Water and Cooperation within the Zambezi River Basin (WACOZA)

National University of Science and Technology, Zimbabwe (NUST, ZIM)

FINAL REPORT:

Zambezi River Basin Groundwater Hydrology Characterisation in Zimbabwe

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EXECUTIVE SUMMARY

The project “Zambezi River Basin Groundwater Hydrology Characterisation in Zimbabwe” was a contribution to the “Water and Cooperation within the Zambezi River Basin (ZRB)” case study project for Southern Africa Centres of Excellence (CoEs) in the framework of AU/NEPAD ACEWATER2 project. The general objective of the case study project was to assess Water-Energy-Food-Ecosystem (WEFE) interdependencies across the Zambezi River Basin. The following specific objectives guided scientific activities related to groundwater hydrology characterisation in Zimbabwe:

1. To provide a multi-scale groundwater hydrology baseline database at ZRB and selected countries level, based on literature review, available data sources and existing country/regional scale studies of major relevance to WEFE nexus;
2. To provide baseline conditions database on groundwater hydrology and water demand vs. availability for few shared regional case studies, by gathering and processing data and by-products and to perform groundwater assessment;
3. To perform vulnerability assessment to contamination of selected aquifers across the ZRB.

The scientific activities yielded the following outcomes which are detailed in this report:

1. Baseline report and a spatial database for groundwater hydrology in the ZRB in Zimbabwe
2. Baseline report and data on demand for water for different water users and spatial database on water availability represented by recharge and borehole yields in the ZRB in Zimbabwe.
3. Report on State of the art aquifer vulnerability assessment and a groundwater vulnerability map for the ZRB in Zimbabwe.

The water-energy-food-ecosystem nexus has implications on the demand for groundwater for various uses in the basin and the availability of groundwater in the basin to meet the demand. The nexus is also affected by availability of surface water in the Zambezi River and climatic conditions that allow for recharge of groundwater and generation of energy to access the groundwater for use.

ACKNOWLEDGEMENTS

The scientific team would like to acknowledge the following organisations for allowing access to data therefore enabling analysis of the groundwater hydrology, groundwater availability, groundwater vulnerability and demand for groundwater in ZRB in Zimbabwe:

- Government of Zimbabwe
  - Rural WASH Information Management System (RWIMS)
  - Zimbabwe Geological Survey
  - Meteorological Services Department
  - Zimbabwe National Water Authority
- SADC- Groundwater Management Institute (SADC-GMI)
- Zambezi Watercourse Commission (ZAMCOM)

European Commission, Joint Research Centre is acknowledged for funding as well as technically reviewing and coordinating the project. The AU/NEPAD Southern African Network of Water Centres of Excellence Secretariat is acknowledged for project administration. The National University of Science and Technology is acknowledged for facilitating the activities of the scientific team in terms of staff time and working facilities.

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1.0 INTRODUCTION

1.1 Background

Evidence from National Plans for water supply and sanitation indicate that in almost all the riparian countries of the Zambezi River basin, groundwater is the main source of rural water supply. It is also an important source of urban and peri-urban water supply for rural towns and some major cities (SADC-WD/Zambezi River Authority, 2008). Therefore it is imperative that groundwater hydrology and quality investigations are key to the "Water and Cooperation within the Zambezi River Basin (ZRB)" case study project for Southern Africa Centres of Excellence (CoEs) in the framework of AU/NEPAD ACEWATER2 project. The general objective of the case study project was to assess Water-Energy-Food-Ecosystem (WEFE) interdependencies by developing and testing a Spatial Decision Support System on Water Cooperation, across the Zambezi River Basin.

In order to contribute to the development of the Spatial Decision Support System on Water Cooperation, the following specific objectives guided scientific activities related to groundwater hydrology and quality:

1. To provide a multi-scale groundwater hydrology baseline database at ZRB and selected countries level, based on literature review, available data sources and existing country/regional scale studies of major relevance to WEFE nexus;
2. To provide baseline conditions database on groundwater hydrology and water demand vs. availability for few shared regional case studies, by gathering and processing data and by-products and to perform groundwater assessment;
3. To perform vulnerability assessment to contamination of selected aquifers across the ZRB.

1.2 Selected Study Areas within the Zambezi River basin in Zimbabwe

The Zambezi Basin is home to over 40 million people and projected to be 51 million by 2025 (ZAMCOM 2019). Zambia and Zimbabwe have the biggest area shares inside the basin, therefore, their populations in the watershed are also substantial. The population for Zimbabwe in the Zambezi River Basin is estimated to be 10.5 million (ZAMCOM 2019). The Zambezi River enters Zimbabwe at the Zambezi-Chobe confluence close to Kazungula, where the boundaries of Namibia, Botswana, Zambia and Zimbabwe merge as shown in Fig 1.1. The Zambezi River forms the border between Zambia and Zimbabwe. The river is divided into 3 segments, the Upper, Middle and Lower Zambezi. The Zimbabwean sub-basins form part of the 853 km long middle Zambezi, which stretches from Victoria Falls to Cahora Bassa Gorge. The sub basins of the Zambezi river basin in Zimbabwe, namely the Gwayi, Sanyati, Manyame and Mazowe sub-basins also shown in Fig 1.1, constitute 15.8% of the total basin area, and 54.5% of the total area of Zimbabwe.

The combined mean annual surface runoff from the Zimbabwean sub basins is estimated to be 50mm (Sanchez, 2018). The sub basins in Zimbabwe form four of the seven hydrological zones in Zimbabwe. The population in the ZRB, Zimbabwe has increased from 7.9m in 2010 (World Bank 2010) to 10.5m in 2017 (ZAMCOM 2017) impacting on the water, energy, food and ecosystems nexus.

Studies of rainfall records such as by Tumbare (2004) in the basin covering two centuries reveal that droughts were recorded in 60 years out of the 200 years. Studies have also revealed that during drought years the demand for groundwater for food production increases demonstrating the interdependencies of Water, Energy, Food and the Ecosystem (WEFE). Droughts are expected to become more frequent and more intense due to climate change (Tumbare, 2004).

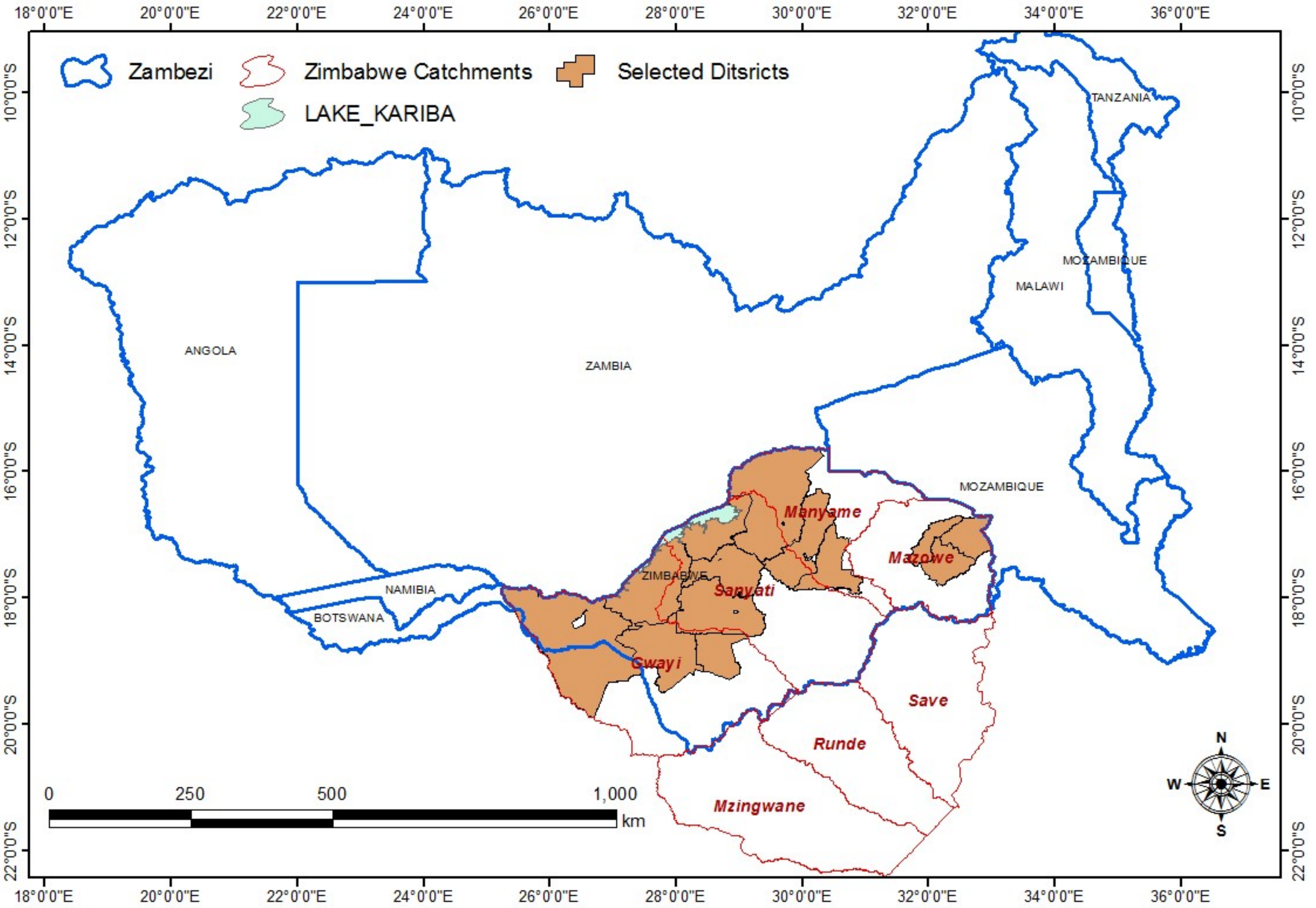

Fig 1.1 Extent of the Zambezi River Basin showing the location of Zimbabwe in the basin (generated from DEM data)

1.3 Structure of the report

The context of this final report was to provide a baseline database to characterize the ground water hydrology in the Zambezi River Basin (ZRB) in Zimbabwe as presented in specific objectives 1 and 2 as well as to produce an assessment of the vulnerability of the groundwater to contamination as presented in specific objective 3. For the purposes of this report, baseline data was analysed for the following thematic areas:

- Groundwater hydrology
  In this section an analysis of the state and spatial distribution of aquifers in the ZRB in Zimbabwe was made based on available data and literature review.
- Groundwater availability and quality
  Groundwater availability in the ZRB in Zimbabwe was analyzed in the form of spatial distribution of boreholes and the respective yields of the boreholes found in the river basin.
- Water demand and water use patterns
  Water demand and water use patterns in the ZRB in Zimbabwe were analyzed according to selected districts in the different catchments.

An assessment of the vulnerability of the groundwater to contamination was carried out using the Arc GIS based model DRASTIC. Inference to the landuse in the different sections of the ZRB in Zimbabwe was done to explain the spatial variations in groundwater vulnerability to contamination.

2.0 MULTI-SCALE GROUNDWATER HYDROLOGY BASELINE AT ZRB AND ZIMBABWE SCALE

2.1 Surface Hydrology

Although the focus of this report is groundwater hydrology, the surface hydrological properties of the basin are introduced briefly since groundwater and surface water systems are linked. The Digital Elevation model (DEM) in Fig 2.1 shows the four major river systems that constitute the Zambezi River Basin in Zimbabwe. The low lying areas act as the recharge zones for the basin since the potential evapotranspiration exceeds the annual precipitation in most parts of the basin (FAO 2016).

The Gwayi catchment covers an estimated area of 88’000km^2, with altitude varying from 600m to 1500m above mean sea level. Mean annual rainfall ranges from 400 mm in the western part of the catchment to 700 mm per annum (ZINWA, 2006; FAO 2016). The Mazowe catchment covers an estimated area of 39’000km^2. Mean annual rainfall varies in the catchment, ranging from 415 – 800 mm per annum. The upper and middle areas of the catchment receive the higher rainfall.

