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Institution	University of Western Cape
Contact person	Haile Mengistu
Postal address	Robert Sobukwe Road, Bellville 7530, South Africa
Telephone	+27-21-9592955
Fax:	+27-21-9593744
E-mail	hmengistu@uwc.ac.za

Executive summary

The University of Western Cape has been conducting compilation of basin wide lithology based aquifer mapping in the Zambezi River Basin (ZRB). Various spatial data are obtained from the public domain of SADC-GMI platform to be used in the data curation, checking, correction as well as further spatial data analyses.

A regional geology map is recreated with corrected spatial attributes of the lithology groups, which are produced on the basis of rock composition, chronostratigraphy as well as porosity class (primary or secondary). The aquifer classification is then created mainly based on the lithology clustering and incorporates aquifer parameters related to hydraulic properties including groundwater storage as well as aquifer transmissivities.

After a careful consideration of all the factors, nine lithology based aquifers are identified:

- Quaternary Alluvial Aquifer
- Kalahari Group Sediment Aquifers
- Mesozoic Marine Sediment Aquifers
- Karoo Volcanic Aquifer
- Karoo Sedimentary Aquifers
- Paleozoic Marine Sediment Aquifers
- Transvaal Carbonate (dolomite) aquifers
- Precambrian metasediment and metavolcanic Aquifers
- Basement Complex Aquifers

Aquifer hydraulic parameters, aquifer geometries including saturated thickness, aquifer media properties are used to estimate the groundwater reserve of the aquifers. Estimations conducted on the storage capacities of each aquifers turns out that roughly 28×10^9 m^3 of groundwater is stored within the entire basin.

Electrical conductivity measurements are used as a proxy for groundwater salinity mapping. It turns out that high salinity water with electrical conductivities in excess of 2000 µSiemens/cm is found in Quaternary alluvial aquifers of the lower Shire River valley in South Malawi & North Mozambique approximately constituting 2% of the ZRB area. Moreover, as expected the Kalahari Group Aquifer of southwest Zambia demonstrate elevated level of salinity, upstream of Victoria Falls and northwest of Choke Swamp.

On the other hand, potential to pollution map is produced using potential source-pathway-recipient analysis and proximity to vulnerable ecosystems. The mapping identified areas of high pollution mainly in central north and northeast of the ZRB where large-scale mining is evident and critical surface water resources are evidently found. Evidence of sever pollution also coincides partly with important carbonate aquifers in central Zambia.

Acknowledgement

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List of Tables

List of Figures

TABLE OF CONTENTS

Introduction

The Zambezi River Catchment is the fourth-largest river basin in Africa, covering an area of 1,359,000 Km^2 draining roughly 5% of the surface area of the continent in southern Africa. The river begins its 2650 km journey in the mountainous region close to the borders of the Democratic Republic of Congo and Angola in the northeastern province of Zambia. The Zambezi River flows south for roughly 650 km before it turns east until it reaches the Indian Ocean with mean annual discharge of roughly 94 x 10^9 m^3 (Fig. 1).

The Zambezi River sub basin around the source is named Upper Zambezi flowing southwest into Angola where Luena and Chifumaga Rivers merge before it enters dense dry forest. In the western Zambian grasslands where Chavuma and Victoria Falls are located, the river takes the name Middle Zambezi. Important tributaries in Middle Zambezi are Kabompo and Lungwebungu Rivers where Barotse floodplain begins as the landform starts becoming relatively less undulating. The Luangwa and the Kafue Rivers are the two largest tributaries of the Middle Zambezi River. The Kafue River then joins the proper Zambezi River in a quiet deep stream of about 180 m (590 ft) wide river course. At the confluence of another tributary, the Luangwa River is where the Zambezi enters Mozambique territory where it becomes the Lower Zambezi, and flow additional 650 km from Cahora Bassa Lake to the Indian Ocean. The Zambezi River receives the drainage of Lake Malawi through the Shire River, which is one of the most important tributaries of the downstream portion of the Zambezi River. The hydrology of Zambezi River on a catchment scale was studied in detail that is being used in past and future surface water resource developments but previous hydrogeology undertaking were limited to few local areas (Gerrits, 2005).

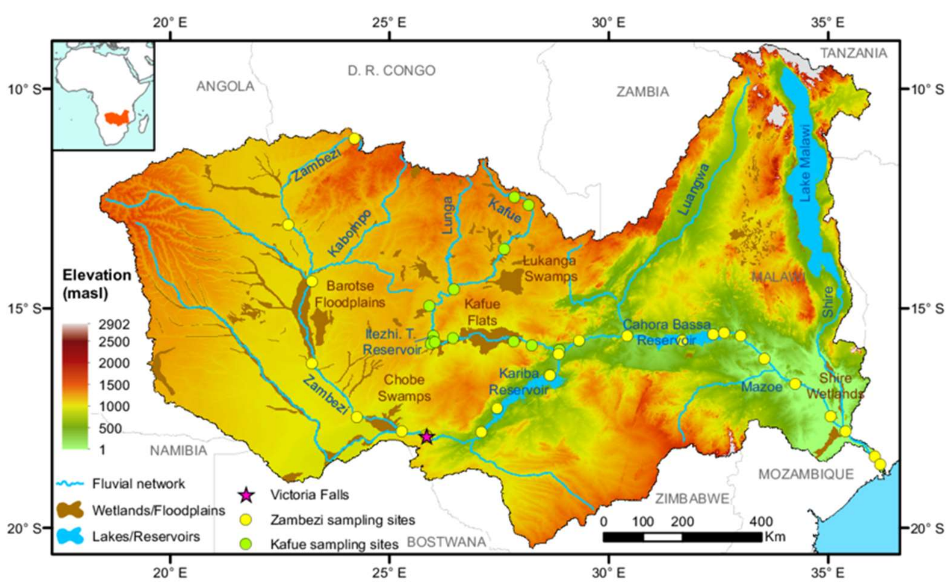

Figure 1 Location map of the Zambezi River Basin.

The highest elevation, roughly 1550 m above mean sea level (amsl) is located mainly in the northern basin boundaries with the low lands coinciding with the river mouth in the southeastern corner of the basin (Fig. 2). The majority of the river basin lies between 600 m amsl and 1200 m amsl.

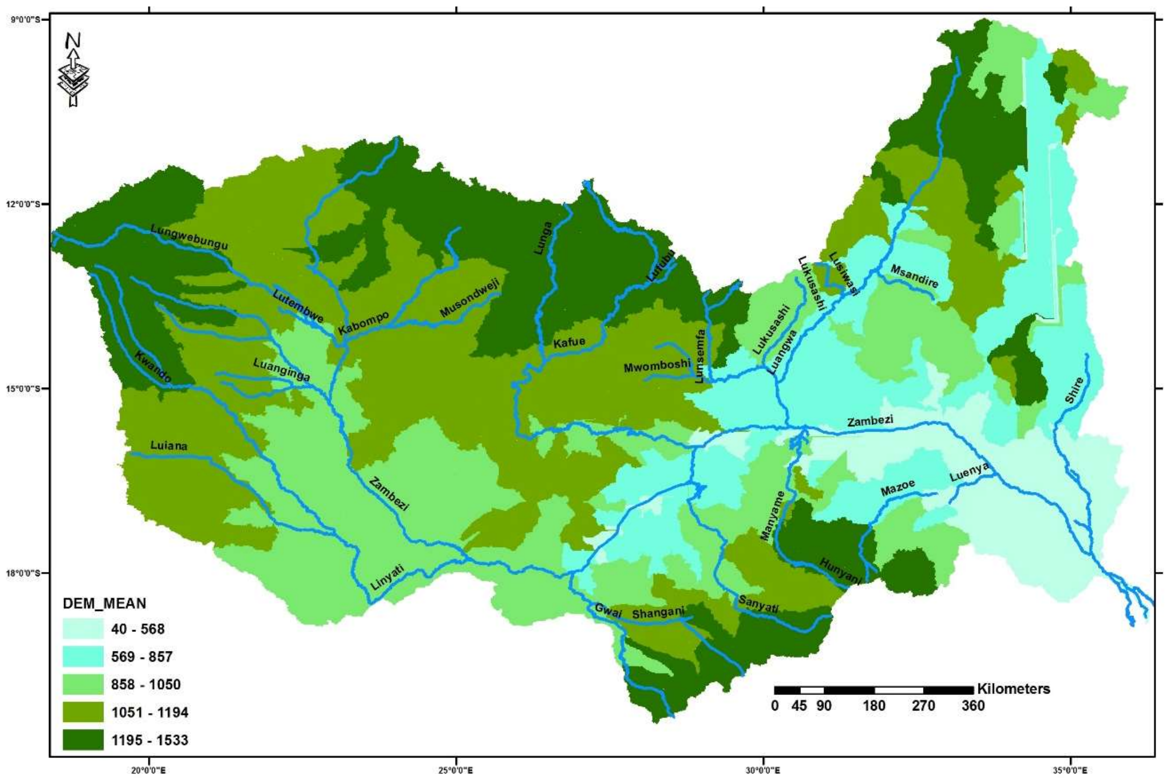

Figure 2 Mean digital elevation model map (data obtained from USGS HydroSheds)

1. Data Availability

Data, regardless of its quality or sufficiency, is available under the custody of various institutions, which in some instances don't share and integrate similar data types archived under two different government or public entities. The SADC-GMI is one of the most important platforms where existing country-level semi-processed spatial data is accessed. A closer look into the SADC-GMI data set, though, shows that proper meta-data is missing and some notations are not clearly defined.

The National University of Science and Technology (NUST) of Zimbabwe provided some lithology and groundwater data. Mainly groundwater physico-chemical parameter data but with major cations, major anions as well as Nitrate, Fluoride, Manganese and Iron in half of the samples were obtained from the University of Zambia and Malawi. Spatial data of mine coverage, tailings dam, tailings lake of Zambia and Zimbabwe are shared by the University of Zambia and NUST of Zimbabwe. Additional country level land-use, geology, hydrology data are obtained through a colleague from the University of Western Cape.

In Zambia and Malawi, groundwater data (borehole locations, depth to water level, lithology and some physicochemical data) is properly archived in a centralized manner recently through the University of Zambia (a partner in the groundwater component) and the Council for Geoscience in the case of Malawi but it is not the case in every ZRB countries. Therefore, access to existing data is entirely dependent on the willingness of institutions of ZRB countries as well as availability of known individuals who has local knowledge of responsible parties in the region. The current availability of data is summarized as follows (Table 1).

Table 1 Summary of the available data used in the analysis at the present time.

Available Data	Data Source
1. Geology Data I. Regional Geology II. National Geology III. Aquifer productivity (rank)	SADC - GMI
2. Aquifer Data a. Aquifer type (unconsolidated intergranular, low permeability, fissured, karst, intergranular) b. Yield class c. Rock type	SADC- GMI
3. Primary and secondary rivers	Waterbase http://www.waterbase.org/download_data.html
4. Digital elevation model data	USGS HydroSheds
5. Primary, secondary and tertiary catchments	Waterbase http://www.waterbase.org/download_data.html
6. Water quality Data (Malawi)	Personal communication
7. Water quality and borehole data	University of Zambia
8. Mine coverage, hotspots, tailings lakes and tailings dams	University of Zambia
9. Geology map of Zimbabwe	NUST
10. Geology map of Rhodesia	Personal communication

3. Methodology

3.1. Data Validation

The spatial data obtained from the SADC-GMI public domain is loaded on a GIS platform where the data attributes are exported as an EXCEL readable dBase Table format. Getting the data in a spreadsheet format makes checking each row of data for compatibility and credibility based on local experience, convenient to work with. Visual data accuracy check is a very labour-intensive but a very critical activity that ensures reliability of the spatial data.

