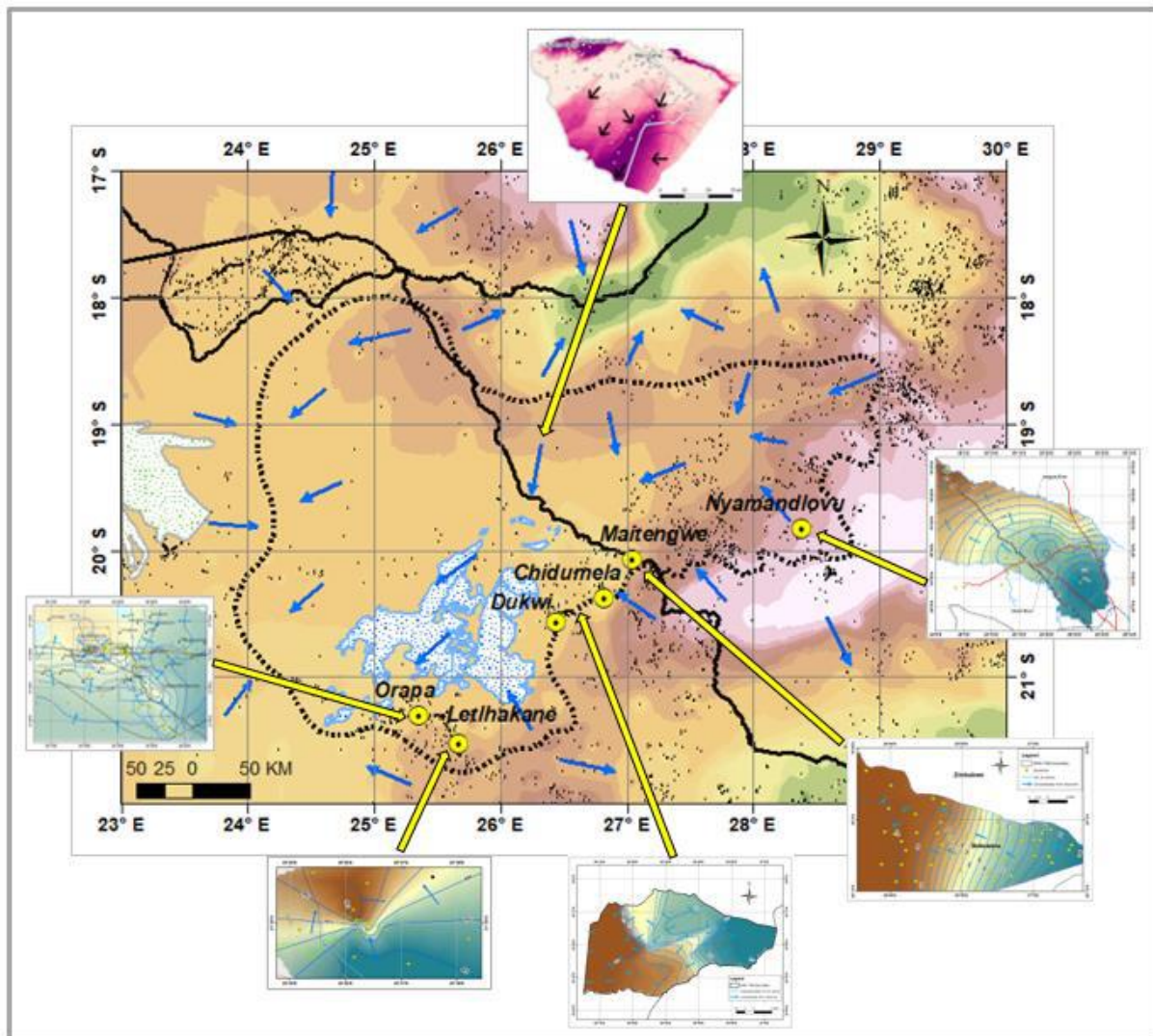


Figure 15: Regional and local piezometry of the EKK-TBA

Source: SADC-GMI (2020b)

Groundwater recharge

Numerous groundwater recharge studies were carried out in southern Africa using various recharge estimation techniques mentioned under the section of local hydrogeological perspective. The results of these studies indicate that with average annual rainfall (which is almost all the precipitation in this semi-arid region) below 350 mm, hardly any recharge occurs, [Figure 16](#) (Beekman et al., 1996; Xu and Beekman, 2019). The values are mostly from Botswana (Beekman et al. 1996), South Africa (Bredenkamp et al. 1995; Xu et al. 2007; Van Wyk et al. 2011), Namibia (JICA 2002; Stone and Edmunds 2011) and Zimbabwe (Houston 1988; Nyagwambo 2006; Shamboko-Mbale et al. 2012).