The Manyame catchment has an estimated area of 40’500 km^2. Elevation ranges between 300m to 1800m above sea level. The mean annual rainfall in this catchment is 750 mm, with the upper Manyame receiving the higher average of 800 mm per annum, while the lower catchment receives 700/year. Although this catchment receives higher than the national average rainfall, localized areas in the Lower Manyame and Angwa Rukomechi areas receive lower rainfall than the rest of the basin. These rainfall ranges are within the ranges described for the entire Zambezi River Basin (ZAMCOM, 2019). The distribution of the mean annual rainfall in the Zambezi River Basin in Zimbabwe is shown in Fig 2.2.

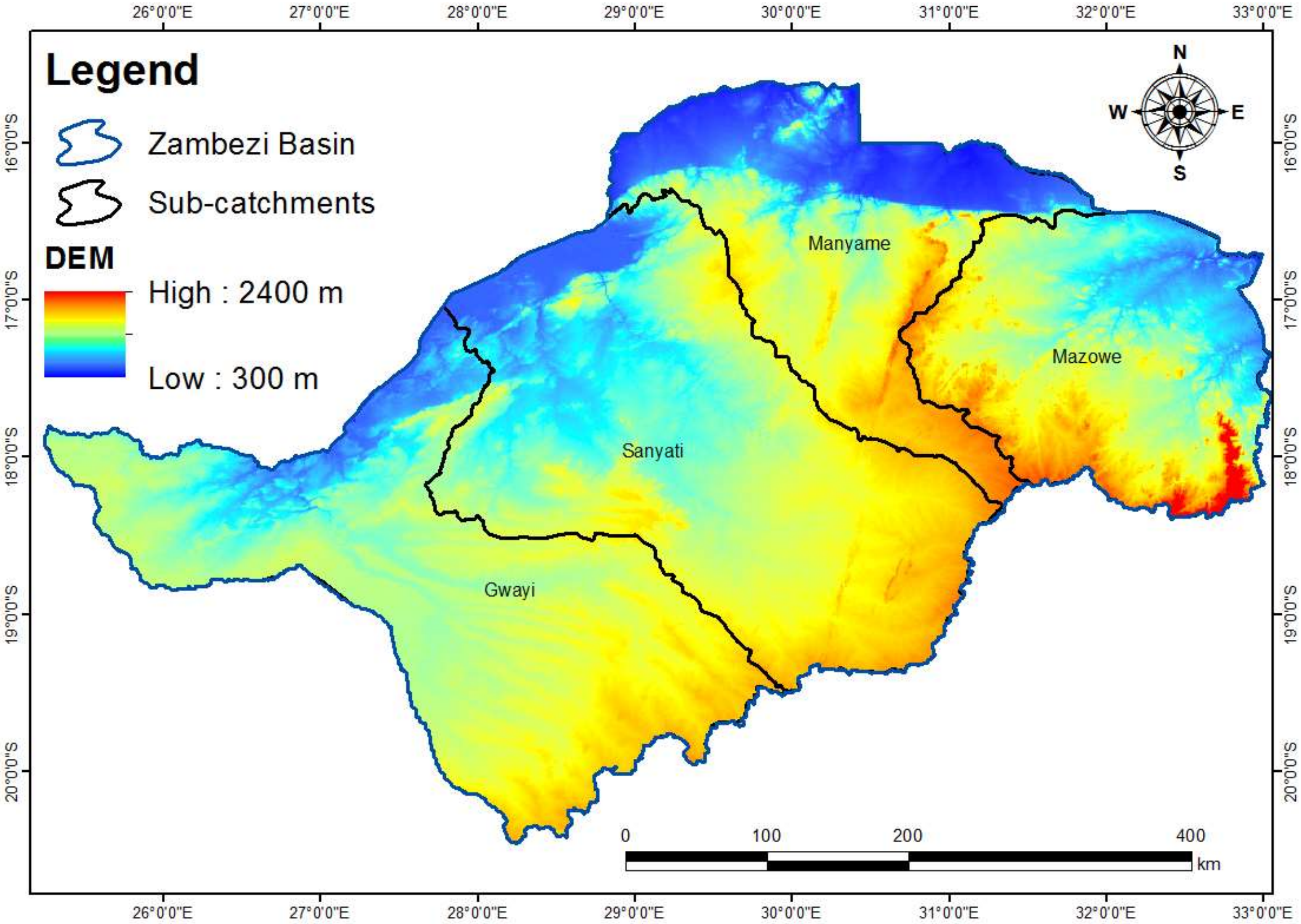

Fig 2.1 The DEM of the Zambezi River Basin in Zimbabwe

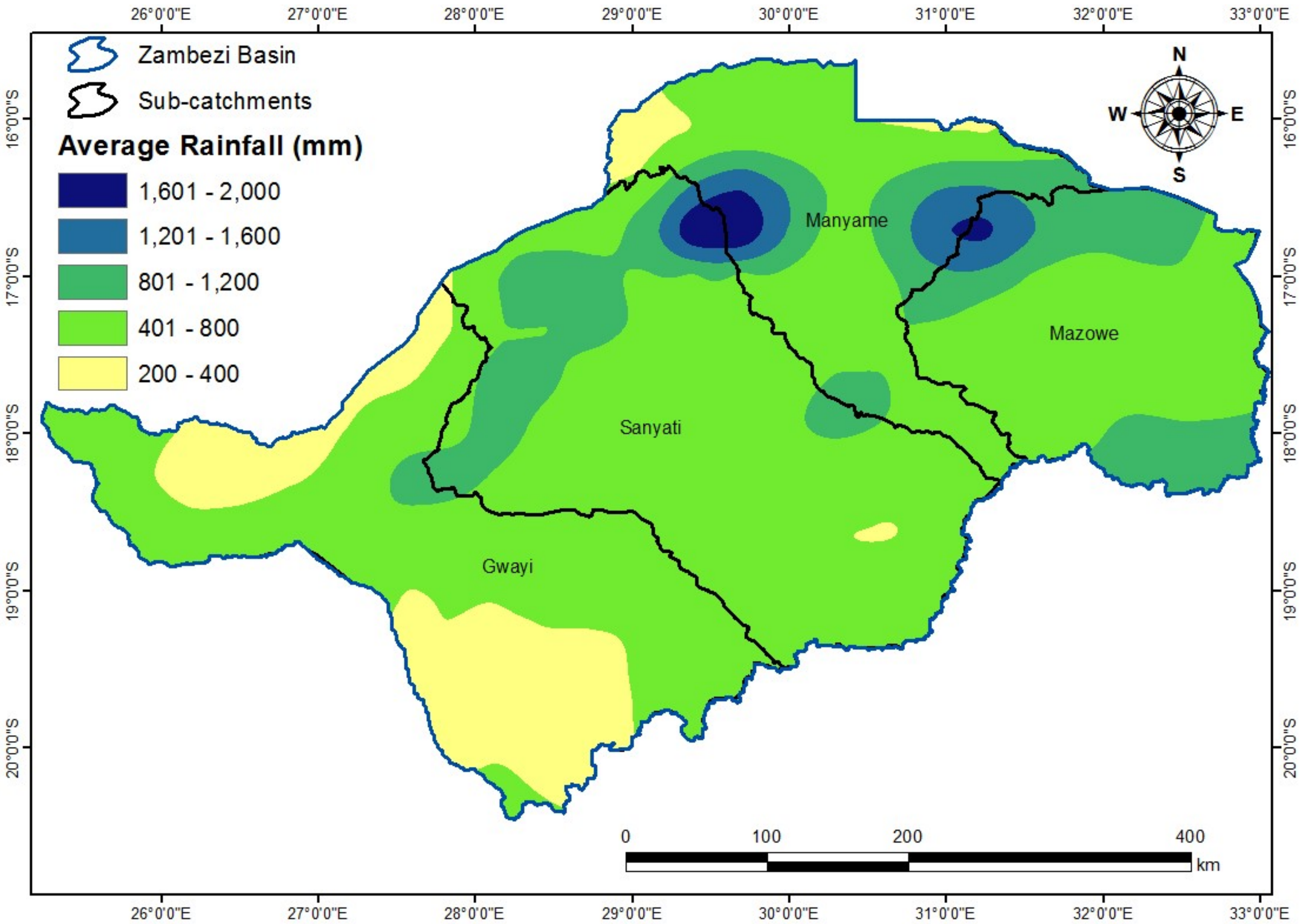

Fig 2.2 Mean Annual Rainfall in the Zambezi River Basin in Zimbabwe (Source: Meteorological Services of Zimbabwe, 2015)

2.2 Geological setting of the Zambezi basin in Zimbabwe

The geological origins of the Zambezi basin in Zimbabwe are complex as described by Davies (1986) and Key et al. (2015), among others. Overall, Zimbabwe's groundwater resources are limited since about 60% of the country is underlain by crystalline basement rocks (Mudimbo et al., 2018; Davis and Hirji, 2014). The geology of Zimbabwe comprises, in chronological order, the broad classes of recent unconsolidated sediments (aeolian sands and alluvium), Kalahari basin sedimentary formations, Upper and Lower Karoo formations, igneous intrusives, and basement complex formations, respectively (Mudimbo et al., 2018). These broad classes are depicted in Fig 2.3.

The recent sediments generally do not exceed 25m depth except in the Sabi Valley and the Zambezi valley where they reach depths of 40m or more. The sandstones, siltstones, grits and Kalahari sand, mainly covering Western Zimbabwe, constitute the Kalahari basin. A substantial thickness of alternating sandstones, siltstones and mudstone of the Lower Karoo is overlain by the Upper Karoo Batoka basalts and metavolcanics.

The Great Dyke is a geological feature that extends more than 550 km northeast to southwest across the centre of Zimbabwe (shown in green in Fig 2.3). The Great Dyke is an intrusive feature that hosts economically important deposits of mainly chromite and platinum. The various metasediments that include quartzite, shales and phyllites overlie the basement complex that covers at least 60% of the country (Mudimbo et al., 2018).

Within the basement complex, weathering plays an important role in groundwater occurrence. Weathering thicknesses less than 30m tend to occur on the younger granites and gneisses, while greater thicknesses occur within the greenstone belts and the older African erosional surface.

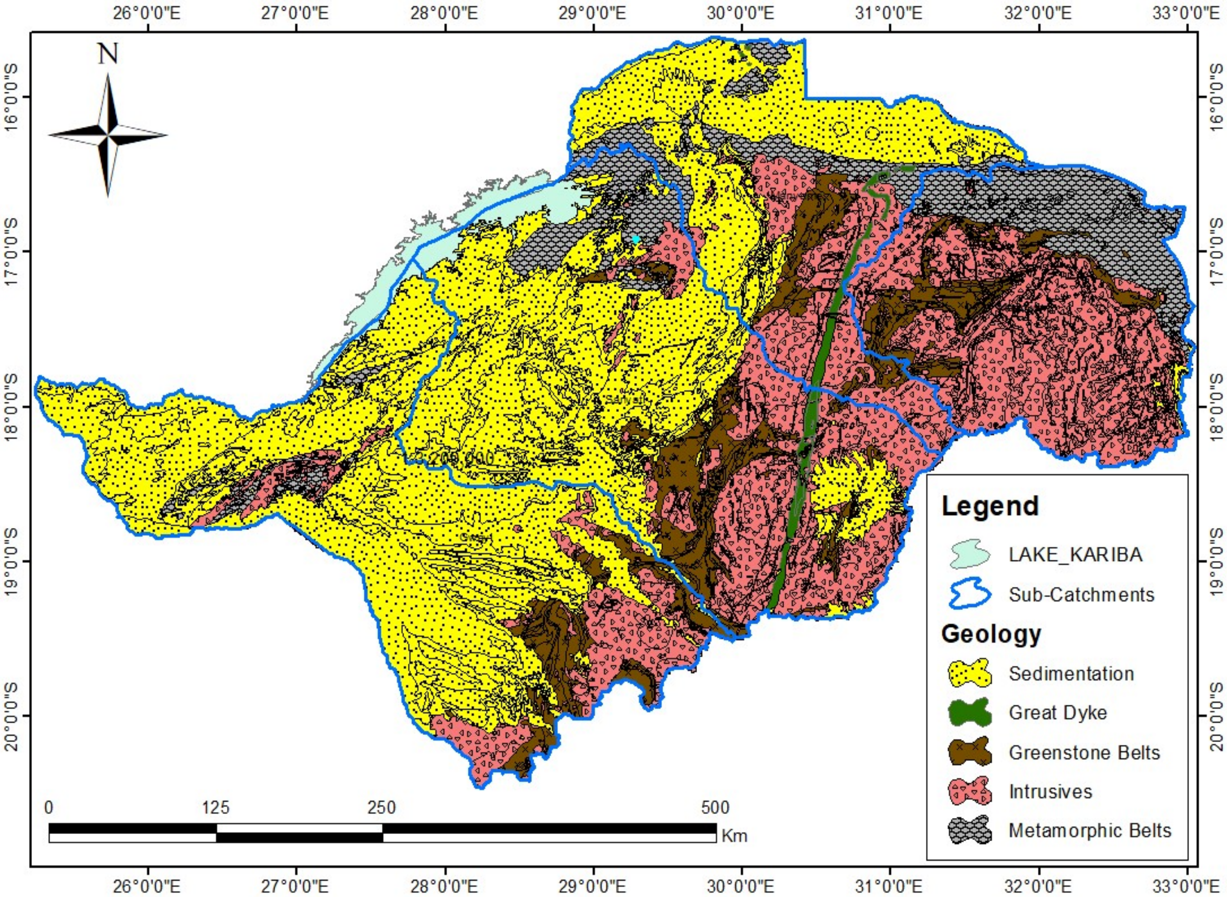

Fig 2.3 The geology of the Zambezi River Basin in Zimbabwe (Source: Zimbabwe Geological Survey, 2016)

2.3 Characterisation of ZRB groundwater hydrology in Zimbabwe

Previous studies tend to characterize aquifer units primarily according to rock type, with additional characterisation according to annual rainfall, topography, land use and land cover. Local aquifers occur within basement rocks in areas with high fracture density, or a substantial thickness of weathered regolith. Within the Zambezi basin, there are local aquifer systems with varying groundwater potential.