The entire attribute of geological database are checked and manual correction of inconsistent records of regional geology records between the country scale and river basin scales is performed. Use of old geological map of Zimbabwe and the SADC Transboundary Aquifer Map from the Council for Geoscience provided critical information to fill data gaps identified in the SADC-GMI spatial database. Cross reference of regional and level spatial nomenclature is performed with Friends of Southern Africa (1997) database for consistency.

Spatial water quality data, obtained from various sources show conductivity unit inconsistency and in some instances unexpectedly too low or too high data records, which are scrutinized and corrected. Result cross checking with published reports, personal communication as well as experience are used to improve data accuracy. With regards to pollution related data, the original spatial information is adapted as is, as preliminary overview of the database reveal no unreasonable and suspicious data.

3.2. Data Analysis

The SADC-GMI semi-processed spatial data has two databases:

1. Geological database of about 2100 rows arranged with eight column description:
    - Aquifer type (primary, fractured, intergranular and karst);
    - Aquifer production (low, intermediate, high and None);
    - Yield (high, medium, low);
    - National geology (52 formation names);
    - Regional geology (nine classes and water);
    - Area and Length).

2. Aquifer hydrology database: totalling roughly 2600 rows of data with each row configured to have nine columns:
    - Aquifer Type: Fissured, Karst, Low Permeability, Unconsolidated intergranular and intergranular
    - Yield class: High potential, Medium potential, very low permeability and limited potential
    - Hydrogeological code (Ar, Cl, Di, Dy, G, Pg, Qa, Sh, Ss, Sst, Vc)

ArcGIS 10.3 platform was used to process the manual spatial data correction and g revised geological map was generated. Additional spatial data manipulation was conducted to recreate the aquifer map using the geology and hydraulic parameters as well as aquifer media properties into account.

3. Water quality database: Half of the data from Malawi has roughly 680 rows of data with each row having up to 19 columns of data, which consists of sample location, physicochemical, major cations and anions including nitrate, fluoride, iron and manganese. The other half of water quality data from Zambia incorporates water levels, site information, mean yield, screen position and electrical conductivity data. It is also evident that the majority of records are incomplete, in some instances even missing location data. Electrical conductivity unit and location inconsistency (UTM versus longitude-latitude) corrections are some of the activities carried before the data are integrated and loaded on EXCEL spreadsheet for contour drawing using SURFER 9,2™ software. The generated isolines using kriging interpolation are exported as shape files before being imported onto the GIS platform.

4. Potentially polluted areas database: Most of the spatial data, sourced from the university of Zambia and NUST, is comprised of 258 mines, 398 tailings lakes, 37 tailings dams and 24 identified hotspots (highly polluted sites). All shape files are added onto the GIS platform where a preliminary map is generated. Taking into account the hotpot locations, tailings lakes, tailings dams and vicinity to sensitive ecosystems such as reservoirs and rivers, a map of potentially polluted areas as well as mine locations was created. The lack of distinction between large and artisan mining in the reported data did not permit to further investigate the differences in potential groundwater contamination.

4. Results and Discussion

Various studies completed in the region unveiled 14 aquifers on the basis of national classification system. Furthermore, in transboundary and extensive multi-formation groups. The following local aquifers are identified on national level and it should be noted that some portions might be outside the Zambezi River Basin:

1. Karoo sandstone Tanzania and Mozambique
2. Tuli Karoo Subbasin: Botswana and Zimbabwe
3. Ramtoswa Dolomite: Botswana
4. Cuvelai and Etosha Basin Angola and Namibia
5. Coastal Sedimentary Basins: Tanzania and Mozambique
6. Shire Valley Aquifer Malawi and Mozambique
7. Congo Intra-cratonic Basin Angola
8. Middle Zambezi Aquifer Zambia and Zimbabwe
9. Dolomite Aquifer Angola
10. Sands/gravel aquifer Malawi, Zambia
11. Kalahari/Karoo Basin Botswana and Namibia

12. Easter Kalahari/Karoo Basin   Botswana, Zimbabwe

The various aquifers had to be regrouped and reclassified on the basis of common hydraulic properties of the various litho-stratigraphic and chronostratigraphic units on basin scale into nine units. It has to be taken into consideration that during the merging processes, details and few unique and localized aspects of the aquifers would obviously be diluted and somehow lost in the range. Implementing a generalized, inclusive river basin (large) scale mapping compromises information accuracy but at least it provides a platform on which future and detailed follow up undertakings can be designed.

4.1. Detail description of each aquifer

I. Quaternary Alluvial Aquifers

Alluvial aquifers are mainly composed of unconsolidated coarse gravel and minor fine sand, situated on either side of major river flood plains and interestingly scattered around the river basin. Its aerial coverage is estimated to be approximately 16.2% or 32.6 x 10^6 hectares, third in areal coverage. Properly sited and developed borehole can have a productivity exceeding 14 l/s, which is recorded in the SADC – GMI attribute data. However, within the Zambezi River Basin, the average yield is estimated 3.3 l/s, according to the Friends of Africa Group Report (1989). In terms of usability, it is the most easily accessible aquifer type because of its shallow depth and widespread existence. Quaternary Alluvial Aquifers are categorized as inter-granular aquifers because it allows storage of water in a primary porosity. The aquifer's estimated reserve can be efficiently used for small-scale irrigation besides its domestic and dairy uses. Developing these aquifers require careful construction to withstand the rainy season flooding. Nevertheless, it is also one of the most heavily utilized resource especially by rural communities for domestic and dairy farms.

The estimated total potential storage of Quaternary alluvial aquifer is roughly 19. 6 x 10^9 m^3 based on average specific capacity, effective porosity and saturated thickness of similar lithologies in Southern Africa. Taking into account the average borehole productivity, wide spread occurrence and other agricultural and borehole construction advantages, the aquifer provides a relatively high potential for development (Fig. 3).

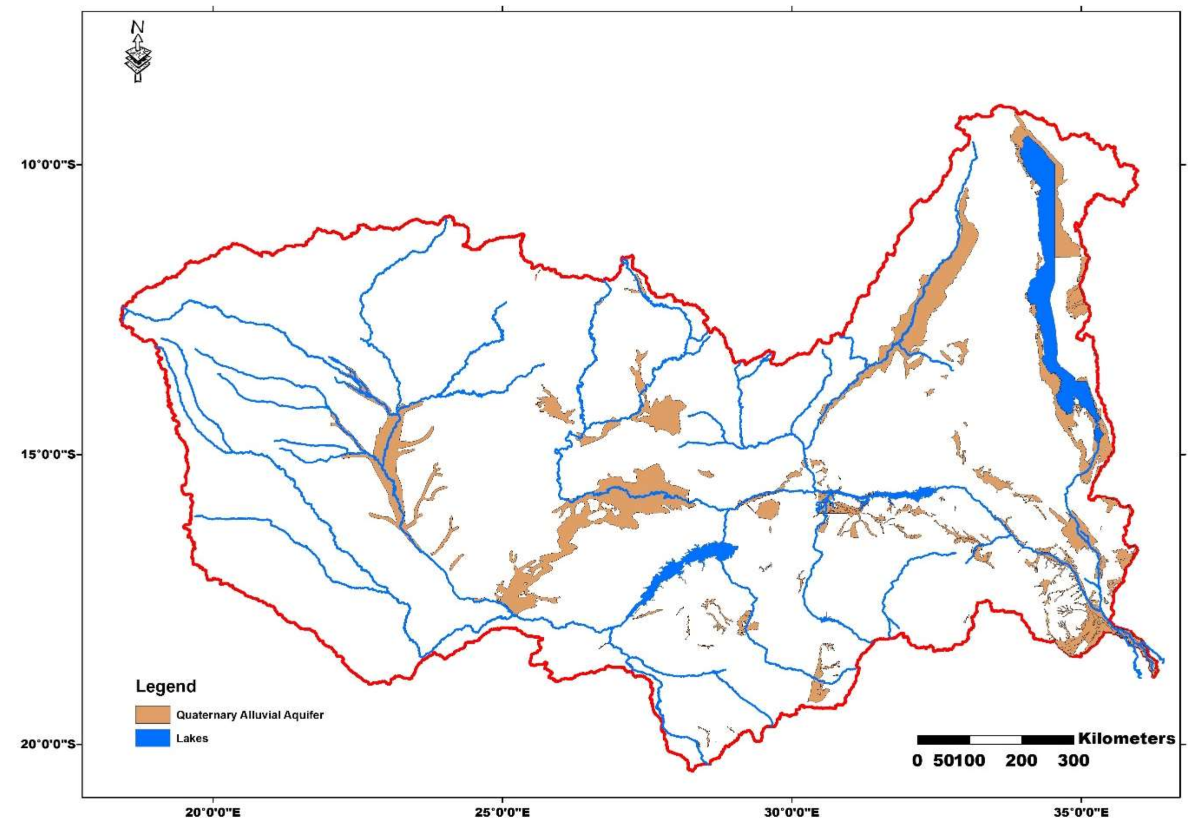

Figure 3 Map showing Quaternary alluvial aquifer in the ZRB.

Water quality data from Malawi shows high salinity water in the lower Shire River valley presumably due to hydrogeochemical data originating from dissolution of gypsiferous and halite minerals associated with Cretaceous evaporite deposits. Groundwater is critically important to irrigate large area of plantation in the Lower Shire plain that saddles Southern Malawi and Northern Mozambique. It is highly likely that high salinity condition in Quaternary Alluvial is site specific to southern Shire Valley and may not represent the whole of the Zambesi Basin. In fact, water quality data in South Africa and elsewhere show rather low TDS (Total Dissolved Solids) content.

Generally, the aquifer produces groundwater of good quality if properly managed in regards to protection. Repeated flood irrigation and subsequent evaporation leads to gradual salt precipitation and eventual soil salinization, which is flushed by recharging water to the groundwater. Therefore, salinization of groundwater in Quaternary Alluvial Aquifers in Shire River Valley is likely due to poor management of return water from the farming activities. It is also attributed to a result of evaporation and dissolution of evaporate minerals. The chemistry of groundwater in the high salinity cluster originates from dissolution of gypsiferous and halite evaporite minerals associated with Cretaceous and Karoo sedimentary formations. However, for samples located close to marshes along Shire River, where there is a shallow water table and patches of saline and sodic soils, evaporative concentration also plays a significant role (Monjerezi, 2012). It is also critical to highlight that in general, Quaternary Alluvial Aquifers are one of the most vulnerable aquifers to pollution because of the unconfined nature of the formation as well as its location very close to surface water courses where various industrial, municipal and other liquid and solid waste are intentionally or unintentionally disposed.