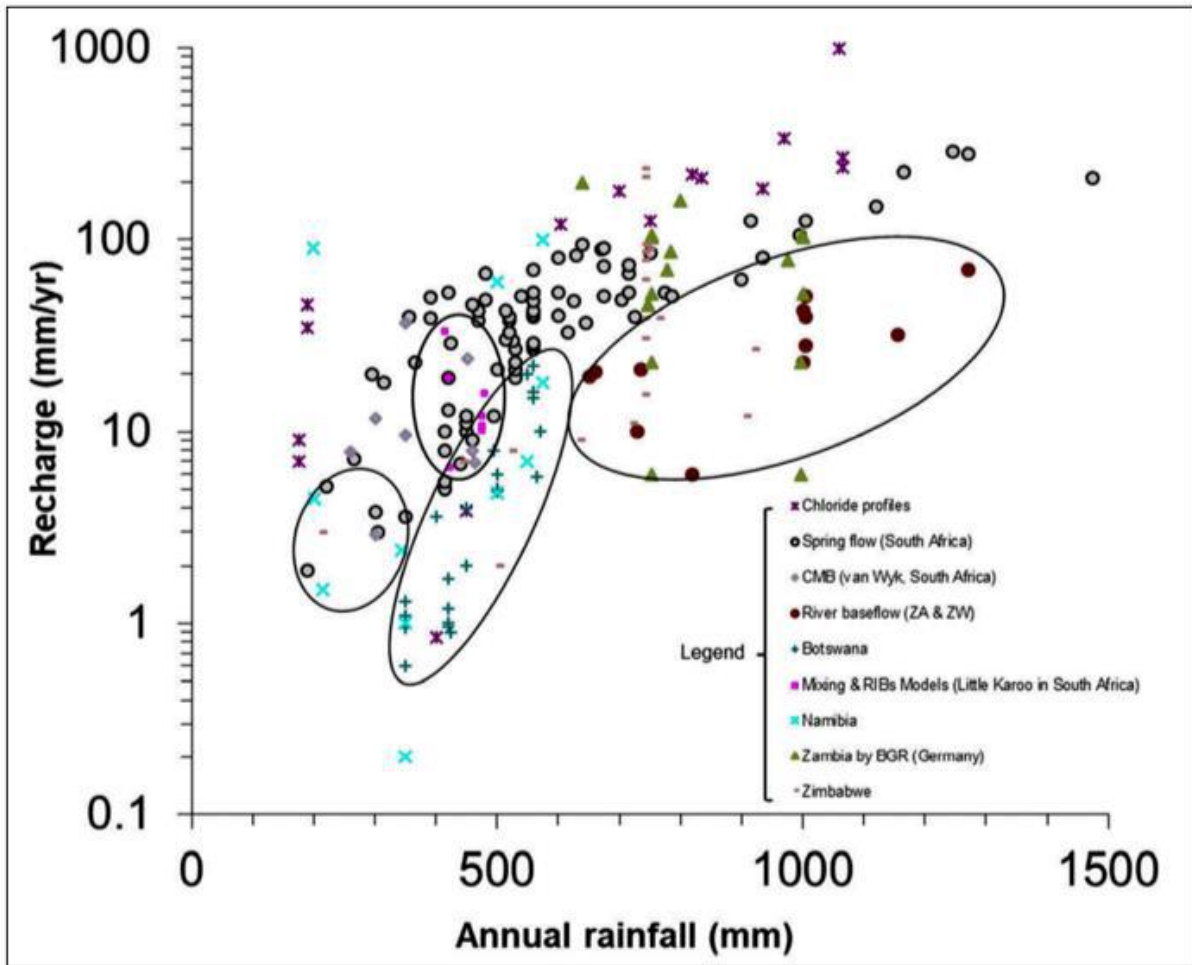


Figure 16: Recharge versus annual rainfall in southern Africa

Source: Xu and Beekman (2019)

Figure 16 also shows that there is a wide variation between recharge rates for the same amount of rainfall and is up to a factor difference of 100 and could be a result of preferential recharge along fault or fracture zones as opposed to diffuse recharge.

Based on Figure 16, a linear correlation between annual recharge and annual rainfall data from within the EKK-TBA and surroundings (Botswana, Namibia, Zambia and Zimbabwe) shows that the data falls within ± 1 standard deviation (SD), Figure 17. The annual recharge and annual rainfall relationship for the EKK-TBA wellfields show much less variation, with most of the values enveloped by the linear best fit $\pm \frac{1}{2}$ SD. The rainfall threshold of 350 mm/yr below which hardly any recharge occurs can be clearly observed from the figure.

The average recharge rates of the five EKK-TBA wellfields appear to be related to average annual rainfall (between 378 and 560 mm/yr) according to the linear equation $Y=0.07X-24.45$ (where Y the recharge estimate in mm/yr; and X the average annual rainfall in mm/yr; $R^2=0.99$), albeit the few data points (SADC-GMI, 2020b). This equation can be used in conjunction with the average annual rainfall map of the EKK-TBA, Figure 3, to construct a groundwater recharge potential map of the Basin, Figure 18.