In the Gwayi catchment, the forest sandstone aquifer is part of the transboundary Karoo Aquifers, shared by Botswana, Namibia, South Africa, Zambia and Zimbabwe. This catchment consists mainly of Kalahari sands and the Karoo sedimentary formations. Within the Karoo sequence, different lithologies account for differences in the groundwater potential within the catchment. The Upper Karoo sequence comprises the Batoka basalt, the forest sandstone, and the escarpment grit, whereas the mudstone, and the upper and lower Wankie sandstone constitute the lower Karoo. The aquifers in this catchment have good primary porosity and excellent groundwater potential (Pavelic et al, 2012; Davis and Hirji, 2014). Although the groundwater potential is high, it may be uneconomic to abstract the groundwater due to water table depths in excess of 100m in the sandstone formations as shown in Fig 2.4.

Manyame catchment is dominated by granite and metamorphic rocks, with Karoo sediments accounting for just 20% of the geological formations. Aquifers in this region are mainly as a result of extensive weathering of the basement rocks. However in this catchment, weathered argillites do not make good groundwater reservoirs due to the high proportion of fines in the weathered regolith.

The geology in Mazowe catchment is entirely crystalline metamorphic rock province. The major rock types are gneiss and young intrusive granite on post African and Pliocene surface. As such, aquifers in this area are all due to secondary porosity due to weathering and fracture porosity. The groundwater potential is marginally higher in the watershed areas where the regolith is deeper, than in the downstream areas with limited regolith. Groundwater development potential is generally low, with water table depth being less than 10 metres. Borehole depths in this catchment rarely exceed 70m (Fig 2.4) and are mainly controlled by the depth of weathered regolith.

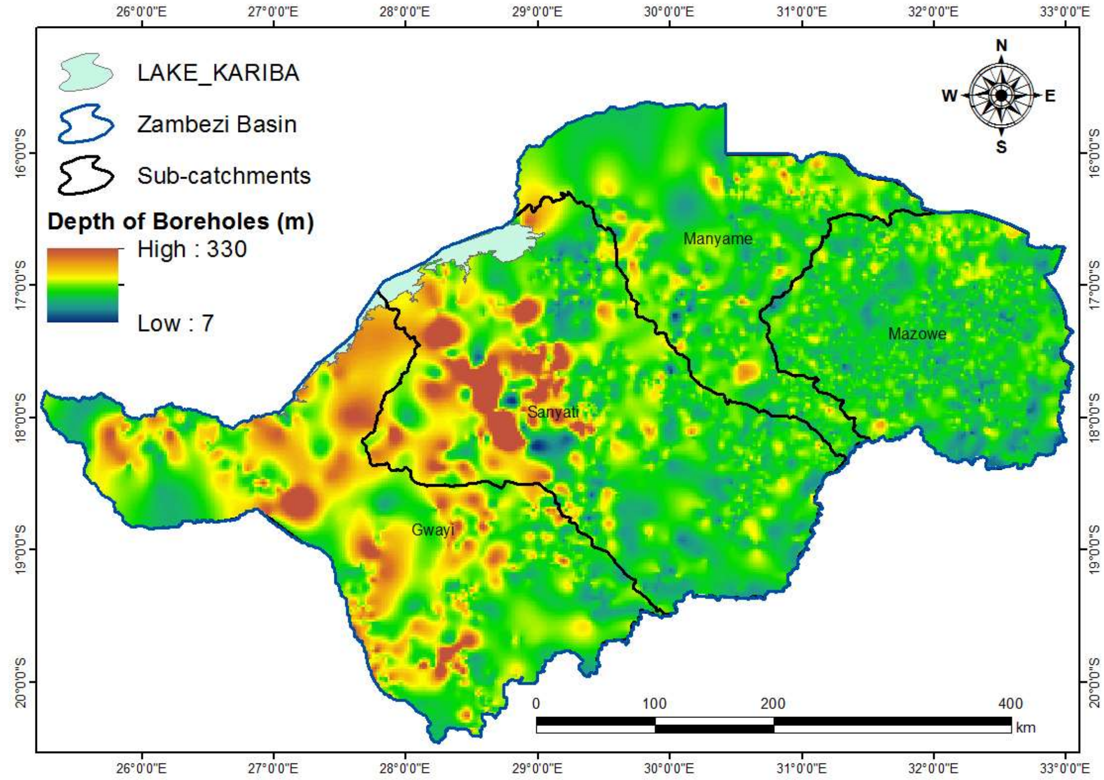

Fig 2.4 Depth of boreholes in the Zambezi River basin in Zimbabwe (Data Sourced from SADC-GMI, 2010)

Geological formations in the Sanyati catchment include crystalline and metamorphic rocks (70%) with low groundwater potential, and Karoo sediments (30%) with good groundwater potential. The Lomagundi Dolomite aquifer occurs at the centre of this catchment as shown in Fig 2.5 this aquifer has very high borehole yields of 500 – 2000 m^3/day. Average borehole depths in the dolomite are 50 – 80 metres (Pavelic et al., 2012).

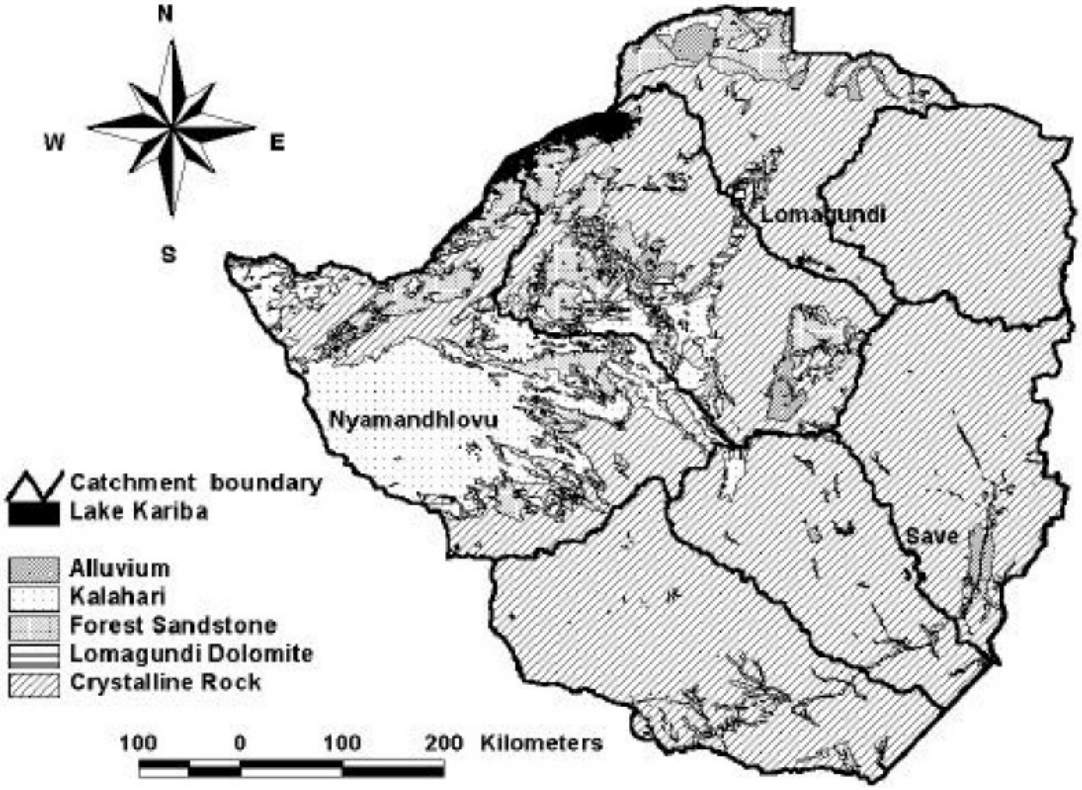

Fig 2.5 Major aquifers of Zimbabwe (Sunguro et.al, 2000)

2.5 Major findings on multi-scale groundwater hydrology baseline database at ZRB and Zimbabwe scale with reference to WEFE

Access to water, food, energy and ecosystem (WEFE) services are the four crucial elements for human well-being and they are intrinsically linked (Nhamo et al., 2018). When studying river basins, understanding the interactions between these elements is vital in ensuring that different and often competing needs are met in a coherent manner. Generally, the demand for water, energy, food and ecosystems services and goods is expected to increase in the whole ZRB due to demographic changes, economic growth, as well as changes in climate ZAMCOM (2017). The productivity of the ground water sources in the basin depend very much on the geology in the area and hence vary across the different catchments of the river basin as the geology varies. This is helpful for analysis of WEFE interdependences in the river basin. Understanding the hydrogeology of the river basin is crucial in determining the groundwater available in the basin to meet the requirements of the population for food production and other uses. The hydrogeology of the basin also informs the energy input required to access the groundwater at particular locations in the river basin. For example different technology and energy are required to access ground water from crystalline and metamorphic rocks with low groundwater potential, and groundwater from Karoo sediments.

3.0 GROUNDWATER DEMAND VS. AVAILABILITY AND QUALITY IN ZRB IN ZIMBABWE

3.1 Groundwater demand in the ZRB in Zimbabwe

3.1.1 Introduction

Within the context of this study, water demand was analysed in relation to the different land uses in the basin. WEFE interdependencies are informed by land use patterns of an area. The spatial distribution of the different land use patterns in the river basin in Zimbabwe is shown in Fig 3.1. These land uses are urban land, communal land, small scale commercial farming area, large scale commercial farming area and recreational and national parks. As shown in Fig 3.1, communal lands are dominant in all catchments. Based on these land uses multiple water demands in the basin can broadly be classified as domestic, industrial, mining, agricultural and recreational water demands.

Large scale commercial farms are more pronounced in the Sanyati and Manyame catchments, whereas small scale commercial farms feature more in Sanyati and Mazowe catchments. Recreational and National Parks are dotted across the river basin with the largest parks being found in Gwayi catchment, Sanyati catchment and Manyame catchment. The country's largest national parks are found in the ZRB for example, Zambezi National Park; Victoria Falls National Park; Hwange National Park; Chizarira National Park; Matusadona National Park; Lake Kariba Recreational Park and Mana Pools National Park.

Mining activities are generally concentrated around the urban areas and hence are not classified in Fig 3.1. The major mining areas are presented in Fig 3.2 for clarity as they coincide with other land use activities represented in Fig 3.1. Mining activities are mostly found in the Gwayi catchment, Sanyati, Manyame and Mazowe catchments along the Great Dyke. The major mining activities are the coalfields in the lower Karoo rocks of Hwange in the Gwayi catchment, platinum mining in the Great Dyke in the Sanyati catchment and goldfields distributed across the four catchments.