II. Kalahari Group Sediment Aquifers

Kalahari Group sediments covers roughly 2.5 x 10^6 km^2 of central southern Africa (Haddon, 2005), stretching some 2200 km from South Africa in the south, northwards through Botswana, and up into Angola. In northern Angola, the Kalahari Basin appears to narrow before extending about 200 km into the Democratic Republic of Congo. Lithologically, the Kalahari Group aquifer is composed of Tertiary to Quaternary age four major formations Wessels, Budin, Eden and Mokalanen Formations (Jonker, 2016). The Wessel Formation is mainly clayey-gravel, while the Budin Formation is comprised of brownish calcareous clay and marl. The borehole yield corresponding to the two formations is very low due to lack of primary porosity. The Eden Formation consists of sandstone, calcareous-grit and conglomerate, which are overlain by Mokalanen Formation that consists of nodular and hardpan calcrete. It has been reported that the borehole yield corresponding to the intergranular aquifer in the central Botswana and Western South Africa area ranges from 0.1 to 0.5 l/s (Tessema et al. 2012).

In the Zambezi River Basin, the Kalahari Group Sediment Aquifer, mainly outcropped in the western portion, covers 26% of the basin by surface area amounting to about 52 x 10^6 hectares of surface area (Fig. 4). If boreholes tap into the Eden Formation of the Kalahari Group, borehole productivities can reach 4 l/s averaging around 1.4 l/s. The Eden Formation is classified as an intergranualr aquifer although other subordinate formations within the Kalahari Group may be grouped as fracture aquifers because of storage of water in secondary porosities. Reports of very low yield to completely dry wells is probably related to improper siting of boreholes in nodular hardpan and calcrete (Wessel and Budin Formation). Estimate of the reserve is often very difficult as the accurate proportion of the most productive aquifer is not known and the complex of heterogeneity of the Kalahari Group aquifer within the basin. Estimated reserve capacity based on existing information is approximately 6.5 X 10^9 m^3 (Table 2).

Previous work completed in the Kalahari Group Aquifer reported that groundwater is generally classifies as being high in total dissolved salts, in many occasions exceeding the drinking guideline (500 mg/l). It is highly likely that moderate to high salinity in groundwater relates more to the arid climate of the region than the geology except in areas where redissolution of calcrete is a possibility. There is also a postulate that propagation of the Okavango-Linyati fault system stretching from Botswana in the south into southwestern Zambia accounted for higher salinity. Geophysical exploration conducted in Simalaha Flood Plain in Southwestern Zambia reveals a shallow freshwater lens overlain by a saline water understating the fact that relatively older Okavango rift system having a characteristic high salinity water underlies the recent freshwater recharge (Chongo, 2015).

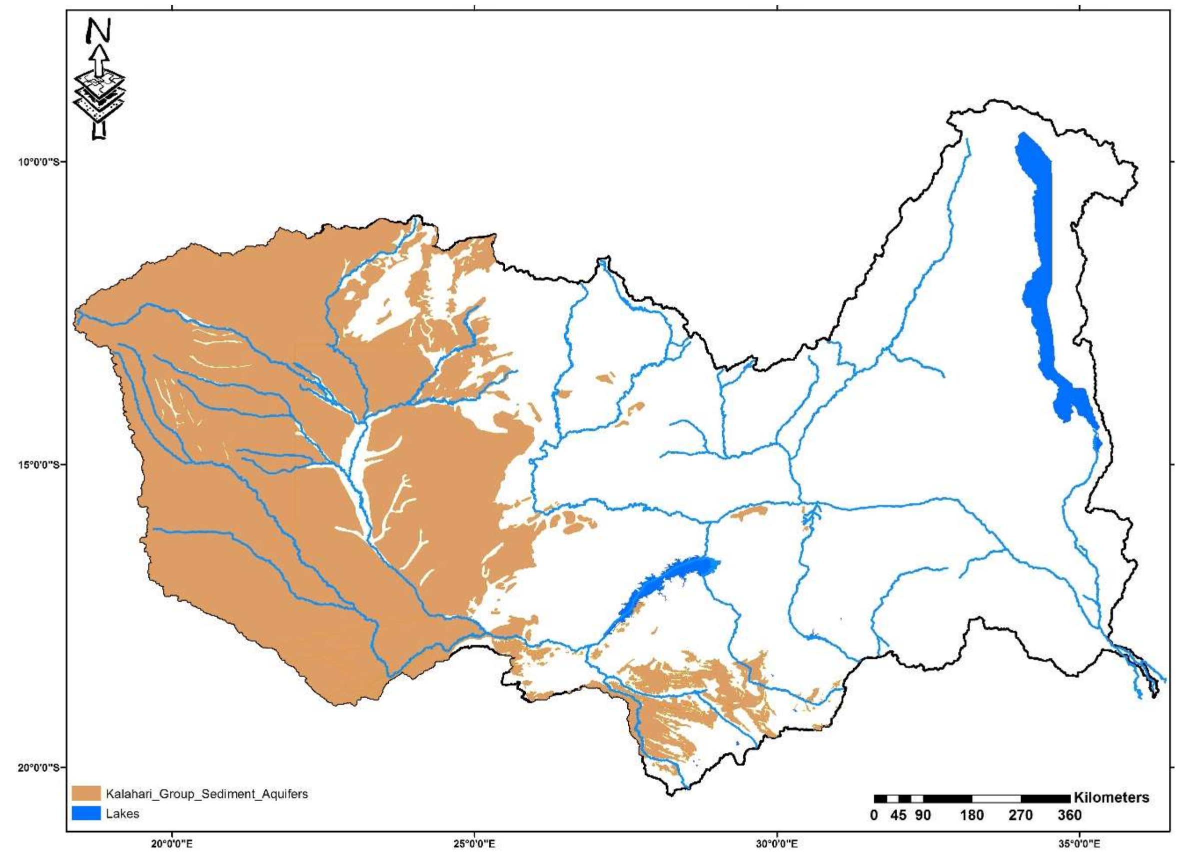

Figure 4 Map showing Kalahari Sediment aquifer in the ZRB.

Considering its wide spread exposure in the western portion of the basin, the Kalahari Unit of Eden Formation is the most productive portion compared with other formations based on hydraulic properties estimated in Botswana and South Africa (Du Plessis, 1993). However, it must be taken into consideration that accurate estimate of the storage coefficient is highly compromised by the spatial variability of the various formations of which only one (the Eden Formation) presents as having high storage potential. Therefore, accurate storage coefficient estimation hinges on accurate mapping of the most important water-bearing unit.

III. Mesozoic Marine Sediment Aquifers

The Late Jurassic-Tertiary interlayered marine sandstones and shale units constitute only a small portion (1.3%) of the entire basin. Evidently, the aquifer is limited to central east portion of the basin in close proximity of the downstream portion of Zambezi River Basin (mainly in Mozambique). There are reports of relatively high yield boreholes, likely tapping the sandy portion of the aquifer, amounting to 1.1 l/s but the average yield is 0.5 l/s. The accuracy of borehole yield on the aquifer is very questionable as negative values are reported. Water quality data is missing in the region but low yield boreholes tapping shale-dominating sands may have a deteriorated water quality. Mesozoic Marine Aquifers show dual aquifer type (intergranular and fracture) because of the presence of units with primary and secondary porosities.

Mesozoic aquifers have relatively small exposure in the Zambezi River Basin (Fig. 5). Storage capacity is estimated around 4.2 x 10^6 m^3 but its low productivity may have contributed to the scant hydrogeological data. The relatively low borehole yield may be related to the extent to which the shale portion of the aquifer drastically minimize the transmissivity and storage capacity.

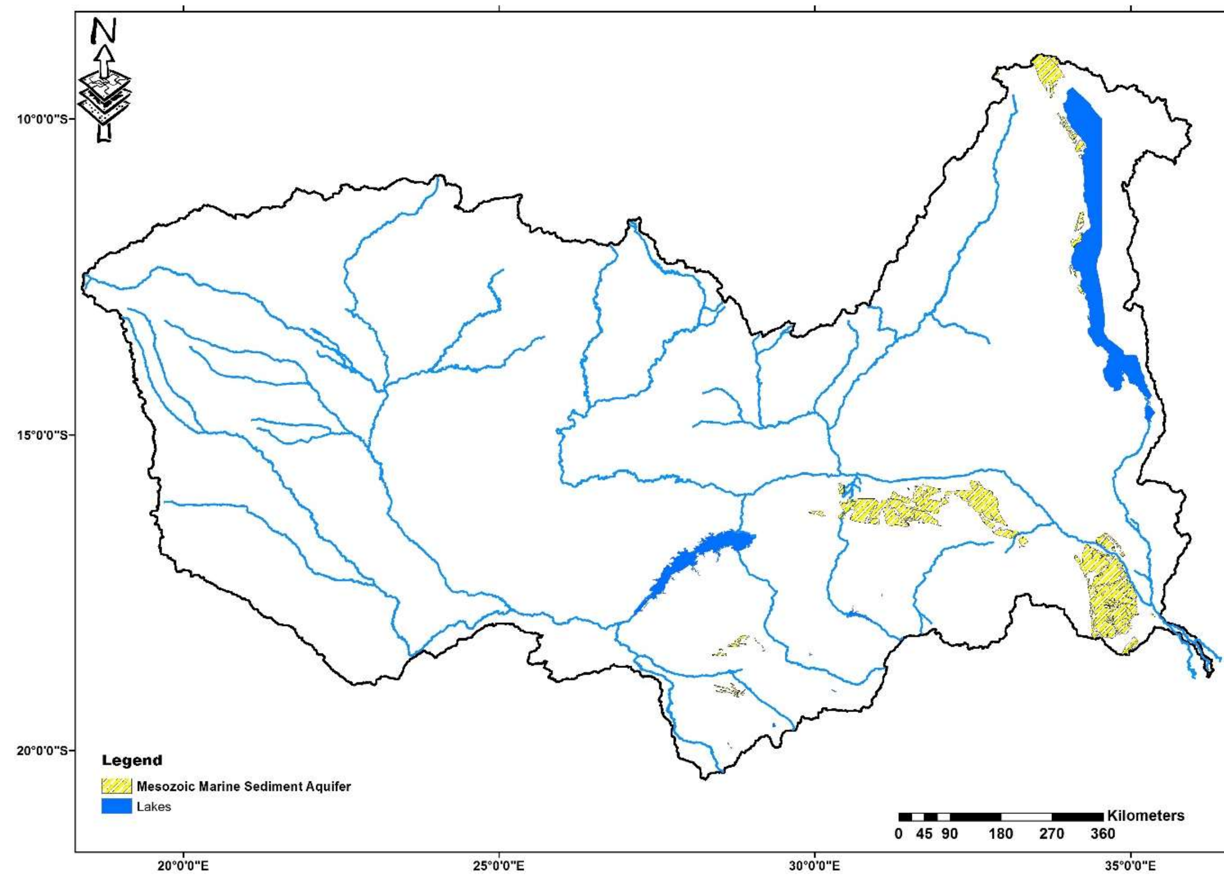

Figure 5 Map showing Mesozoic marine sediment aquifer in the ZRB.