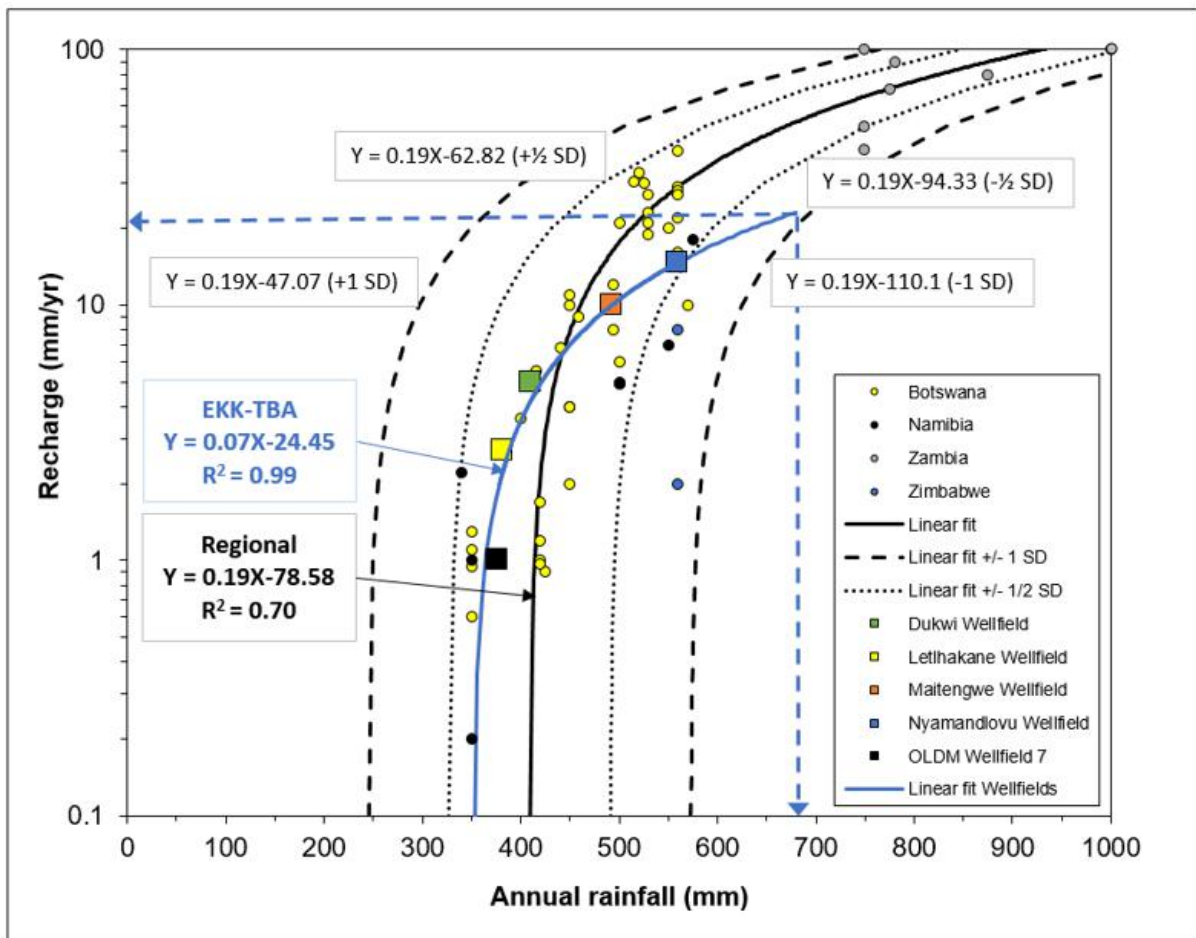


Figure 17: Correlation between annual recharge and annual rainfall
Source: SADC-GMI (2020b)