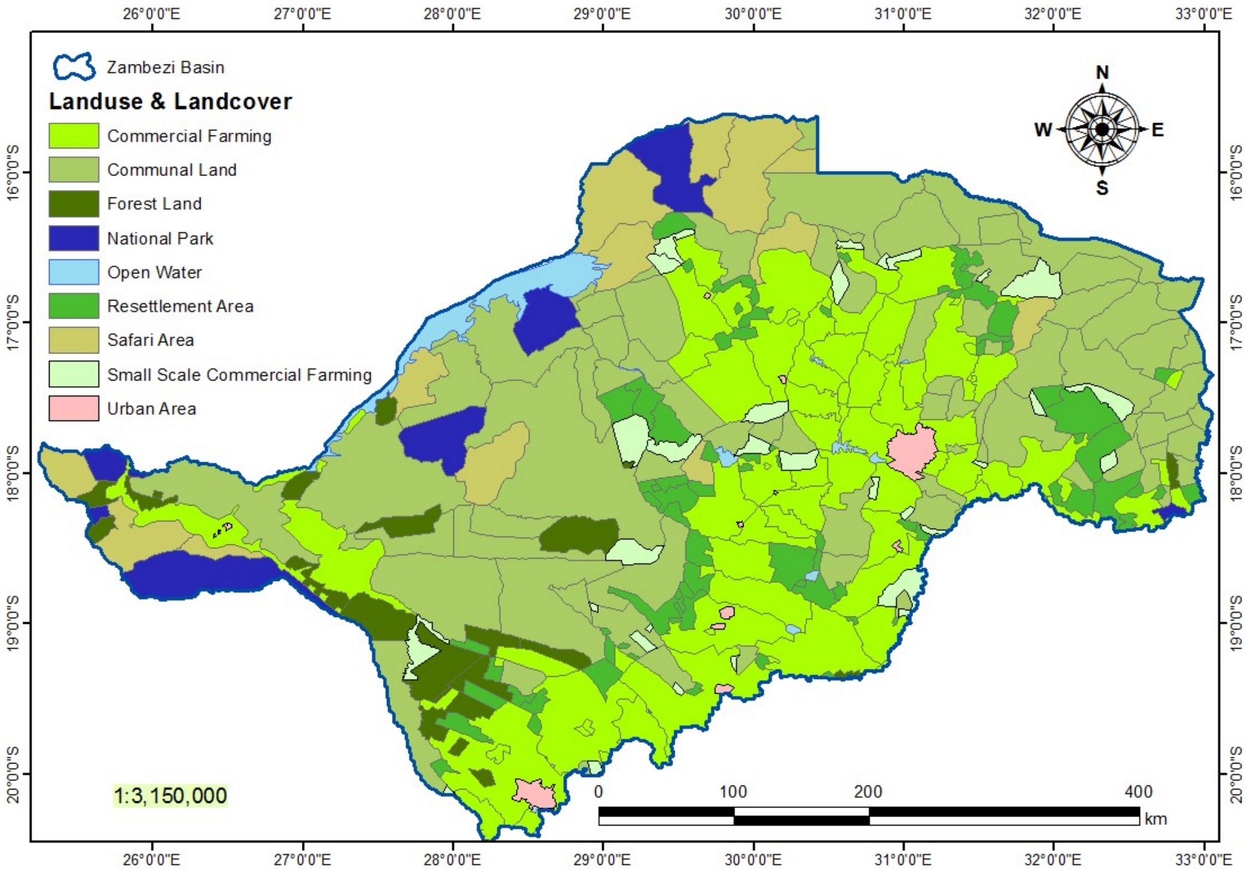

Fig 3.1 Land use patterns in the Zambezi River Basin in Zimbabwe (Source of the data: SADC-GMI 2010)

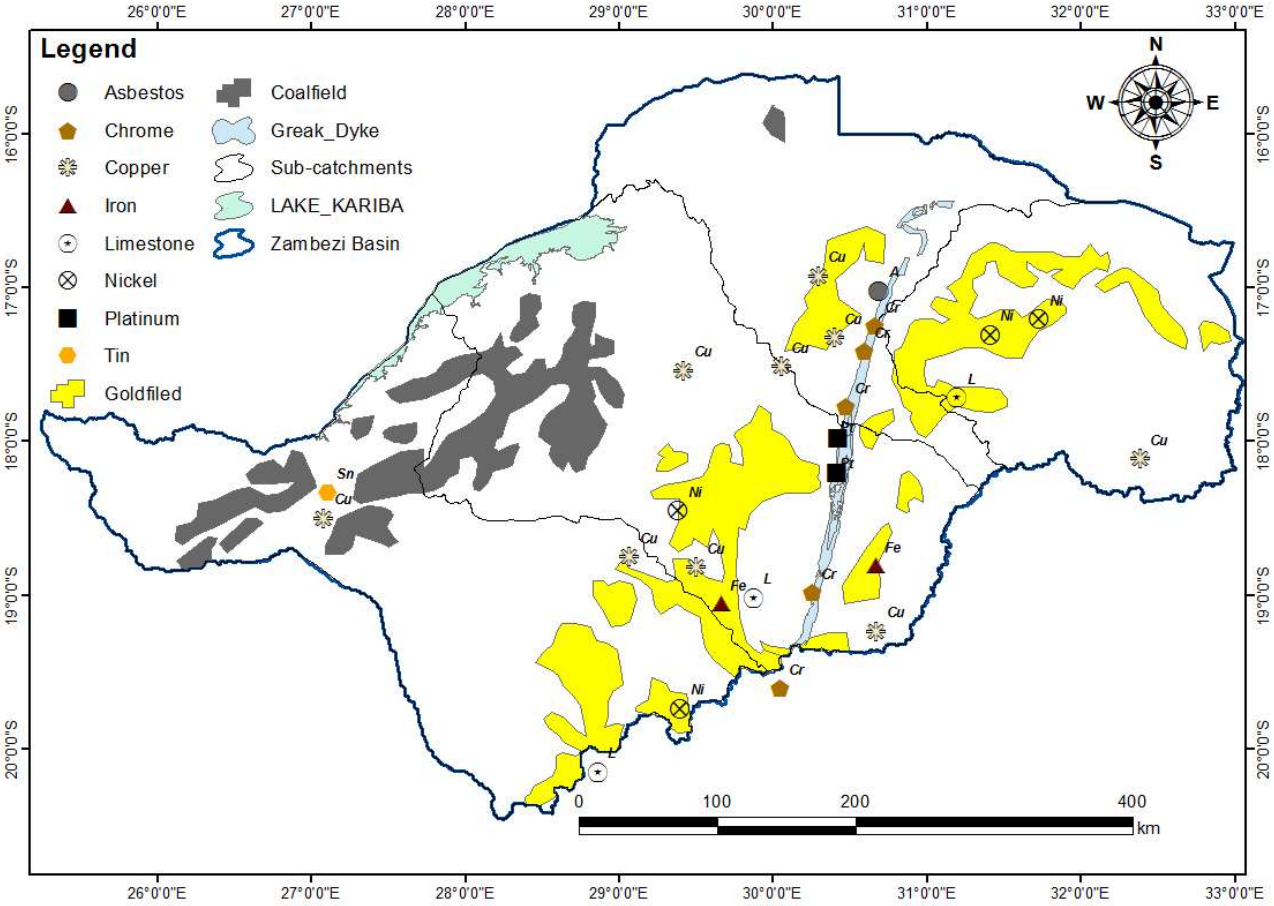

Fig 3.2 Mining and the associated minerals being mined in the ZRB in Zimbabwe (Source: Zimbabwe Geological Survey, 2016)

Proportional percentage land use was as shown in Fig 3.3. The land in the river basin is predominantly used for agriculture in the form of communal lands (41%), small scale commercial farming (10%) and large scale commercial farming areas (30%).

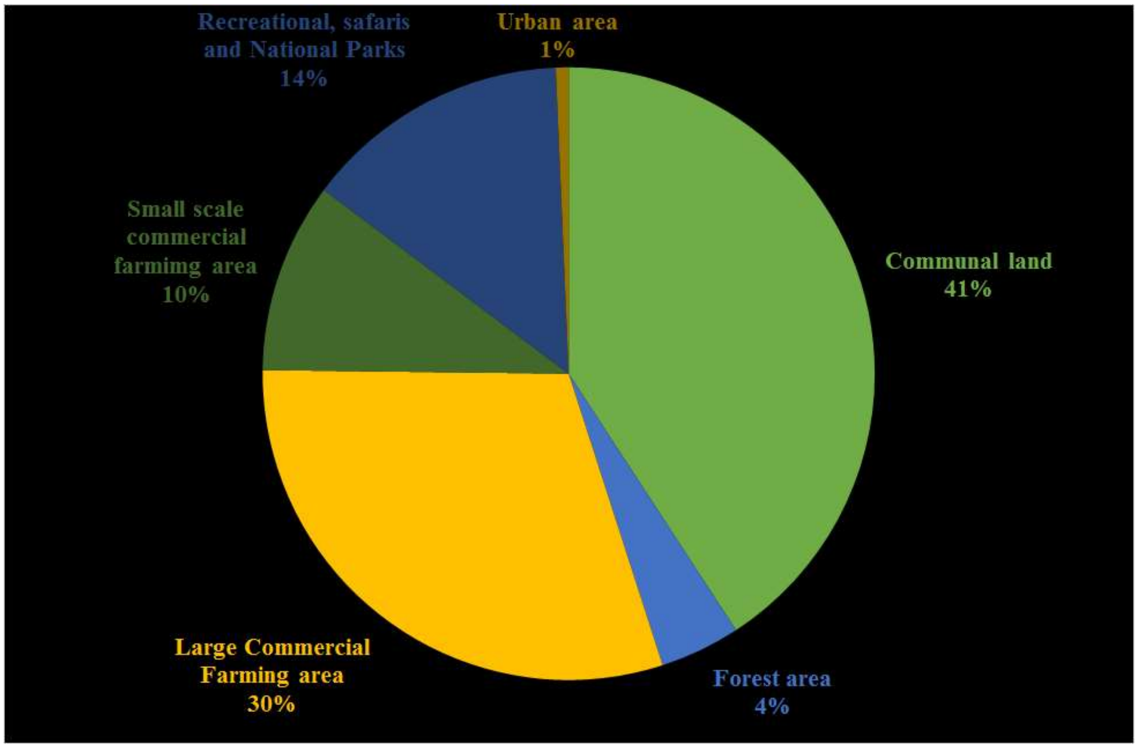

Fig 3.3 Percentage land use in the Zambezi River Basin in Zimbabwe

A substantial amount of land is reserved for safaris and National and recreational parks (14%). Forest areas occupy 4% of the river basin whilst urban areas only make up 1% of the river basin in Zimbabwe.

3.1.2 Domestic ground water demand case studies

Although both rural and urban areas use groundwater sources, their use is more dominant in rural areas. From Fig 3.3 the basin is predominantly rural and an in depth analysis of water use patterns was carried out in selected districts of the basin to establish the level of ground water use for domestic demand. Supplementary data for this analysis was obtained from the RURAL WASH Information Management System (RWIMS) database. For the purposes of analysing baseline conditions of water demand versus availability in ZRB in Zimbabwe thirteen (13) districts which had available data on RWIMS database were purposively selected to represent the different hydrological catchments in the ZRB as shown in Fig 3.4 and Table 3.1.