IV. Karoo Volcanic Aquifers

Dolerite dykes are commonly intruding the Karoo sediments discordantly although surface coverage of the whole basin is about 1.5%. It is a known fact that dolerite dykes are areas of interest in groundwater exploration in Karoo Sediment covered areas because the dykes are known to enhance of high jointing/fracturing thereby favoring secondary porosity and improved groundwater storage and/or permeability (Nhleko, 2008). It is evident from the generated map that Karoo Volcanic rock is outcropped around Victoria Falls and in the downstream portion of the Zambezi River in the central east area of the basin (Fig. 6). Further observation of yield distribution demonstrates that relatively higher yields were recorded in the massive volcanic area of the basin. On the other hand, in areas where intense chemical weathering is evident, where the volcanic rock decomposes to clayey soils, which in turn imped flow and minimize storage. The low average yield measured in the entire basin, 0.15 l/s could be explained by formation of soils between the different lava flows of different ages.

The aquifer is classified as being secondary in view of the fact that fracturing governs groundwater storage and groundwater flow. The relatively low borehole yield is likely due to weathering and subsequent filling of existing fracturing owing to the age of the unit. It is also possible that improper borehole siting contribute to the low borehole productivity. Taking into account of existing information on the Karoo volcanics in South Africa and elsewhere in the region, the total storage capacity in the basin is estimated to be roughly 4.4 x 10^5 m^3. The estimated value must be seen in light of the fact that in areas of limited recharge or low rainfall, amount of available water could be different from the estimate.

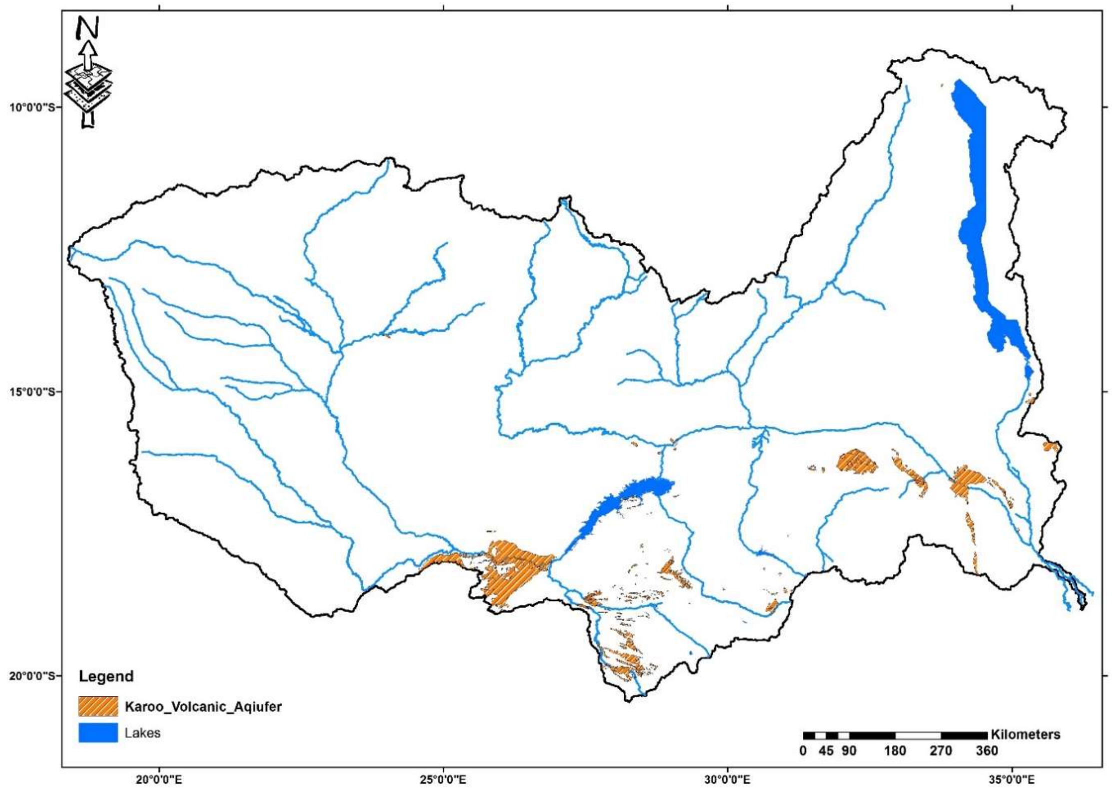

Figure 6 Map showing Karoo volcanic aquifer in the ZRB.

V. Karoo Sedimentary Aquifers

The sedimentary and volcanic record of the Karoo Supergroup extended from the Late Carboniferous to the Early Jurassic (Johnson et al., 1996). Thick successions of coarse clastic sediments, which can be linked to fault-controlled basin margins, occur in the Cabora Bassa and Mid- Zambesi basins in Zimbabwe and the Waterberg basin in Namibia. The Cabora Bassa basin actually represents an east-west trending graben containing up to 10,000 m of generally coarse sediments and can be classified as a true rift basin. The strata were deposited in glacial, deep marine (including turbidite), shallow marine, deltaic, fluvial, lacustrine and Aeolian environments.

In the Zambezi Basin, Karoo sediment groups outcrop in the mid-section in Zimbabwe covering close to 5% of the basin surface area. There are several groups and subgroups that constitute the Karoo Super-group sediments making it very difficult to explore high productivity boreholes. The Dwyka Tillite of Karoo Super-group, is known diminished groundwater potential, which may explain the low median productivity of 0.15 l/s. Low yield boreholes is likely caused by aquifer storage limited to fractures (secondary porosities) and the difficulty of accurately siting boreholes where fractures are dense and suit large amount of storage (Pacome, 2010). According to Catuneanu et al (2005), it is evident that some of the higher potential groundwater storing formations of Ecca, Beaurfort as well as Stormberg lithostratigraphic units, are also found in parts of Zimbabwe, Zambia, Malawi, Mozambique and South Tanzania within the Zambezi River (Fig. 7). Preliminary estimate of storage capacity is 1.22 x 10^9 m^3 assuming similar aquifer and lithostragraphic similarity with Karoo Aquifers elsewhere outside the Zambezi River Basin. The significance of the Karoo sedimentary aquifers in the Zambezi Basin is diminished by its limited information as well as low yield estimates. Karoo sequences in South Africa are known to have low salinity chemistry except those areas impacted by mining or agriculture causing local pollution that may comprise the pristine condition.

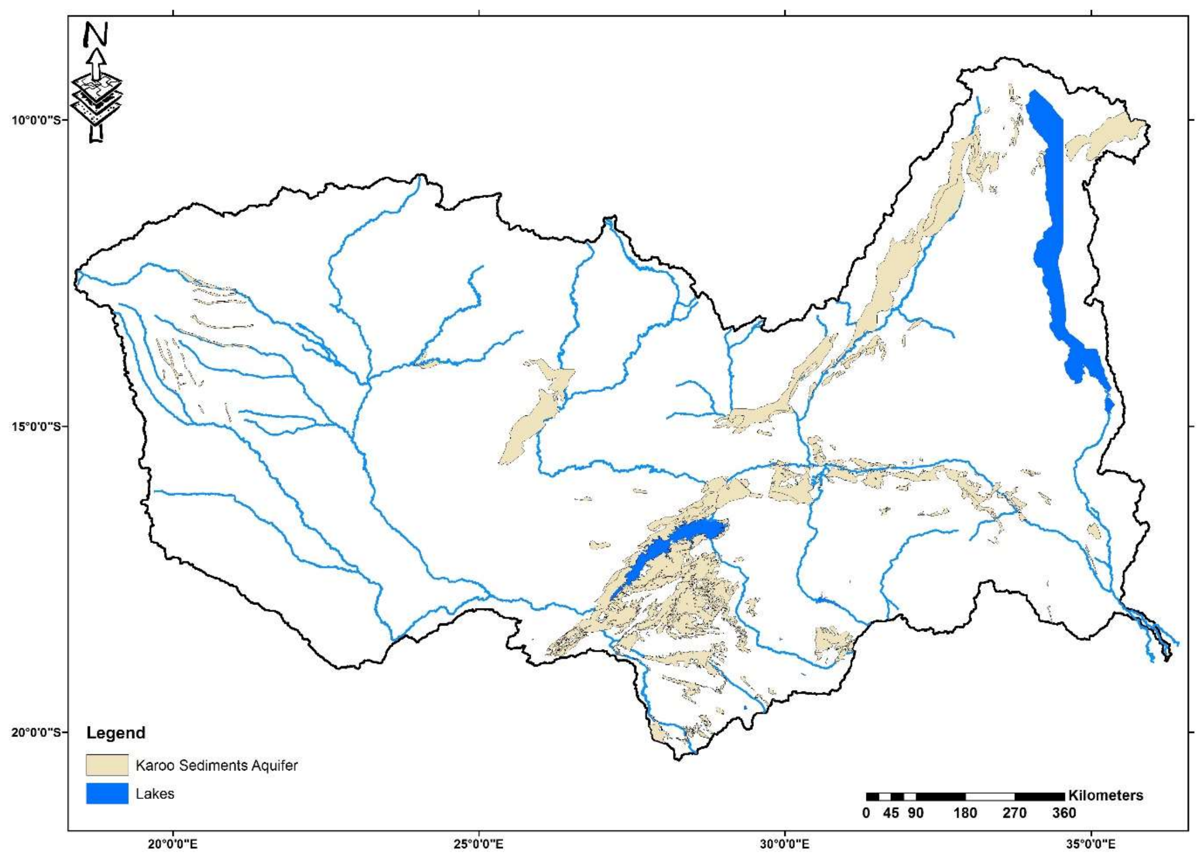

Figure 7 Map showing Karoo sedimentary aquifers in the ZRB.

VI. Paleozoic Marine Sediment Aquifers

These groups of aquifers comprise mainly mudstone and shale silts and marl covering only 0.1% of the Zambezi Basin. Average yield amounts roughly to 0.4 l/s although most areas covered by the Paleozoic marine sediments produce mostly a yield of 0.1 l/s. Some researchers group the sediments with the Cape Marine Sediments while in the Zambezi Basin, Paleozoic Marine Sediments outcrop around the geographical center of the basin (presumably in eastern Zambia and northeastern Zimbabwe (Fig. 8.) Taking into account of surface area of the aquifer and hydraulic parameters of Cape Marine Sediments in South Africa, the estimated storage capacity amounts to 4.4 x 10^5 m^3. However, information is lacking about the variability of the aquifer in the Zambezi Basin making the estimating questionable. Water chemistry data is also not available at the present time. Similar to Mesozoic Marine Aquifers, Paleozoic Marine Aquifers show dual aquifer classes (intergranular and fracture) because of the presence of units with primary and secondary porosities.