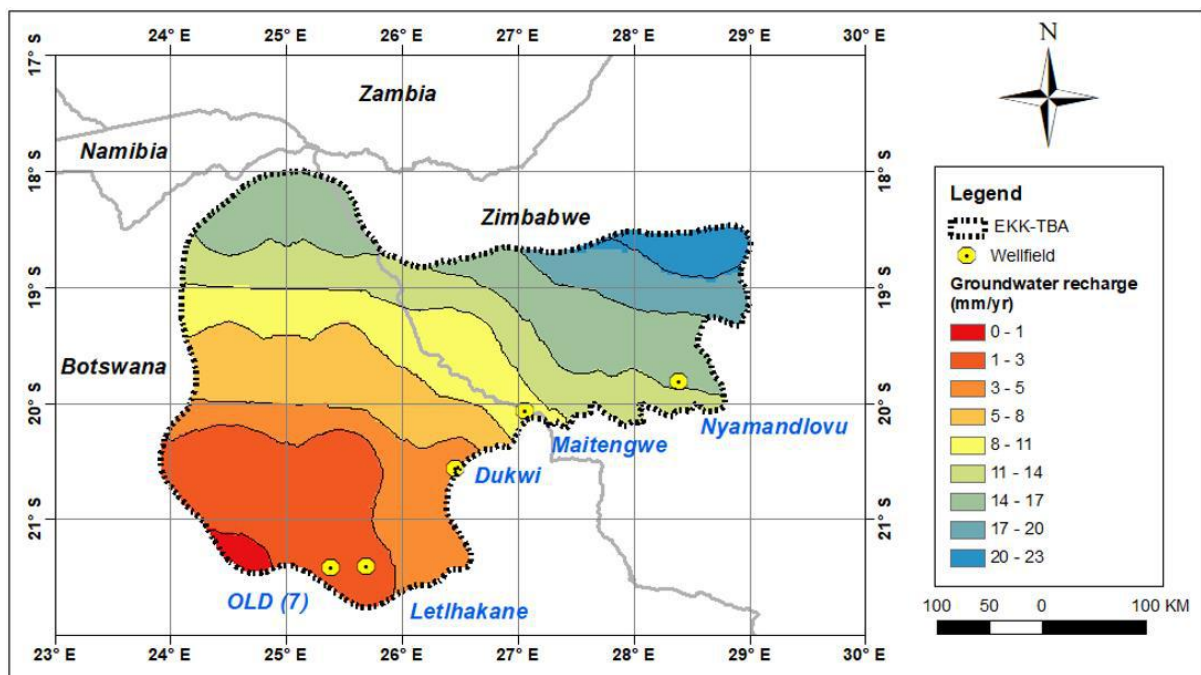


Figure 18: Groundwater recharge potential of the EKK-TBA
Source: SADC-GMI (2020b)

The map can be used to provide initial estimates of recharge in the absence of detailed (local) investigations within the Basin. Note that for annual average rainfall above 560 mm/yr, in the north-eastern part of the EKK-TBA, recharge is likely underestimated up to a factor of two and thus the map can be considered to be providing a conservative recharge estimate.

It must be cautioned that recharge does not occur everywhere as the map would seem to imply as recharge is limited to those areas where unconfined aquifer conditions occur. Also note that in a semi-arid climate setting such as the EKK-TBA, most recharge probably takes place through episodic events.

Hydraulic characteristics

Hydraulic characteristics were available from the EKK-TBA wellfields.

However, there is a lack of comprehensive data and information on the Kalahari Group deposits in the fringes of the EKK-TBA as they are relatively thin (<10m) and hence unproductive. This also applies to the other parts of the Basin (SADC-GMI, 2020b). WWF (2019) postulates that the Kalahari Group deposits within the Hwange National Park is highly productive, however, this needs to be validated through detailed hydrogeological investigations. Lekula et al. (2018) used hydraulic conductivity values of the Kalahari Group ranging from 0.1 to 15 m/d and borehole yields ranging from 4 to 40 m³/hr for their conceptual hydrogeological model of the Central Kalahari Basin.

Although the basalt by and large constitutes an aquitard, locally, high yields are obtained due to fracturing and faulting. The fracturing and faulting may also provide hydraulic continuity between overlying and underlying aquifers.

The Ntane/Forest Sandstone aquifer within the southern and southeastern fringes of the EKK-TBA is generally productive, save for Dukwi. Note that the salinity of the groundwater of the aquifer generally drastically increases within a relatively short distance from the recharge area. Borehole yields are varied and on the average 30 m³/hr. Hydraulic conductivity varies between 0.1 and 10 m/d and the storage coefficient between 10^{-6} and 8×10^{-3} .

The Mea Arkose Sandstone aquifer (and its equivalent Wankie Sandstone in Zimbabwe), although thinner than the Ntane/Forest Sandstone aquifer, has borehole yields of 100 m³/hr, and in the Dukwi area a hydraulic conductivity of 10 m/d and storage coefficients between 10^{-4} - 8×10^{-2} were determined.

Hydrogeological conceptual model for the EKK-TBA

The local and regional hydrogeological perspectives discussed above yield a basin conceptual model as represented in [Figure 19](#).