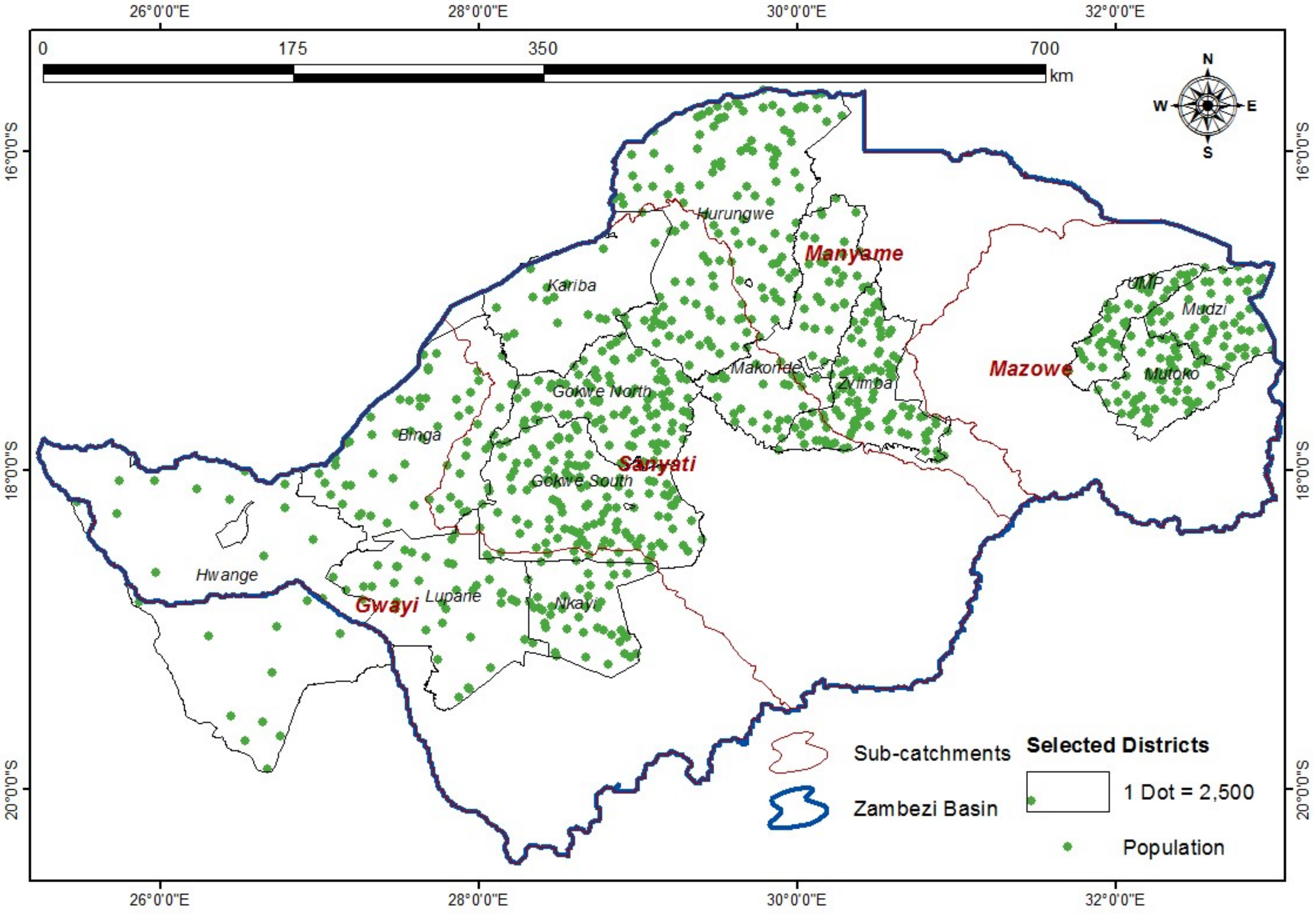

Fig 3.4 Location of the selected districts in the Zambezi River Basin in Zimbabwe and population (Source: Zimstat, 2012)

Table 3.1 Selected District study areas and the respective population

Zambezi Sub catchment	**Selected Districts**	**Population** (Zimstat, 2012)
Gwayi	Binga	139092
	Hwange Rural	62670
	Nkayi	109135
	Lupane	100161
Manyame	Kariba Rural	41369
	Hurungwe	329197
	Makonde	153540
Mazowe	Mudzi	133252
	Mutoko	146127
	Uzumba Maramba Pfungwe	112611
Sanyati	Gokwe North	240352
	Gokwe South	305982
	Zvimba	263020

The water sources in the selected districts are boreholes, dams, rivers, deep wells, shallow wells, artesian wells, springs and other unspecified sources such as rainwater harvesting. These sources are communally, institutionally or individually owned. The demand on these water sources by the communities vary from one catchment to another (RWIMS, 2018).

In Gwayi catchment, four districts namely Binga, Hwange, Nkayi and Lupane were studied which are predominantly rural. In Binga, 38 311 (38% of total households in the district) households use boreholes as their primary source of water, followed by 25 712 households relying on deep wells. Fig 3.5 shows that 90% (91 566) of the households rely on groundwater as a primary source accessing it through boreholes, deep wells, shallow wells, sand abstraction and springs. The remaining 10% (10 621) depend on surface water accessed from the dam and other means.

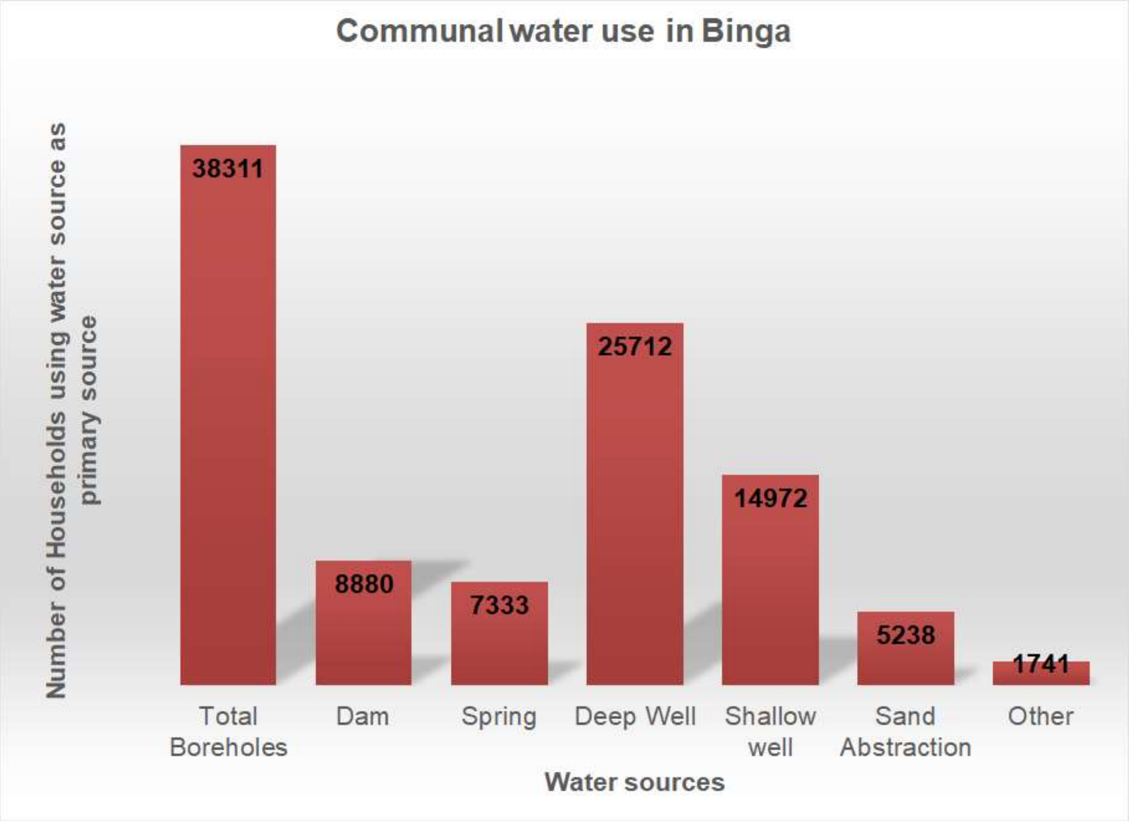

Fig 3.5 Communal dependence of different water source types in Binga District (Source of data: RWIMS, 2018)

In Lupane District the ratios of dependence on groundwater and surface water follows a similar pattern as in Binga District with 87% (17196) using groundwater as a primary source accessing it through boreholes, deep wells, shallow wells, sand abstraction and springs and 13% (2564) using surface water as primary source of water as shown in Fig 3.6. The dependence on boreholes is very high in Lupane (66% of total households) compared to Binga where 38% of the total households in the district use boreholes as their primary source of water. This could be because Binga District is close to the Zambezi River and Lupane has a few seasonal rivers which can be used as sources of water.

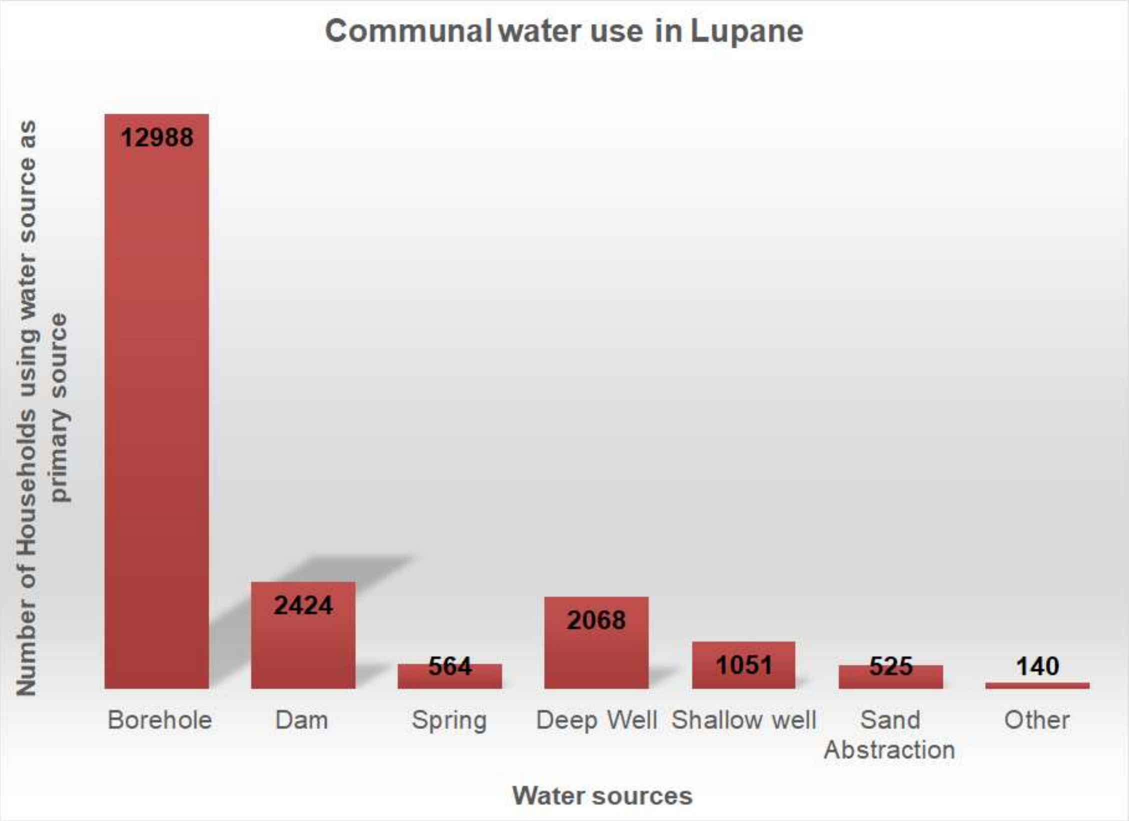

Fig 3.6 Communal dependence of different water source types in Lupane District (Source of data: RWIMS, 2018)

In the Nkayi District, 60% (18160 households) of the total households access water using boreholes and 79% (23895 households) of the total households in the district use ground water as a primary source of water as shown in Fig 3.7. In this district surface water sources contributed 21% (6192 households) as primary water sources and a sizeable number of households (2376 households) relied on the river as a primary source.