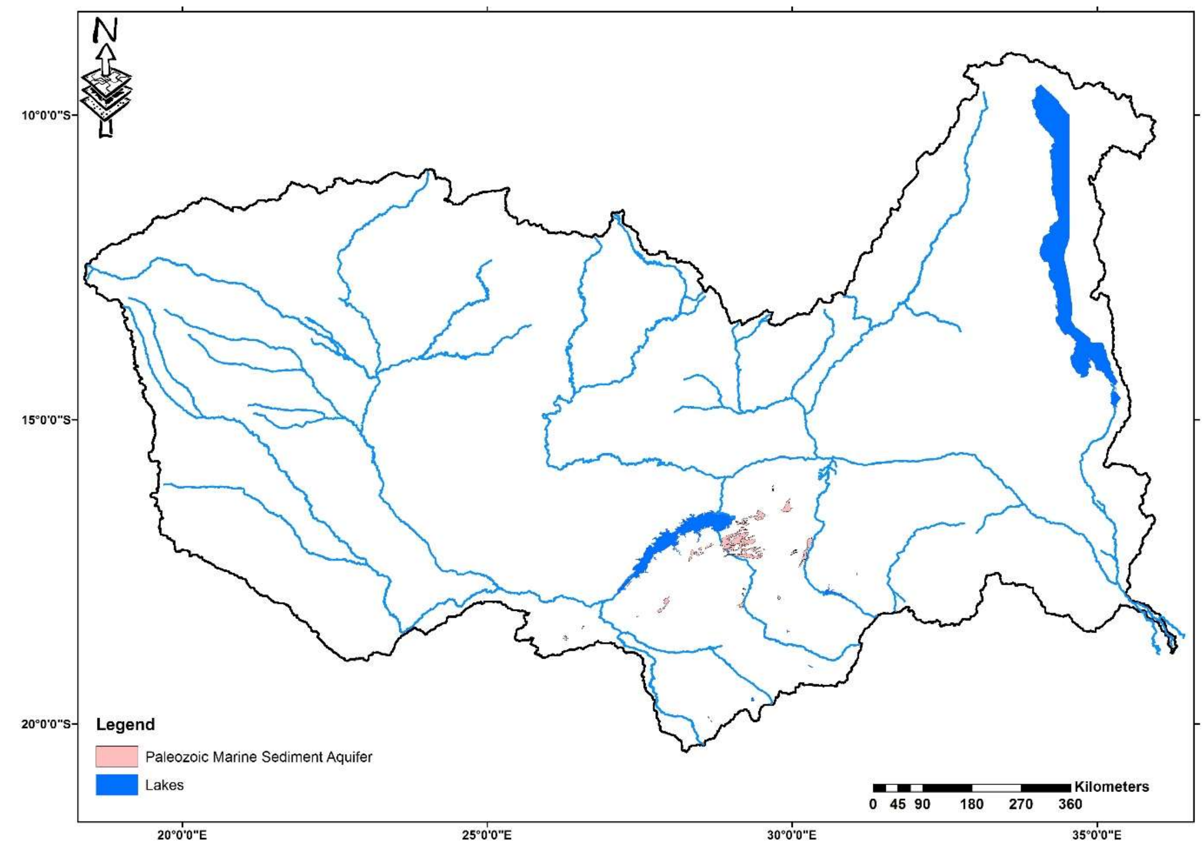

Figure 8 Map showing Paleozoic marine aquifer in the ZRB.

VII. Transvaal Carbonate (dolomite) Aquifers

The Precambrian carbonate formation aquifers are geographically limited mainly in Central Zambia and relatively small coverage in western Zimbabwe. With a coverage of slightly over 6%, it is one of the most productive aquifers with blowup yields measured up to 19 l/s averaging roughly 4 l/s, evidenced from the SADC-GMI spatial data attribute table. Similar range is evident in South Africa that high yields are linked to dolomites with noticeable intercalation of chert-rich layers. In carbonate areas where the dolomite unit is chert-poor, yields are low dramatically of up an order of magnitude less. The majority of the carbonate aquifer is situated in Zambia, Zimbabwe and Mozambique (Fig. 9).

The carbonate aquifer provides one of the highest storage capacities estimated roughly at 397 x 10^6 m^3 considering that at least half the unit is karstified. It can be a very critical water supply in a region (Zambezi) that is known to have high water stress condition in the substantial portion of the basin.

Water chemistry data is currently not available but similar unit in South Africa shows Ca-Mg-HCO_3 type water groups with highly buffered water in the circum-neutral pH range and low salinity values. The aquifer is very vulnerable to pollution because of open dissolution channels and open network fractures. It is very evident that the Central as well as Western Witwatersrand goldfields cause considerable pollution of the aquifers from acid mine drainages in South Africa. Similar case histories were reported in mining areas of Zimbabwe. The aquifer can supply substantial amount of drinking water quality water if properly managed in a sustainable way.

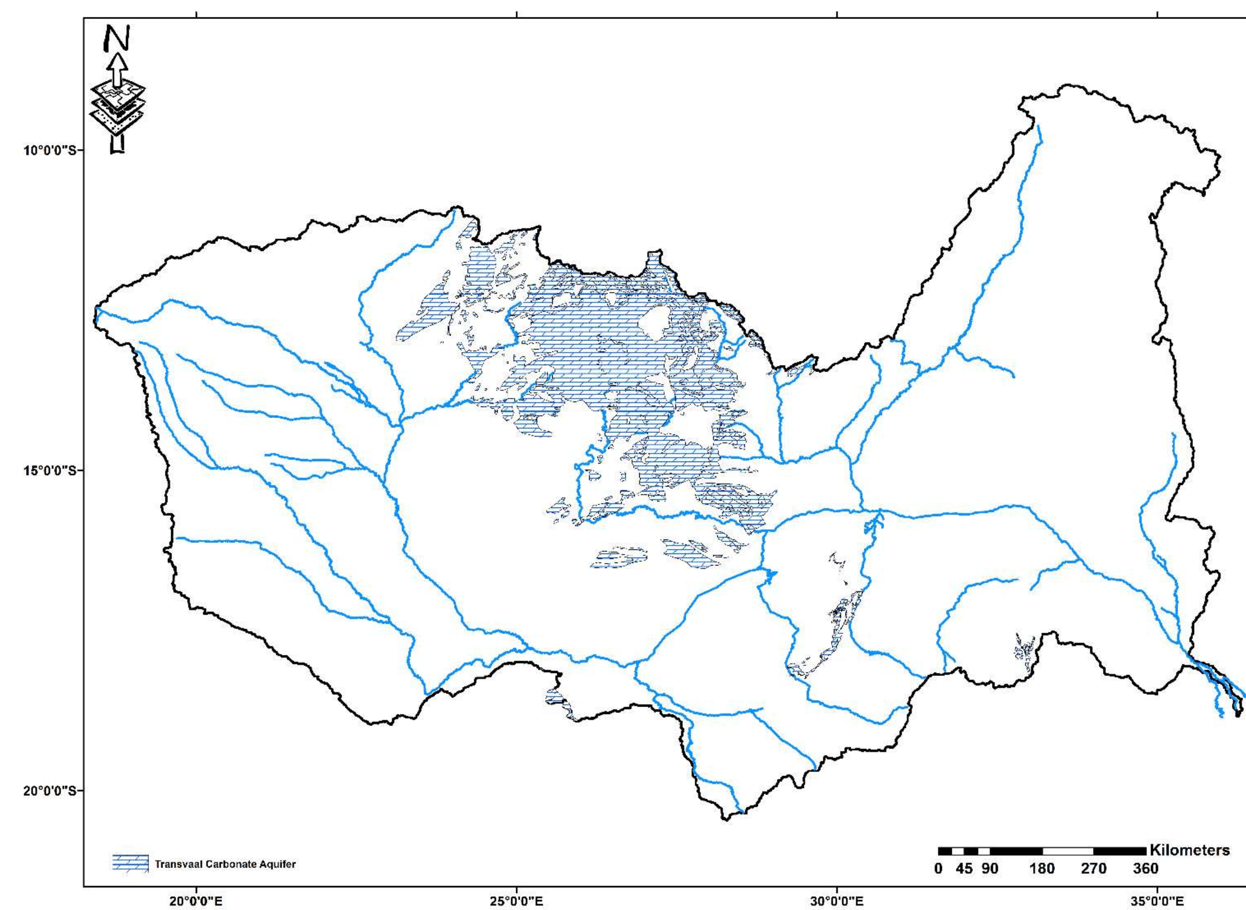

Figure 9 Map showing Transvaal carbonate (dolomite) aquifer in the ZRB.

VIII. Precambrian Metasediment and Metavolcanic Aquifers

With 7% coverage of the total river basin surface area, the aquifer is evidently outcropping in few central areas of the ZRB. The majority of the aquifer is exposed in the far northeast margin of the basin but also it is evident that the central margin and few areas in Zimbabwe and in the downstream areas of the Zambezi River in Mozambique (Fig. 10). The aquifer is categorized as being generally controlled by network of fractures and faults that create secondary porosities. However, the metamorphism process experienced by the units could have played a role in drastically diminishing open fractures thereby diminishing groundwater storage and permeability. The relatively higher occurrence of water strong capacity is the main reason for the unit to be on its own from being merged with the basement complex aquifers. Average yield is reported to be 0.4 l/s but in the ZRB region, there appear to be boreholes, which can produce as high as 1 l/s. Estimated total storage capacity is roughly 34 x 10^6 m^3, which is considered a significant volume taking into account the limited occurrence compared to the basement complex aquifers.

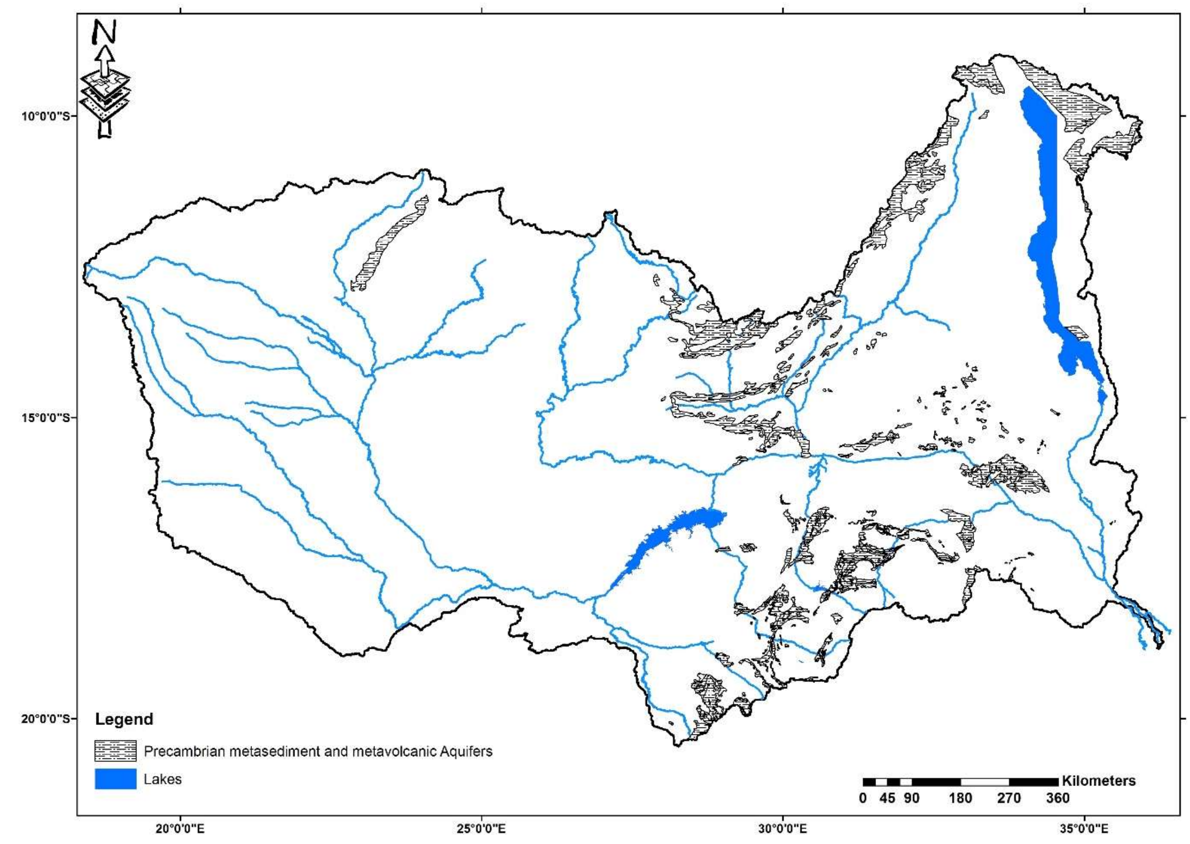

Figure 10 Map showing Precambrian metasediment and metavolcanic Aquifers in the ZRB.