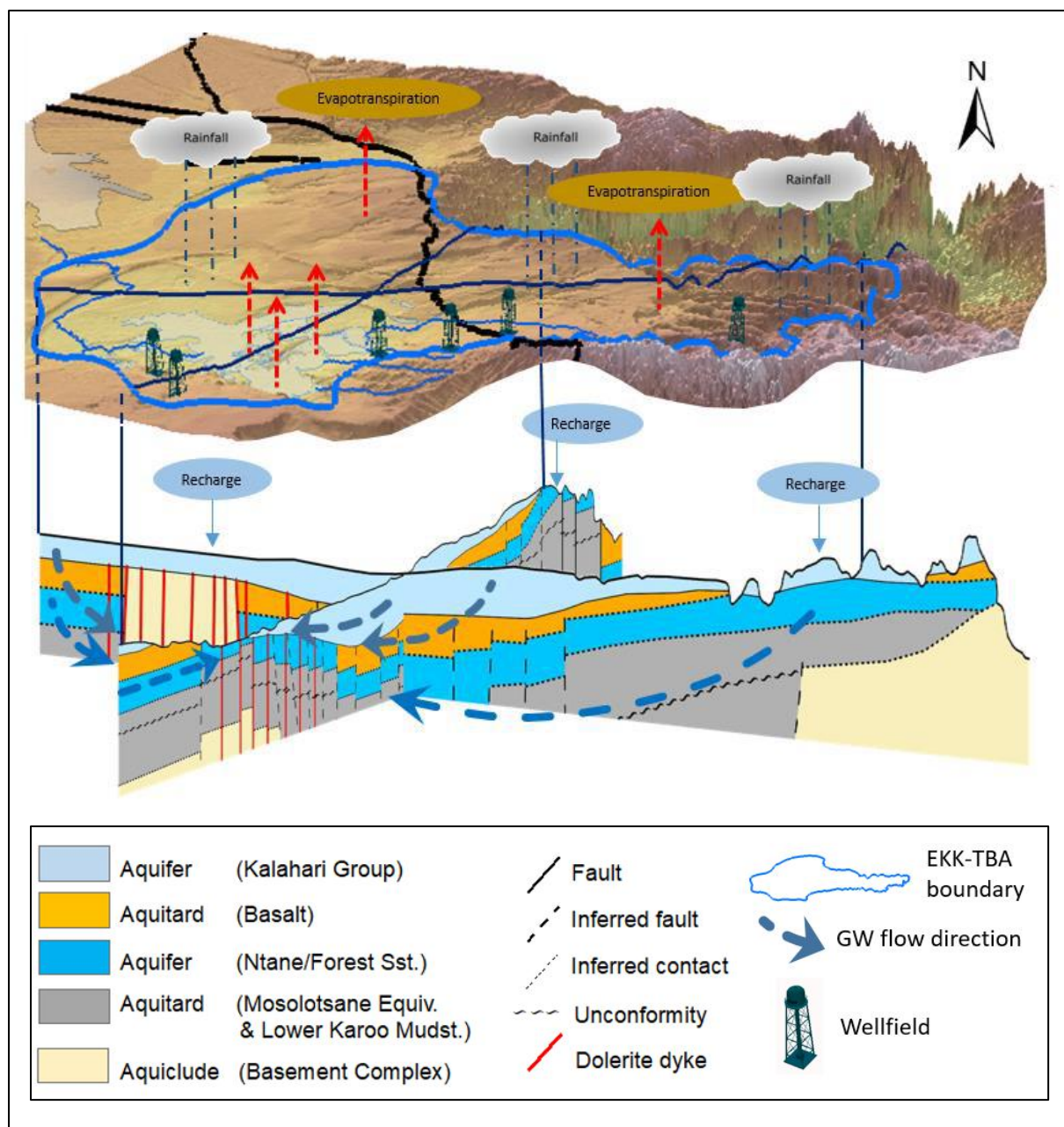


Figure 19: EKK-TBA hydrogeological conceptual model

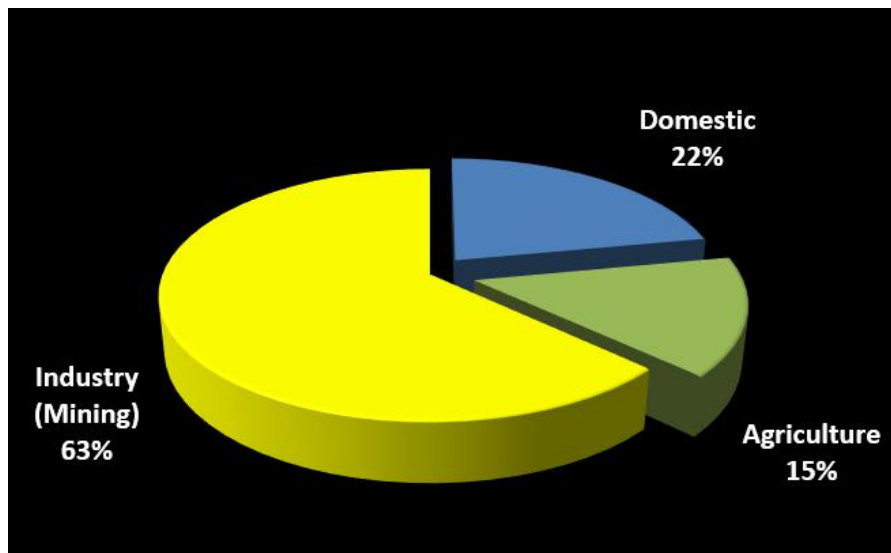
Source: SADC-GMI (2020b)

Groundwater use, development and management

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

Groundwater use

Sectoral groundwater use from the Ntane/Forest Sandstone and Mea Arkose aquifers within the EKK-TBA, based on current abstractions and excluding groundwater use for the environment, is estimated at 22% for the domestic sector, 15% for the agricultural sector and 63% for the industrial (mining) sector, [Figure 20](#) (SADC-GMI, 2020b).



[Figure 20](#): EKK-TBA sectoral groundwater use

Source: SADC-GMI (2020b)

Sustainable groundwater abstraction

Ponce (2007) suggests that sustainable groundwater abstraction of about 40% of the average annual recharge may be used where there is limited data and information. [Figure 21](#) shows the daily sustainable groundwater abstraction (in 10^{-6} m/day) derived from the recharge potential map ([Figure 18](#)) and based on the 40% rule. The daily sustainable abstraction rate in m^3/day is obtained from multiplying the value of the daily sustainable abstraction representative of the specific recharge area read from the map ([Figure 21](#)) by the size of the specific recharge area (km^2). Illustrations in the form of two examples are given below.

Note that the determination of the size of the recharge area of the particular aquifer is critical for estimating the sustainable abstraction rate and can only be derived from a comprehensive analysis of the geology and hydrogeology of the area including groundwater level monitoring data, and groundwater chemistry (salinity and water type) and isotopes (groundwater age).