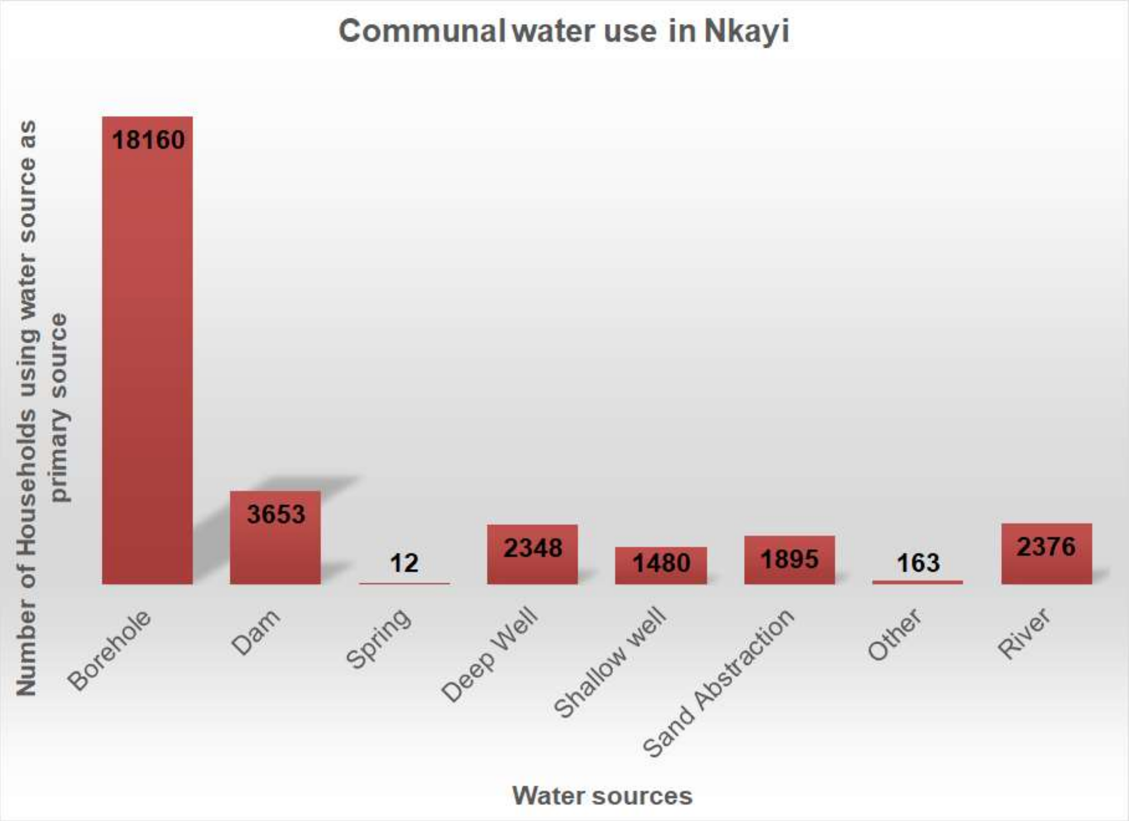

Fig 3.7 Communal dependence of different water source types in Nkayi District (Source of data: RWIMS, 2018)

The trend in Hwange District showed similar patterns as the other three districts with dependence on ground water sources being very high (89% i.e. 19659 households of the total households), accessing through boreholes, wells, sand abstraction and springs as shown in Fig 3.8. Access through boreholes is very high in this district at 71% of the total households (15556 households). The use of surface water was restricted to 11% of the total households in the district (2308 households) who access water from dams, rivers and other sources.

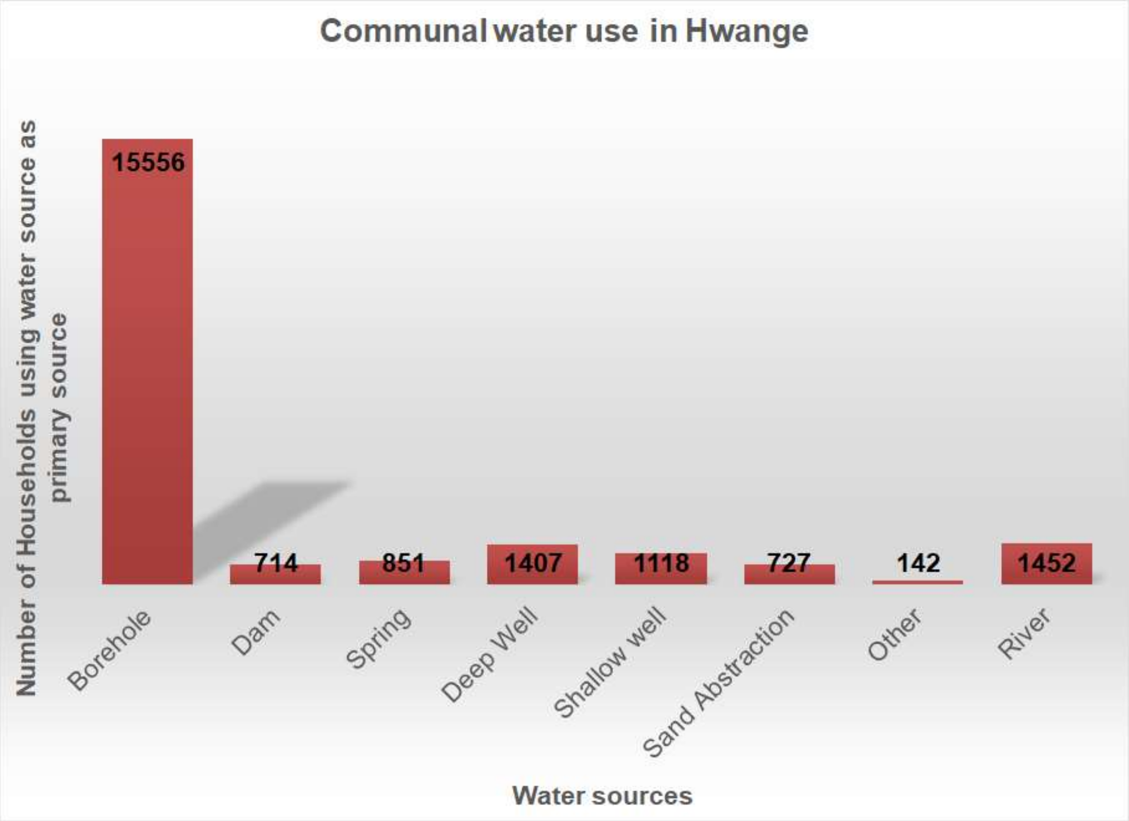

Fig 3.8 Communal dependence of different water source types in Hwange District (Source of data: RWIMS, 2018)

On aggregation of the primary water sources in the four districts in Gwayi catchment, it was found that 87% of the total households (174 001 households) depend on groundwater and 13% of the total households (21 685 households) rely on the surface water sources. Fig 3.9 presents an aggregated distribution of the dependence on different primary water sources for the four districts and use of boreholes is high at 49%.

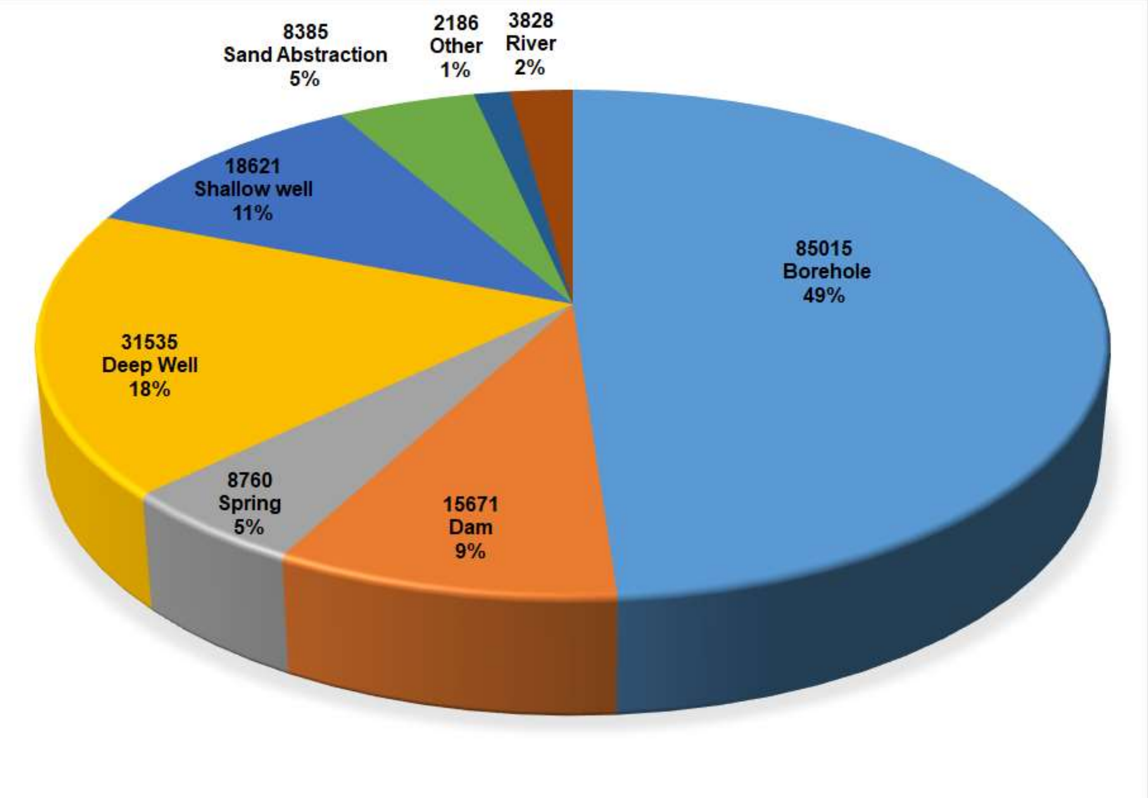

Fig 3.9 Percentage distribution of water source types in Selected Districts of Gwayi Catchment (Source: RWIMS, 2018)

In Manyame catchment ground water is tapped from boreholes, springs, and deep wells, shallow wells and sand abstraction and surface water from rivers and dams (RWIMS, 2018). In Hurungwe District, 73% (105 715 households) of the total households depend on groundwater as a primary water source and 27% (39 185 households) of the total households in the district depend on surface water as shown in Fig 3.10. The dependence on boreholes is also relatively high in Hurungwe, at 61% of the total households.

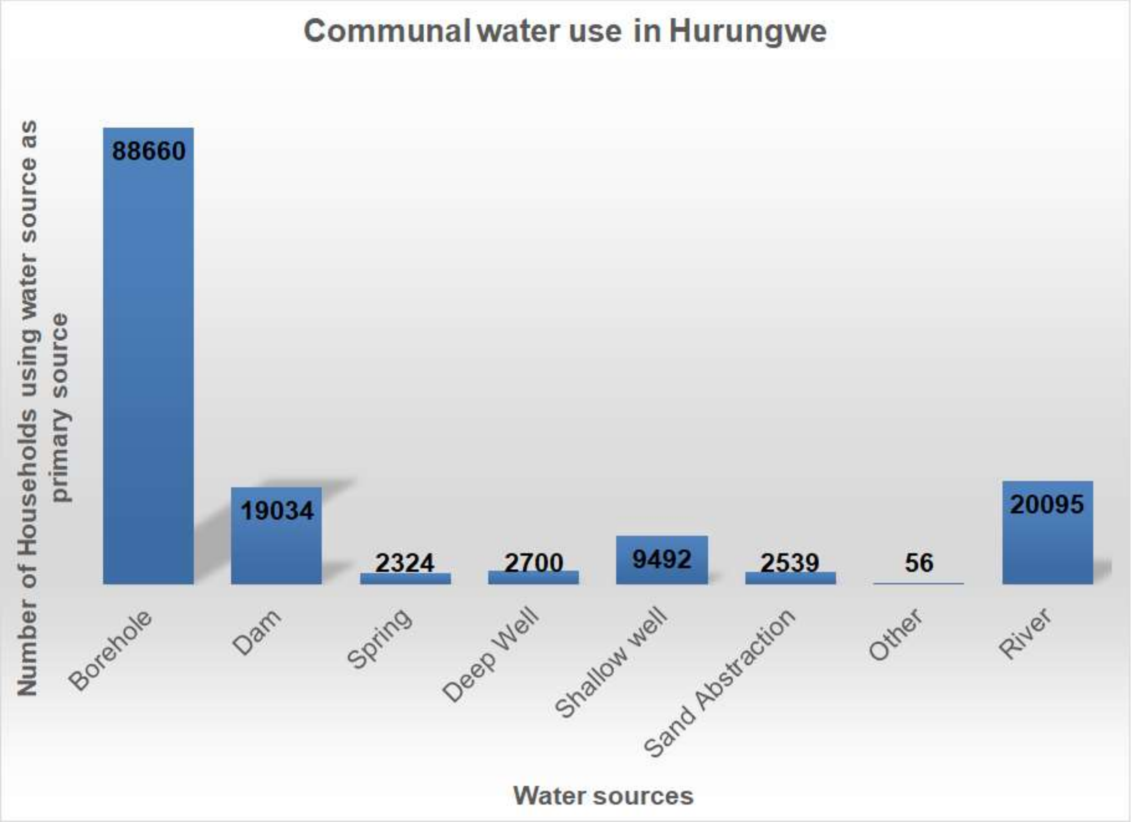

Fig 3.10 Communal dependence of different water source types in Hurungwe District (Source of data: RWIMS, 2018)

In Kariba District, 84% (12180 households) of the total households depend on groundwater as a primary water source and 16% (2315 households) of the total households in the district depend on surface water as shown in Fig 3.11. However the dependence on boreholes is low in Kariba, at 29% of the total households. Other ground water sources of wells and springs and sand abstractions are equally popular as access to the groundwater in the district. Access to surface water is predominantly through the river presumably by the communities close to the Zambezi River.