Water quality data is not available but similar formations elsewhere show no evidence of exceptionally high salinity or other water quality issues. Large-scale development of this aquifer ties to its low productivity.

IX. Basement Complex Aquifers

Basement Complex Aquifers comprise mainly Archaean age granites, gniesses as well as other subordinate units. The aquifers cover roughly 35% of the basin outcropped largely in the eastern half of the basin. Intense weathering and alteration could justify the low yield aquifer averaging 0.2 l/s very typical of basement aquifers elsewhere. Basement complex aquifers are the most diverse units mainly dominating the surface geology of the eastern portion of the Zambezi River Basin (Fig. 11). Basement aquifers in the ZRB are shallow in thickness limited to the upper intensely weathered portion of the unit (regolith). The aquifer designated as basement complex is known to have up to 13 different geological units according the SADC national geological nomenclature and therefore a range of high aquifer hydraulic parameters is expected and hence high degree of yield variability. Especially in areas characterized by intensive intrusion, the variability is likely to be significant compared to areas considerably far from structural features such as faults and joints. Basement complex aquifers have three major groups categorized as follows:

- Granite, syenite, gabbro, gneiss and migmatities
- Paragneiss, quartzite, schist, phyllite and amphibolite
- Intrusive igneous complexes

Up on availability of hydraulic properties of the three major groups, it is possible to classify the basement aquifers into three different aquifers. With the current information, it is probably the only option to merge the unit and treat the unit as assemblage of different lithology having close hydraulic properties with respect to groundwater flow and storage.

Groundwater storage for basement aquifers is estimated taking into account that the aquifer storage is mainly related to weathering (65%) and fracturing (35%). The total basin storage of weathered basement complex aquifer is estimated at 550 x 10^6 m^3, whereas the storage estimate in fractured basement complex aquifer is about 22 x 10^6 m^3 (Table 2).

Basement aquifers typically produce very good quality groundwaters and the ZRB is not an exception. Basement aquifers can be explored and exploited to supply water to subsistence farmers for domestic and dairy farming. Unconfined basement aquifers have the risk of being polluted and careful aquifer protection plan must be in place to sustainably use the groundwater resource. Groundwater storage in Basement Complex aquifers is limited to fractures and weathered rock or regolith. Intergranular aquifer classes are practically non-existent in Basement Complex Aquifers.

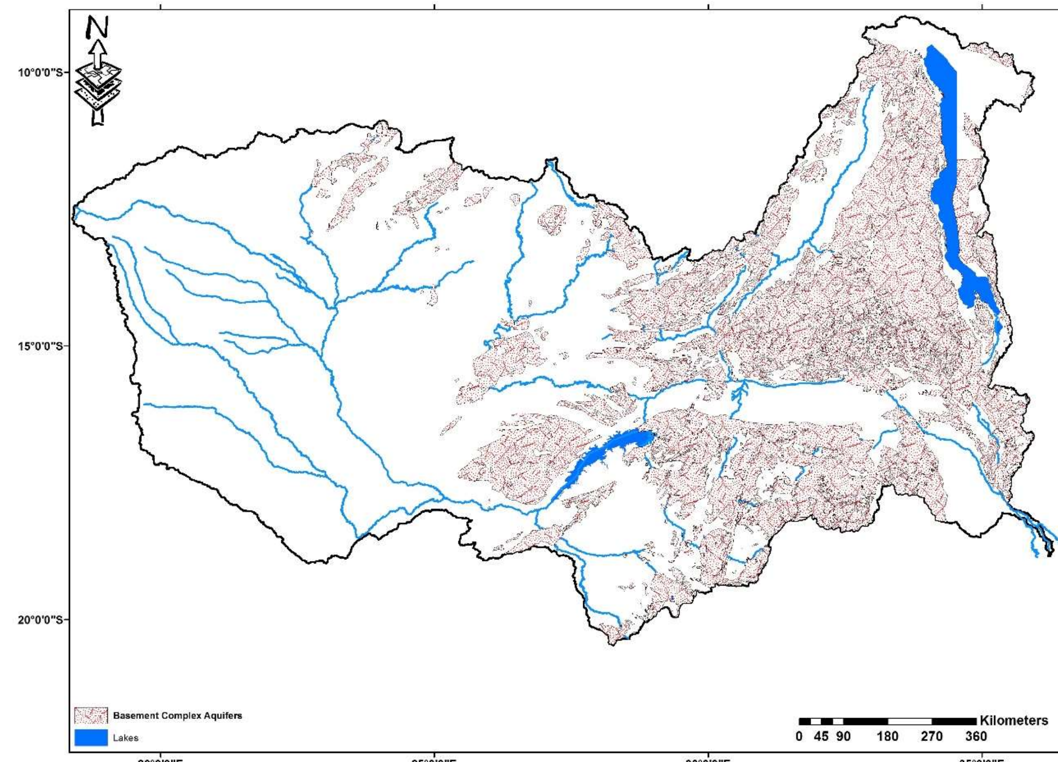

Figure 11 Map showing basement complex aquifers in the ZRB.

4.2. Comprehensive ZRB Aquifer Map and compiled reserve capacity

The majority of the ZRB is covered with basement complex aquifers amounting to nearly 35% followed by the Kalahari Group Sedimentary aquifers outcropped mainly in the western half of the ZRB. The complete lithology based aquifer map of the ZRB consisting of all the nine major aquifers is compiled as follows (Fig. 12).

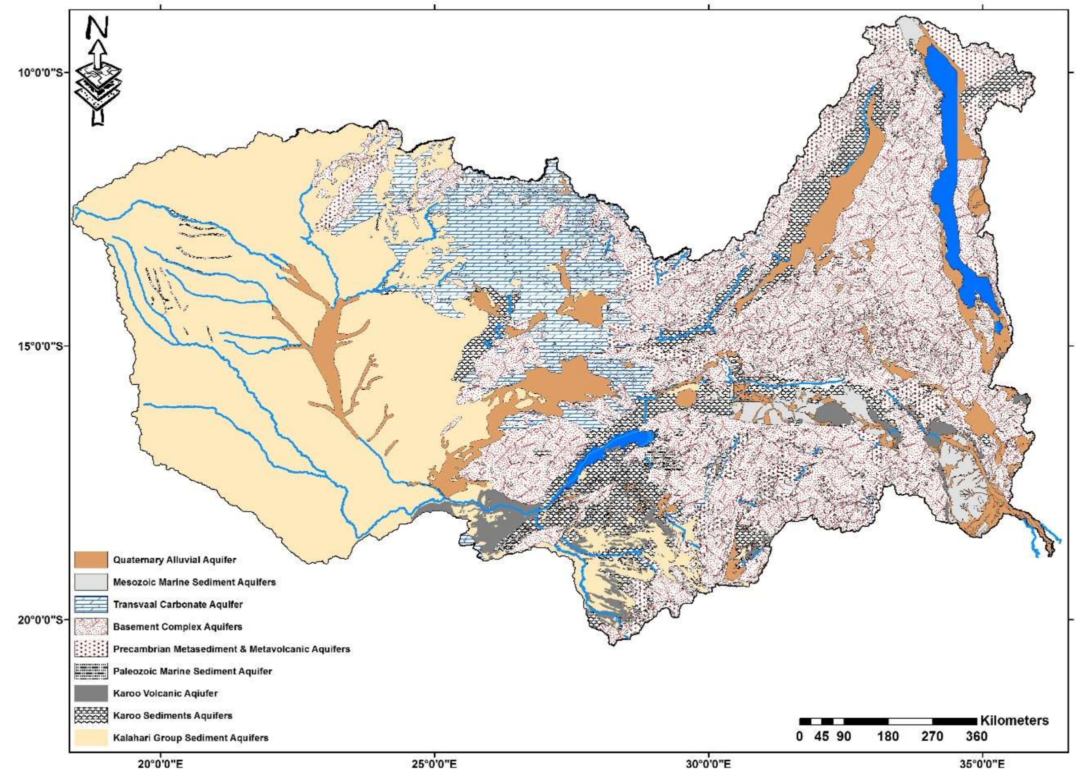

Figure 12 Lithology based aquifer map of the ZRB.

Reserve estimation of the major aquifers in the ZRB is done taking aquifer surface area, effective porosity, average storage coefficient or specific storage (in the case of unconfined alluvial aquifers) and minimum saturated thickness (for conservative approximation) into consideration. Among all aquifers, despite a coverage of roughly 16%, Quaternary alluvial aquifers account for nearly 68% of the total reserve 28 x 10^9 m^3 whereas basement complex aquifers with 35% coverage show a reserve of roughly 572 x 10^6 m^3 accounting only of 2% of the total. Complete reserve estimation is compiled here below (Table 2).

Table 2 Summary of estimated reserves in the ZRB aquifers.

No	Aquifer Name	Surface area [km^2]	Effective porosity [%]	Storage coefficient [-]	Average Saturated thickness [m]	Storage capacity (reserve) [x 10^6 m^3]
1	Quaternary Alluvial Aquifer	326,184	12	0.05	10	19,571
2	Kalahari Sediment Aquifers	520,485	10	0.005	25	6,506
3	Mesozoic Marine Sediments	26,660	4	0.0002	20	4.2
4	Karoo Volcanic Aquifers	28,623	2	0.000055	15	0.44
5	Karoo Sedimentary Aquifers	97,422	5	0.01	25	1218
6	Palaeozoic Marine Sediment Aquifers	2758	4	0.0002	20	0.44
7	Transvaal Carbonate (dolomite) Aquifers	124,072	8	0.002	20	397
8	Precambrian Meta sedimentary and Meta volcanic Aquifers	139,823	4	0.0004	15	34
9	Basement Complex Aquifers I. Weathered (65%) II. Fractured (35%)	705,168	4 3	I. 0.003 II. 0.0002	10 15	550 22

4.3. Salinity and Pollution Map

Groundwater quality assessment has not been given appropriate attention as much as reserve assessment within the continent of Africa in general and specifically in the ZRB. This lack of appreciation is manifested by the lack of groundwater quality data or poor documentation of the available data. Owing to absence of credible, accessible and acceptable water quality data, electrical conductivity, a physico-chemical parameter, is used as a proxy to salinity, which is used as an indicator of the groundwater quality. With the exception of localized areas such as mines, large industrial plants, large irrigation farms and big cities, it is expected that low salinity prevails in much of the ZRB because of the fact that basement complex and Precambrian meta-sediment and meta-volcanic lithologies cover over 40 % of the ZRB. According to the World Health Organization (WHO) potable water guideline, total dissolved solids in excess of 600 mg/l (roughly 1000 µS/cm) is considered unsafe but Food and Agriculture Organization (FAO) stipulated that salinity in excess of 2000 mg/l is categorized as sever salinity for agriculture (Ayers and Wescot, 1985). ZRB water electrical conductivity demonstrates that high salinity groundwater are evident in the Shire River Valley (east ZRB) in

South Malawi and North Mozambique as a result of either evaporative concentration or dissolution of evaporate minerals in sedimentary rocks (British Geological Survey, 2014).