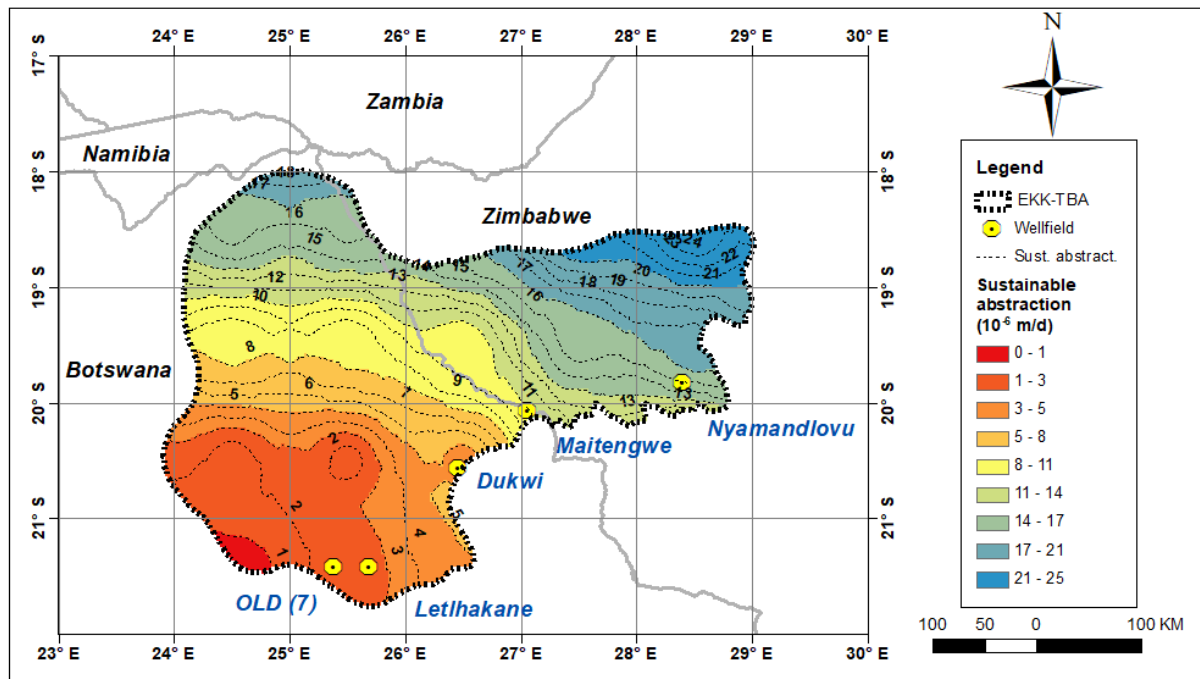


Figure 21: Sustainable abstraction in the EKK-TBA (10^{-6} m/day)

Source: SADC-GMI (2020b)

Example 1: Nyamandlovu Area

The recharge area of the Forest Sandstone Aquifer = 960 km^2 (Beekman and Sunguro, 2015). The sustainable abstraction over this area read from Figure 21 = 15. Then the daily sustainable abstraction = $15 \times 960 = 14\,400 \text{ m}^3/\text{day}$. This daily sustainable abstraction figure tallies well with the recommended sustainable abstraction of $15\,000 \text{ m}^3/\text{day}$ determined from a steady-state groundwater model of the area (*ibid*). Any abstraction above this figure would be unsustainable.

Example 2: Dukwi Regional Wellfield (Phase II)

The recharge area of the Mea Aquifer = 105 km^2 (DWA, 2000).

The sustainable abstraction over this area read from Figure 21 = 4.5. Then the daily sustainable abstraction = $4.5 \times 105 \sim 470 \text{ m}^3/\text{day}$. This figure is close to the sustainable yield of the Mea Arkose Sandstone Aquifer, which was calculated at $400 \text{ m}^3/\text{day}$ by DWA in 2000 (DWA, 2000) but may not have taken into account indirect recharge.

Daily groundwater abstractions since 1995 have been more than $1\,650 \text{ m}^3$, which is well above the calculated daily sustainable abstraction of $470 \text{ m}^3/\text{day}$ and has resulted in groundwater levels declining by approximately 22 cm/yr as observed in BH7547, Figure 22.