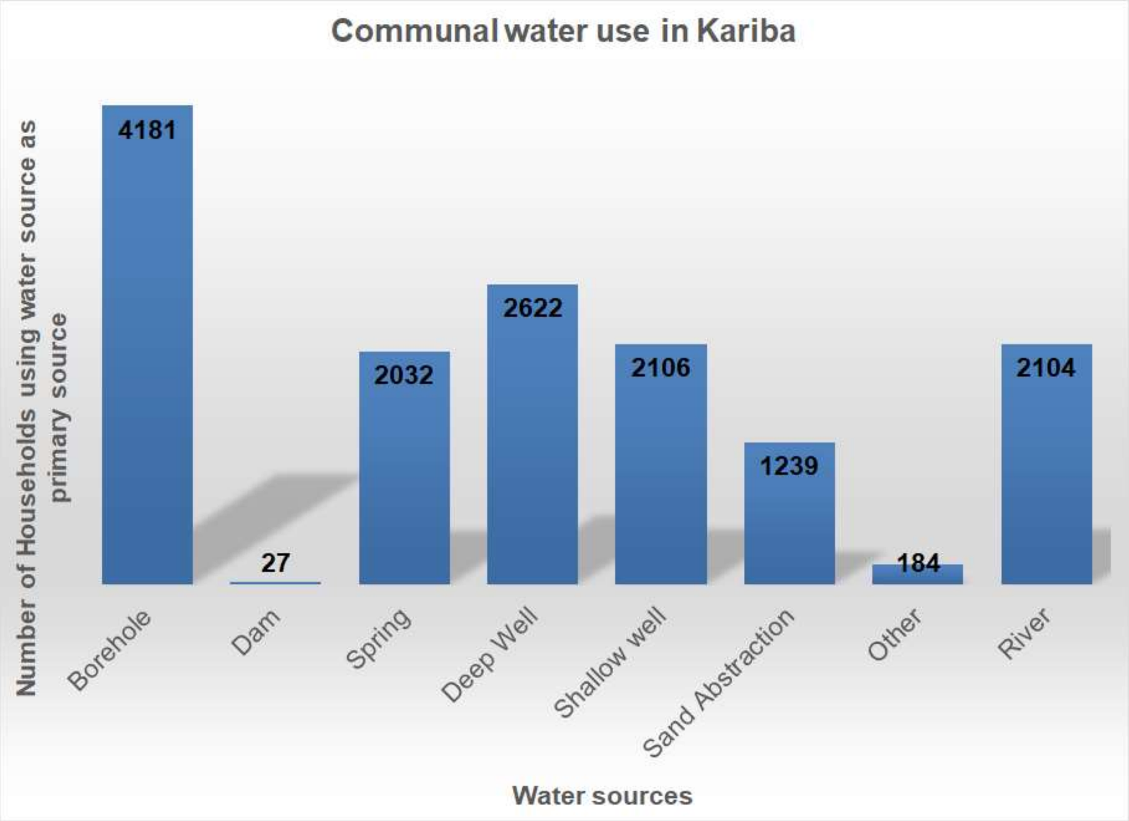

Fig 3.11 Communal dependence of different water source types in Kariba District (Source of data: RWIMS, 2018)

In Makonde District, 87% (25 856 households) of the total households depend on groundwater as a primary water source and 13% (3854 households) of the total households in the district depend on surface water as shown in Fig 3.12. The dependence on boreholes is very high in Makonde, at 73% of the total households. Access to surface water by the households is relatively low and mostly from rivers.

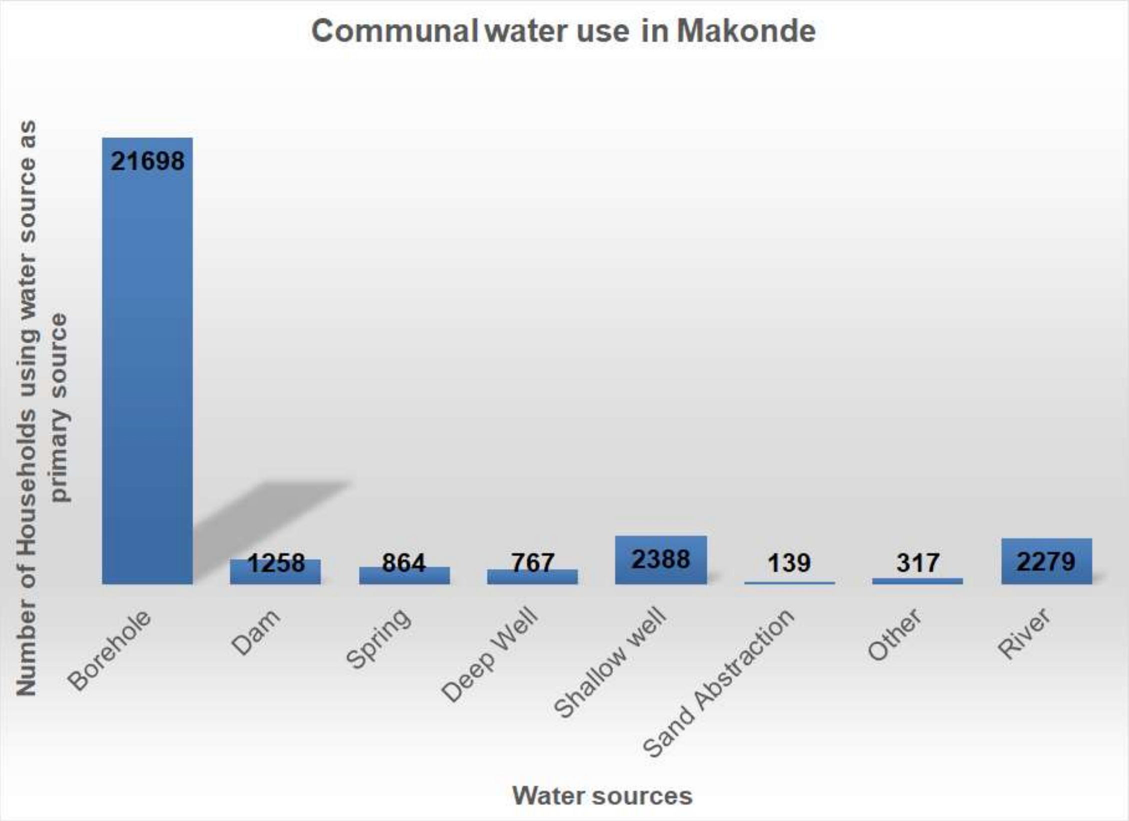

Fig 3.12 Communal dependence of different water source types in Makonde District (Source of data: RWIMS, 2018)

Similar to other catchments boreholes are a dominant source of ground water in the catchment as they constitute 61% of the ground water sources (Fig 3.13). The primary water sources in the three districts in Manyame catchment was found to be 76% of the total households (143 751 households) depend on groundwater and 24% of the total households (45 324 households) rely on the surface water sources.

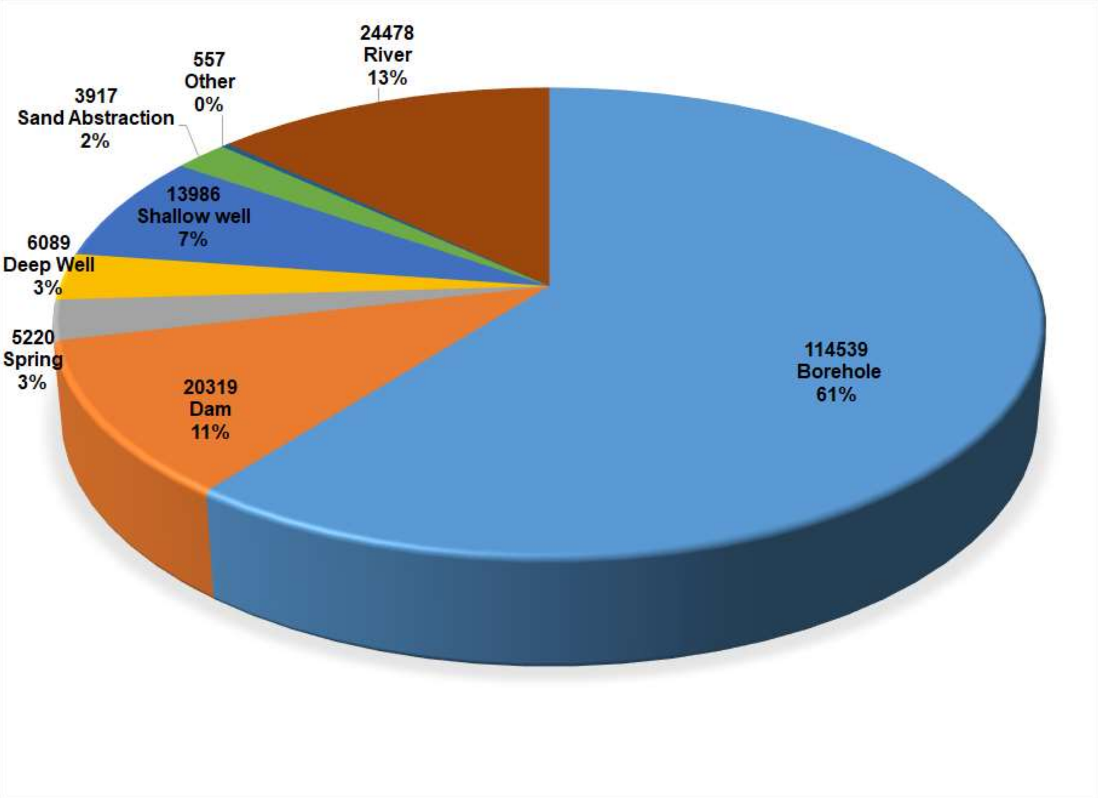

Fig 3.13 Percentage distribution of water source types in selected districts in the Manyame Catchment (Source of data: RWIMS, 2018)

In Mazowe catchment, three districts of Mudzi, Uzumba Maramba Pfungwe and Mutoko were selected for the analysis. In Mudzi District (Fig 3.14), only 19% of the total households (15382 households) depend on surface water as a primary source, where as 81% of the total households (69 352 households) depend on the groundwater sources as a primary source. Of the individual primary sources, 13600 households depend on dams as a primary source and 52 875 households (62%) depend on boreholes as primary source of water.