The other major high salinity zone evident southwest of Zambia, which is related to the Palaeo Lake Makgadikgadi sediments (Chongo et al., 2015). Time Domain Electromagnetic (TDEM) geophysical mapping revealed that the Okavango Graben structure extends northeast to the Machile-Zambezi Basin, which evidently accounts for the relatively high salinity that is shown in the map (Fig. 13). The salinity map of ZRB is put together on the basis of limited available data and open for modification upon availability of additional data especially in the vast western region of the ZRB where Kalahari sedimentary units dominate the surface geology.

The pollution map is constructed on the basis of hot spots, mine coverage, tailings dam and tailings lake spatial data from the University of Zambia as well as comprehensive mine location of the ZRB from NUST. The map most likely overlooked local scale pollutions because of the areal extent of the entire ZRB but mainly captures potential sources causing significant impact to shallow aquifers and surface waters using the source-pathway-recipient approach. Mine point distribution cannot be employed because it incorporates both artisan and large-scale mines together. Therefore, more weight is given to known hotspots mainly around mines but location of tailings dams and tailings lake sites in the creation of potentially polluted areas map (Fig. 13).

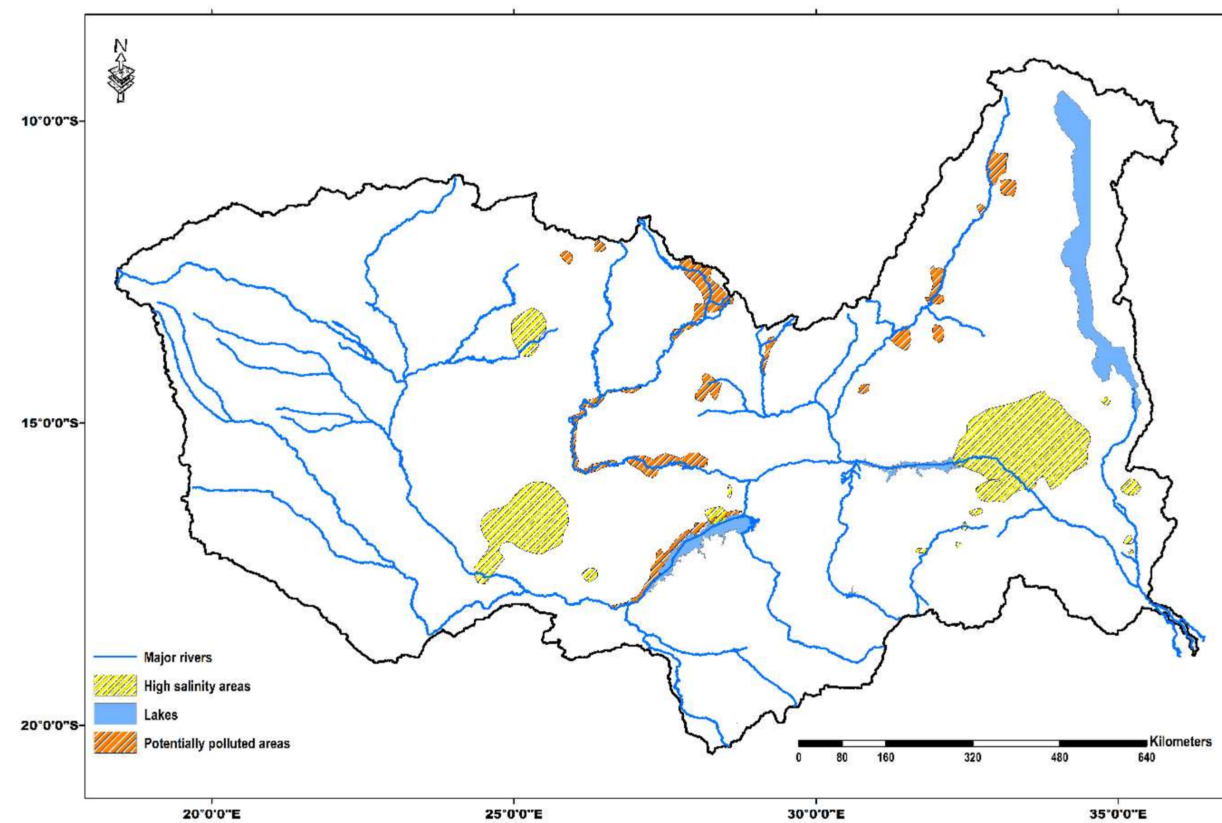

Figure 13 Salinity and pollution combined map. Salinity is based on groundwater electrical conductivity map of the ZRB.

4.4. Aquifer Productivity Map

Aquifer productivity or yield is a critical parameter, which is estimated during borehole drilling and aquifer testing. In most developing countries where monitoring boreholes are not available, air blow productivity is considered as aquifer yield although in many cases the estimated amount is not the accurate aquifer yield. In a properly developed water supply borehole, aquifer yield is governed by the transmissivity of the aquifer, which is determined by aquifer tests. The raw data, extracted from air blow yield data presumably measured during well development activities, is used to produce aquifer productivity map (Fig. 14). High aquifer yield is evident in areas covered by Quaternary aquifers and carbonate rocks. The majority of the ZRB fall in the very low yield category coinciding with areas whose surface lithology is basement complex, Precambrian meta-sediment and meta-volcanic rocks, Palaeozoic & Mesozoic marine sediments as well as Karoo volcanics and sedimentary formations. Kalahari sediment aquifers have average yield (Fig. 14).

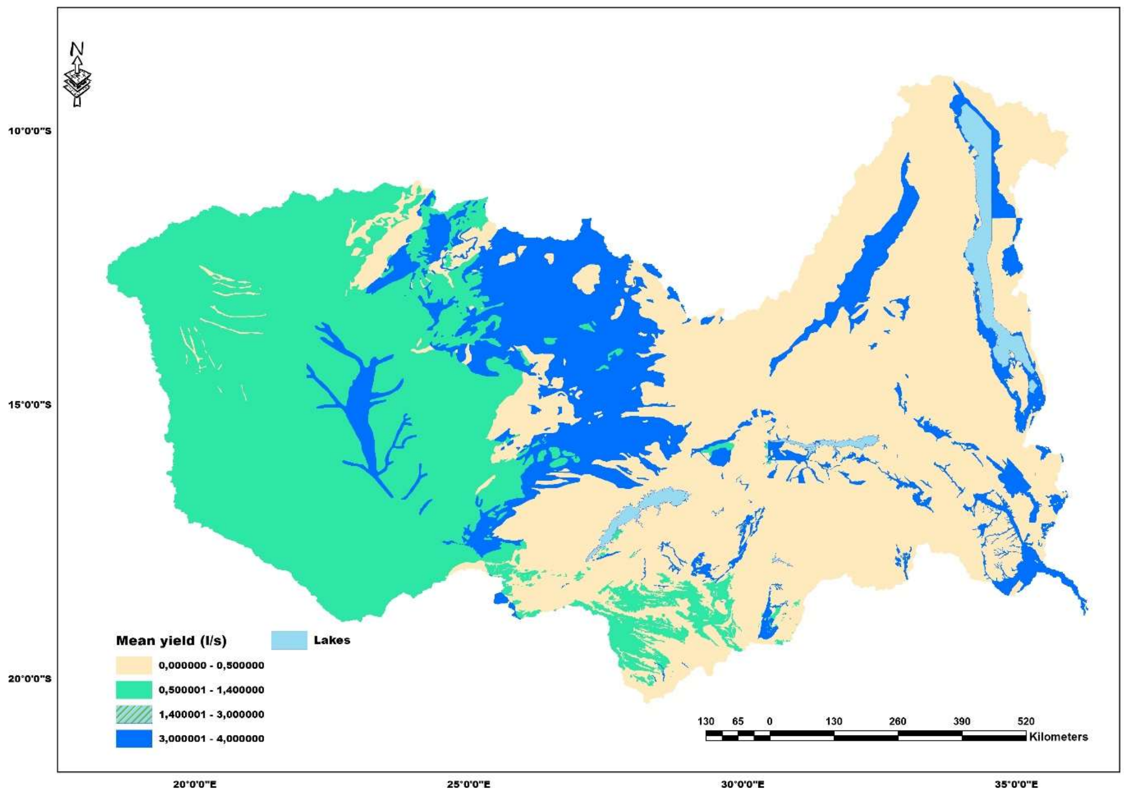

Figure 14 Aquifer mean yield map of the ZRB.

4.5 Groundwater Reserve Map

Aquifer reserve inherently refers to the capacity of an aquifer to store water, as estimated from aquifer storage coefficient determined from aquifer testing. Aquifer geometry, effective porosity and saturated thickness data are also incorporated in the estimation of the reserve. Information on storage capacity of the ZRB is practically non-existent and therefore the information was adapted from similar aquifers elsewhere in Southern Africa. Regional cross boundary aquifers such as the Kalahari Group, the Karoo Super Group, and Carbonate Aquifers are extension of aquifers found in South Africa, Botswana and Namibia outside the ZRB. Saturated thickness of the aquifers are adapted from water levels and few borehole logs, effective porosity and storage coefficients are adapted from similar aquifers in South Africa (Table 2). Storage or reserve map developed from this project displays that Quaternary Alluvial sediments and carbonate units in the ZRB have the highest potential to store groundwater followed by Kalahari Sedimentary Units (Fig. 15). It is also evident that over 60% of the aquifers in the ZRB show low reserve very likely due to the prevalence of basement complex and Precambrian meta-sedimentary and meta-volcanic aquifers. Aquifer productivity and aquifer reserve maps are similar but not identical due to the fact that the parameters derived from inherent aquifer constants, namely transmissivity and storage coefficient.