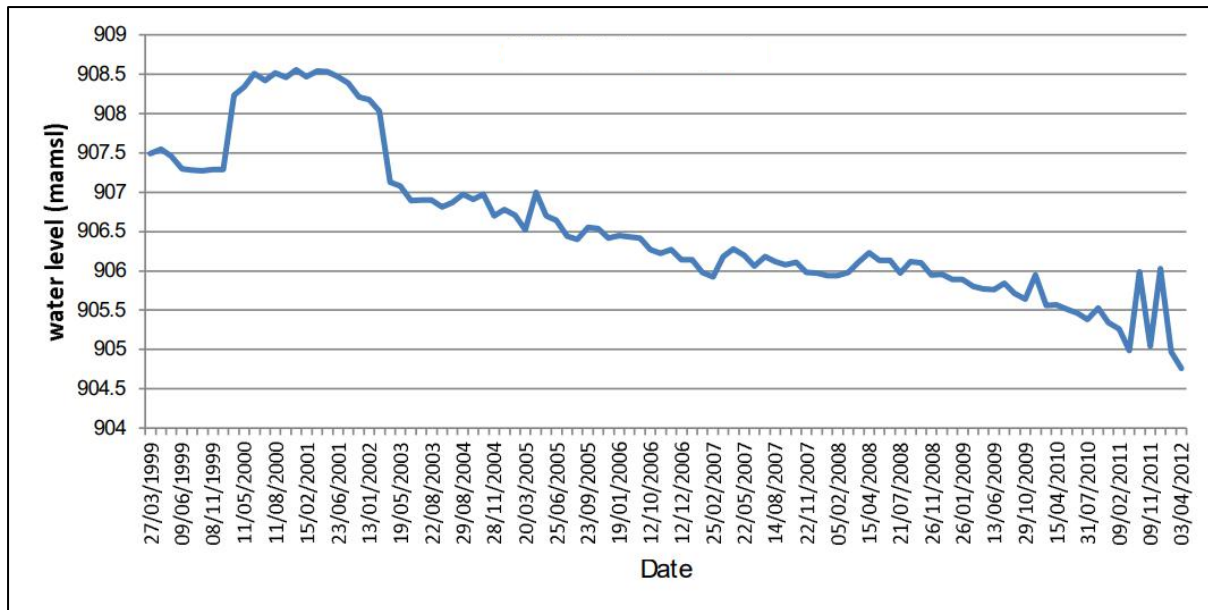


Figure 22: BH 7547 hydrograph

Source: Legadiko (2015)

Potential for future groundwater development

Groundwater development in most of the identified aquifers on Botswana's EKK-TBA has reached its limits and new groundwater resources need to be established. Additional groundwater development within the EKK-TBA could possibly take place in the northeastern part of the Basin, with particular focus on the fringes of the Basin especially where sandstone formations outcrop, and the Kalahari Group (where it is thickest and possessing good hydraulic characteristics), [Figure 23](#). Zimbabwe also has the opportunity to develop groundwater within the Epping Forest area, northwest of the current Nyamandlovu Wellfield, [Figure 23](#).

Complementary to developing the identified potential areas, Managed Aquifer Recharge, being cognizant of the semi-arid nature of the Basin, could be implemented at the local scale to enhance the groundwater potential, e.g. in the Maitengwe area. This, however, requires thorough hydrogeological investigations. A raft of water demand management and water conservation strategies, inter alia, introduction of innovative modern irrigation methods, change in cropping patterns, water recycling in 'urban' centres, timely fixing of burst pipes and leaky taps, blending of saline and fresh groundwater, etc., would assist in ensuring the sustainability of the resources and access to potable water by consumers.