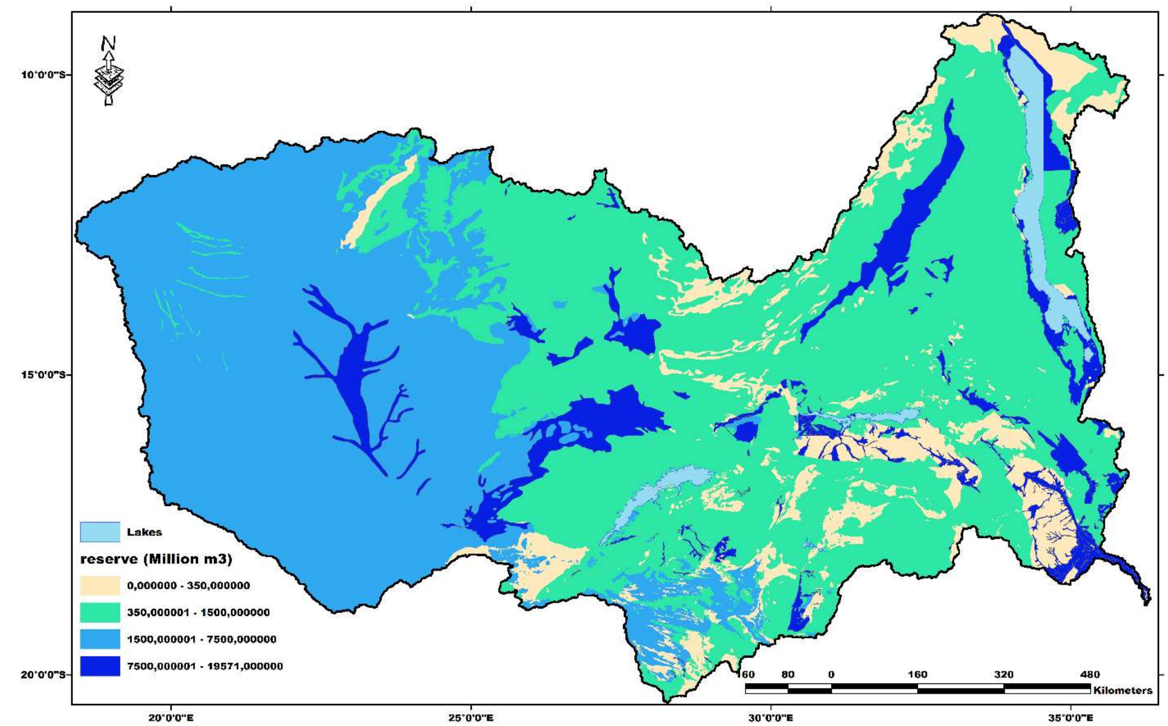

Figure 15 Aquifer reserve potential map of the ZRB in units of Mm^3, which refers to million (10^6) cubic meters (m^3).

4.6 Irrigation Potential Map

The irrigation potential map of the ZRB is adapted from the semi-processed feature data of SADC-GMI information platform. It turns out that the semi-process data is lacking any meta-data that describes how data processing was conducted. The map depicts that areas in the west and east of the ZRB show high potential for irrigation development (Fig. 16). The majority of the ZRB (over 65%) is classified as areas of average potential where as a small coverage of the ZRB (less than 10%) as being classified as low irrigation potential. Reclassification was done with on the basis on 1000 ha (10^7 m^2 or 10 km^2).

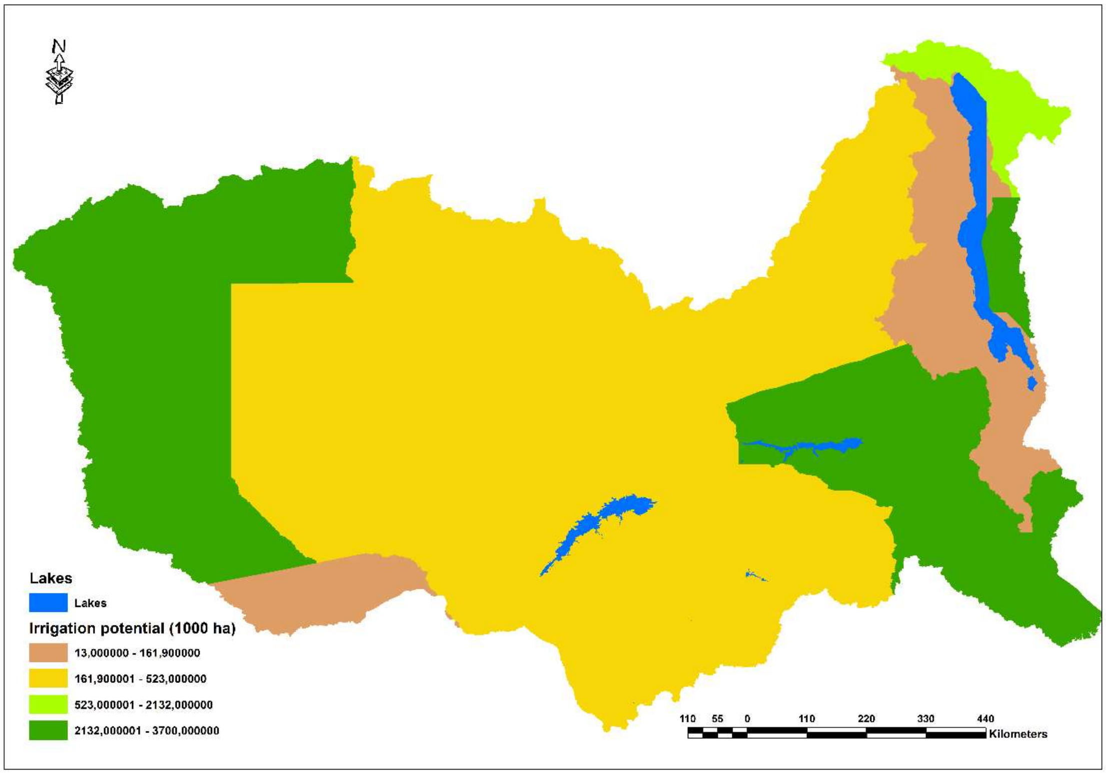

Figure 16 Irrigation potential map of the ZRB with each class measured in 1000 hectares (10^7 m^2)

4.7 Groundwater Development Suitability Map

Aquifer ranking is the product of geospatial processing by overlying three layers: aquifer yield map, aquifer reserve map and irrigation potential maps. Individual maps are reclassified to manageable number of ranges before rasterization procedure. Weighted overlay is the specific method of overlay procedure chosen for its versatility in allowing assigning different weights to parameters of greater significance. Among the three layers, yield is given a weight of 40 % whereas irrigation potential and reserve layers are given a weight of 30%. This is because the ease with which an aquifer can be developed is highly influenced by how productive the aquifer is when pumped using conventional pumping methods. In many instances, aquifers with large reserves may end up not developed as much owing to common challenge of efficiently exploiting with common small scale pumping methods. The salinity map is not directly integrated in the overlay processing mainly because the generated map lacks consistency over the entire Zambezi River Basin area. The ranking assigns four categories; very poor, poor, average and high based on one combined map of the three layers. It turns out that Quaternary alluvial aquifers are the most suitable for development except those areas with high salinities (Fig. 17). Carbonate aquifers show average suitability despite having highest productivity and storage potential. Over 60 % of the ZRB fall into the poor and poor/average suitability rank for large-scale groundwater development. It must be taken into account that this suitability ranking does not show suitability for small scale and subsistence level developments.

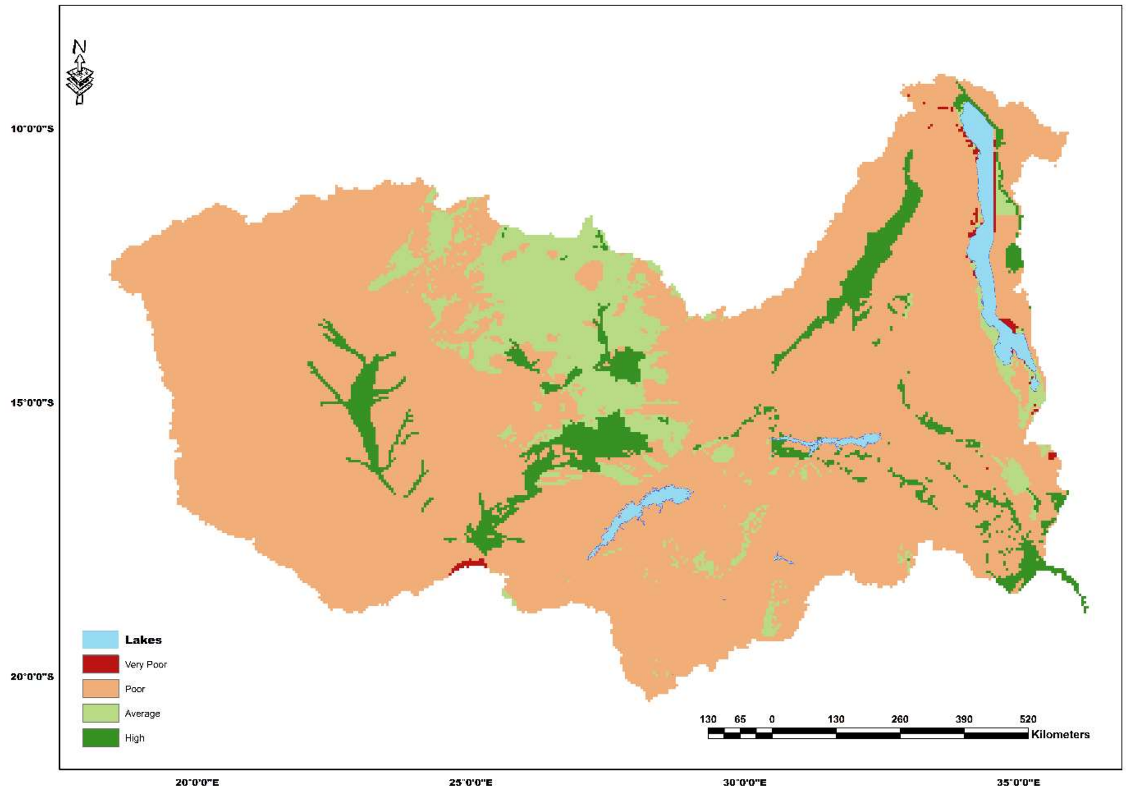

Figure 17 Groundwater development suitability map of the ZRB

5. Challenges and Countermeasures

Water quality data collected by SADC member countries in few instances is observed to possibly be far from accurate owing to the absence of data quality assurance and data quality control documentation. Several unit corrections are made with close consultation with local experts and South African based experts with knowledge of the study area. Basin-wide salinity mapping was not possible at the current time pending availability of groundwater salinity data in all parts of the ZRB.

The manual data correction is very tedious as the consistency of every single data row has to be checked between the country based (national) and regional geologies. It turns out that in the SADC regional geology regional map, there are units that are designated as unknown (designed -9), which was a designated different lithological unit in the (country) national geology map. Moreover, there was lithostratigarphic unit inconsistency among the different national geology map of the SADC countries.

6. Conclusions and Recommendations

The regional geology map compiled and documented in SADC-GMI database exhibits few major discrepancies, which is corrected and repackaged to generate a modified geology map.

Aquifer classifications and mapping is completed on the basis of geology broadly divided into nine major aquifers.

Groundwater quality and pollution map of the ZRB is generated using electrical conductivities as proxies to salinity or total dissolved solids with the available data.

Aquifer productivity and aquifer reserve capacity maps are also produced by making use of SADC-GMI data as well as aquifer parameter data, which is available for similar aquifers elsewhere in the region. Aquifer development suitability ranking is the outcome of the project as it gives a high level information platform from which future development planning can take advantage of.

One of the major benefit of the project is collation, curation, proper documentation of raw, semi-processed and processed spatial data, which will be readily available for public, governments, development partners and research institutions in a convenient and user-friendly platform.

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