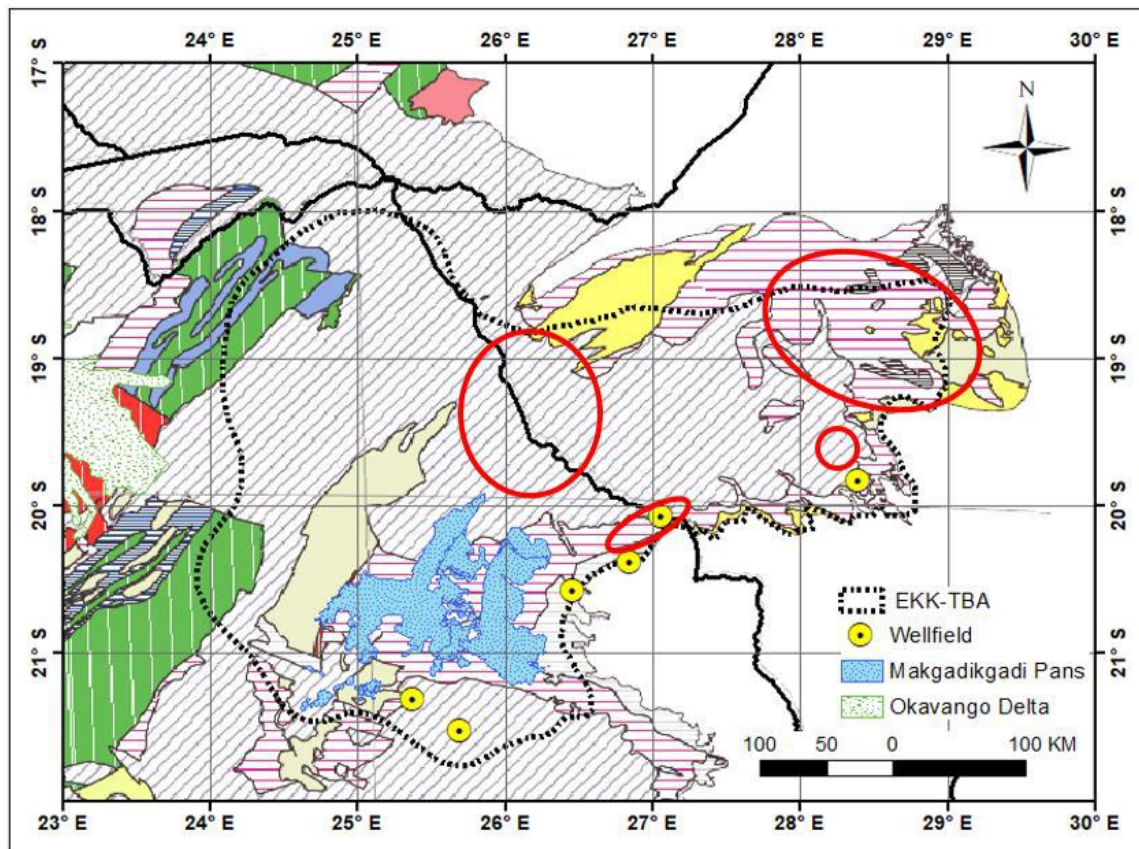


Figure 23: Potential areas for future groundwater development

Source: SADC-GMI (2020b)

Groundwater management and monitoring

There is no transboundary aquifer management organisation and hence there is no basin-wide groundwater management and monitoring. Groundwater management and monitoring is exclusive to the countries, is localized, and is carried out by both the public (DWS and WUC in Botswana and ZINWA in Zimbabwe) and the private sector (Debswana, Lucara, Botash, etc.). It is largely in-coherent and beset by operational challenges which include lack of expertise, equipment and dedicated budget (SADC-GMI, 2020a and b).

The SADC water sector institutional framework allows for the establishment of bi-lateral or multi-lateral water institutions to support specific purposes (SADC-GMI, 2019). Hence, groundwater management (including monitoring, data and information exchange) of the EKK-TBA may be formalised through the establishment of a groundwater management unit or any such unit within OKACOM and ZAMCOM.

An 8 step approach is proposed for designing a groundwater monitoring programme for the EKK-TBA. is provided below. The 8-stage approach was effectively employed in Eritrea (Cavé et al., 2002 cited in Beekman, 2005) and Zimbabwe (Beekman and Sunguro, 2015) and comprises:

- STEP 1: Set monitoring goals
- STEP 2: Establish monitoring status quo
- STEP 3: Coordinate with other monitoring initiatives
- STEP 4: Design monitoring programme
- STEP 5: Address support services and training requirements
- STEP 6: Set up quality assurance/quality control procedures
- STEP 7: Draw up planning document
- STEP 8: Implement and update groundwater monitoring programme, [Figure 24](#)

The development of an EKK-TBA hydrogeological conceptual model is an essential prerequisite for the design of a groundwater monitoring network as this focuses the monitoring network in attaining the set objectives. The hydrogeological conceptual model forms part of Step 4.

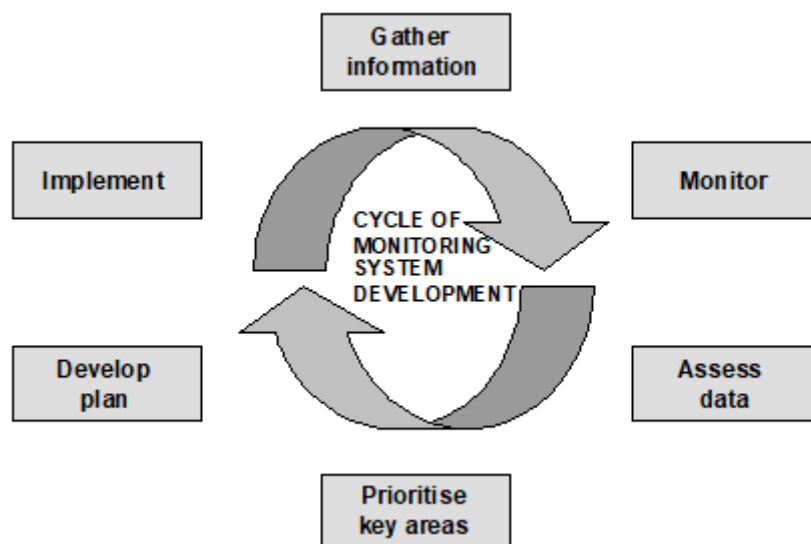


Figure 24: Groundwater monitoring system cycle development

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

Conclusion

The EKK-TBA is in a semi-arid region and has groundwater as the main source of water. The Kalahari Group deposits form the shallow unconfined to semi-confined aquifer and the Ntane/Forest Sst. and Mea Arkose/Wankie Sst. form the deep confined aquifers. Groundwater development is limited to the southern, south-eastern and eastern fringes of the Basin where recharge occurs, and the groundwater is fresh. Groundwater rapidly salinizes away from the recharge zones and with increasing depth of the confined aquifers. Groundwater management is confined to public and private sector institutions and does not have a basin-wide perspective since there is no EKK-TBA management institution and its creation would be pivotal to sustainable groundwater management for the Basin.

Groundwater demand exceeds supply, which prompts for sustainable development and management of the finite resource, coupled with other water conservation strategies. The setting up of a groundwater monitoring system in conjunction with a basin-wide groundwater model, based on the developed hydrogeological conceptual model of the Basin is urgently needed to assist in the sustainable management of the EKK-TBA.

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