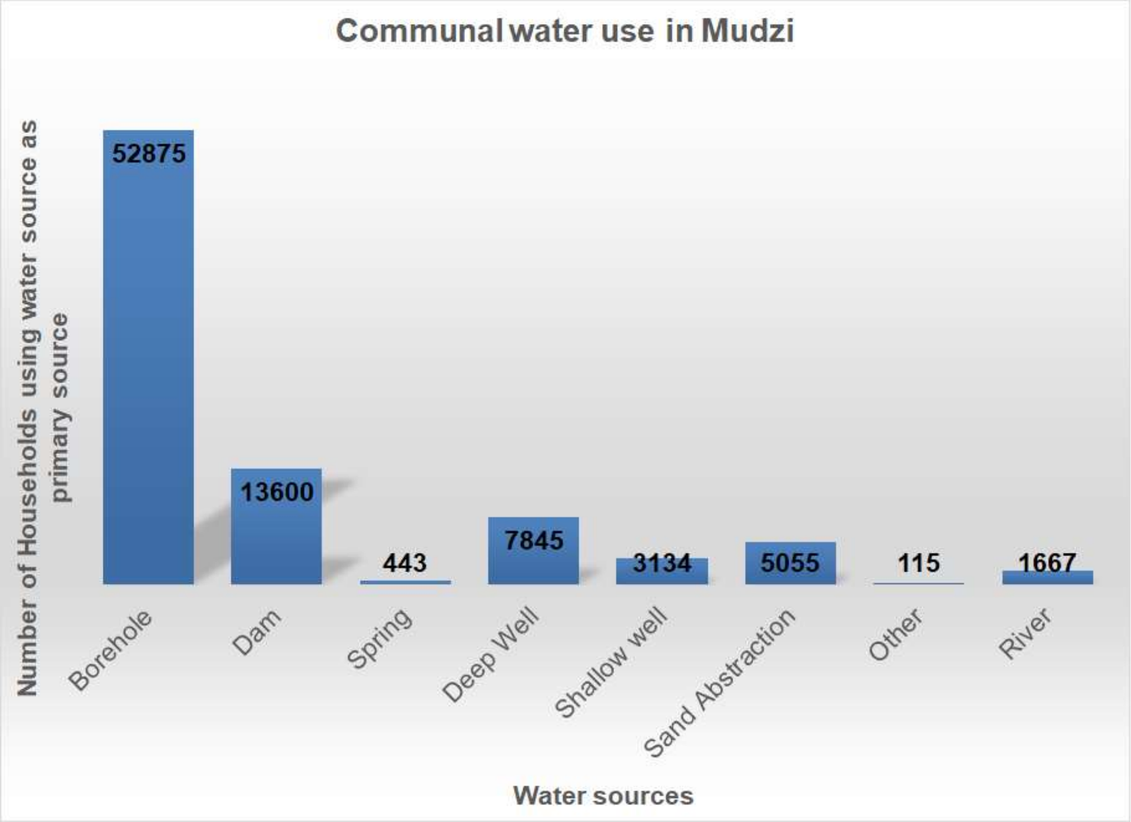

Fig 3.14 Communal dependence of different water source types in Mudzi District (Source of data: RWIMS, 2018)

Mutoko District has a very high dependence on groundwater of 96% of the total households (51 962 households) and only 4% of the total households (2086 households) depend on surface water as a primary source. The boreholes provide water to 58% of the total households in Mutoko and for the surface water sources the predominant sources is the river. The numbers of households in Mutoko served by different sources of water are as presented in Fig 3.15.

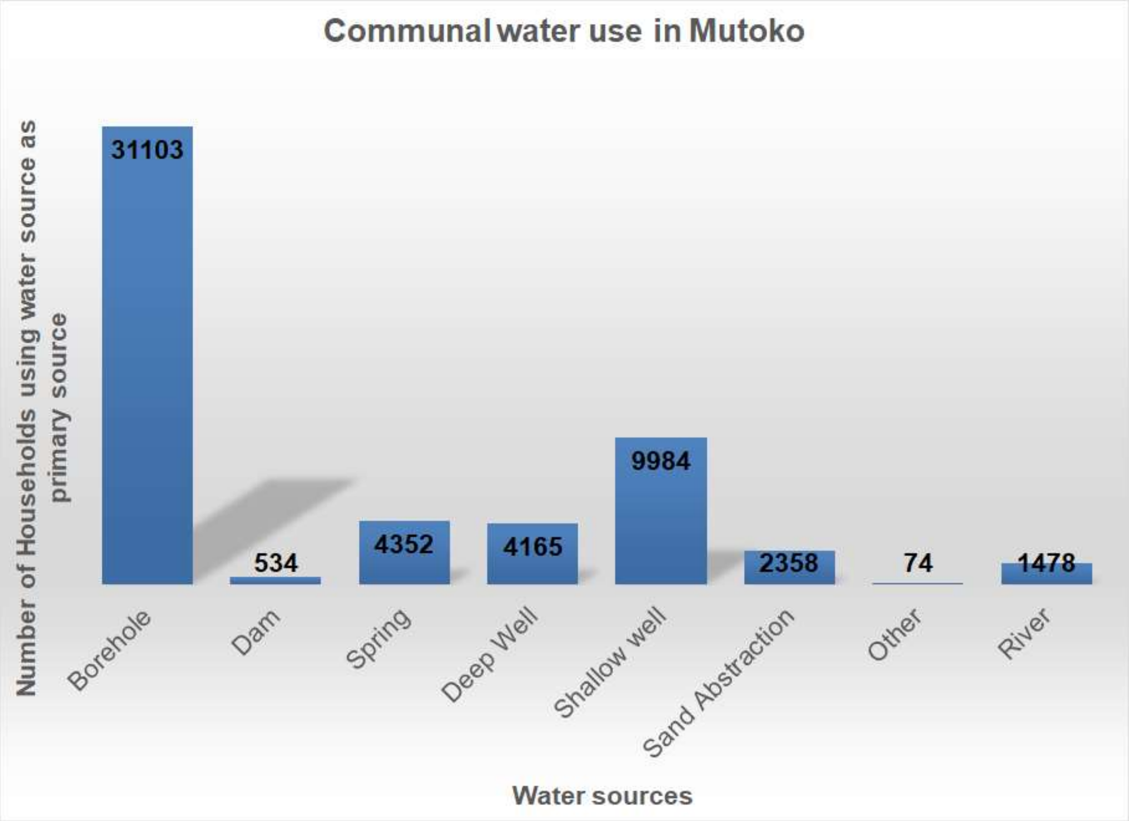

Fig 3.15 Communal dependence of different water source types in Mutoko District (Source of data: RWIMS, 2018)

Uzumba Maramba Pfungwe District also predominantly depends on groundwater for domestic us as shown in Fig 3.16. The dependence on groundwater in the district stands at 88% of the total households (37 366 households) and 12% (4 976 households) on surface water sources. 61% of the total households access the groundwater through boreholes, which reflects a very high dependency.

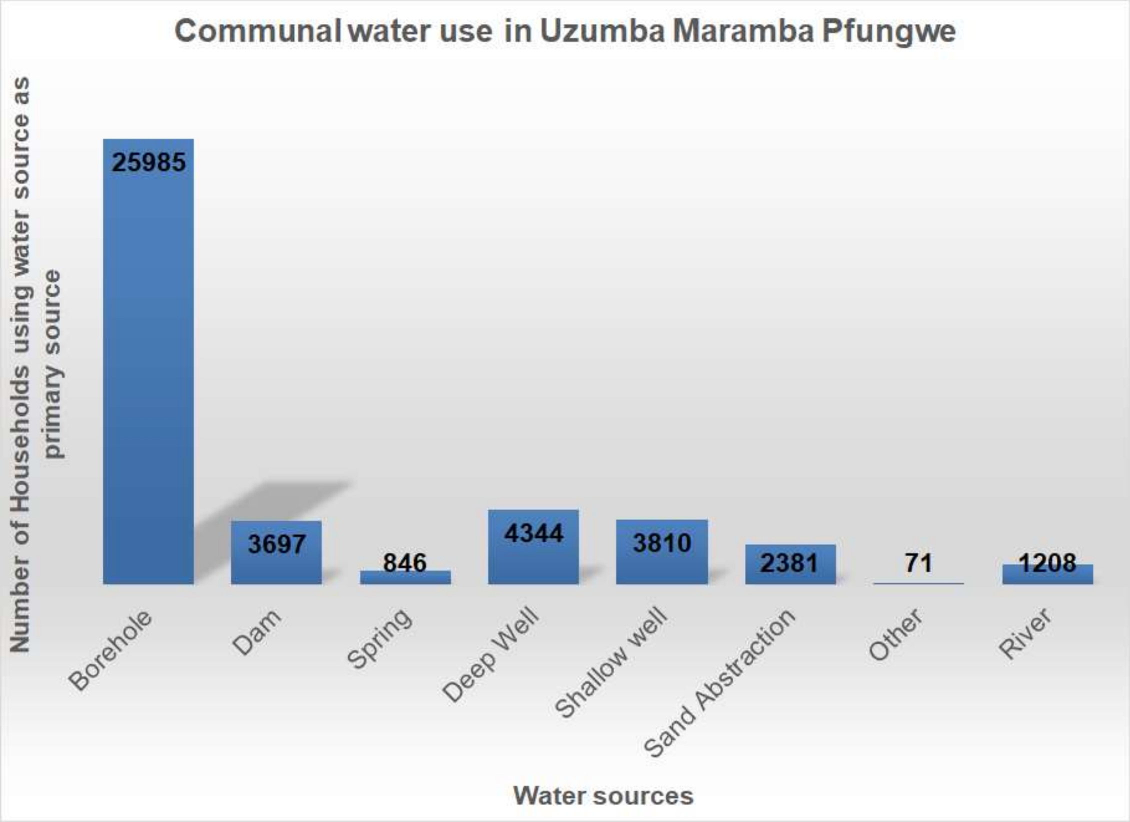

Fig 3.16 Communal dependence of different water source types in Uzumba Maramba Pfungwe District (Source of data: RWIMS, 2018)

For the combined selected districts in Mazowe catchment, the predominant primary source was groundwater at 88% of the total households in the three selected districts (158 680 households). Boreholes also remained the most depended upon primary source at 61% as shown in Fig 3.17.

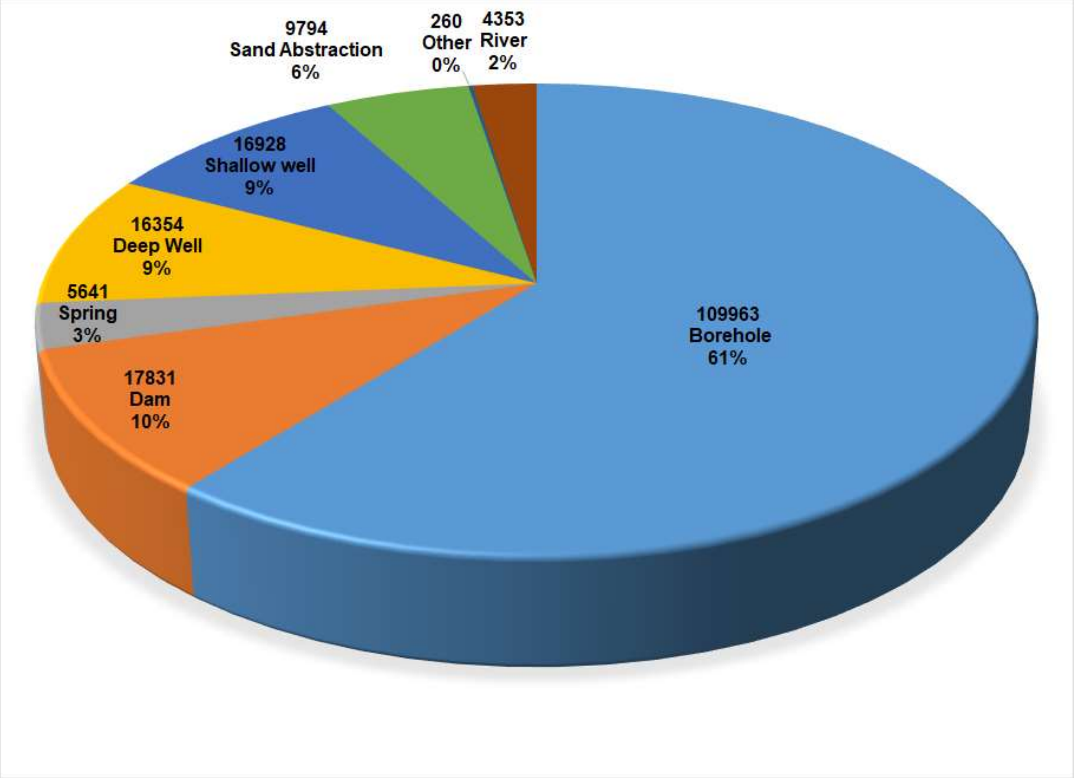

Fig 3.17 Percentage distribution of water source types in selected districts in the Mazowe Catchment (Source: RWIMS, 2018)

Gokwe North, Gokwe South and Zvimba were the districts that had available data on water demand in Sanyati Catchment hence their inclusion in the study. In Gokwe North District, 72% of the total households (106 732 households) rely on groundwater, with boreholes being the predominant source (34%), followed by shallow wells (19%), and sand abstraction (11%) as shown in Fig 3.18. The use of boreholes as a primary source of groundwater is very low in this district compared to other districts studied. Dams as primary sources contribute a significant number of households (25 793 households) to the 28% (41 713 households) of the total households relying on surface water as a primary source.

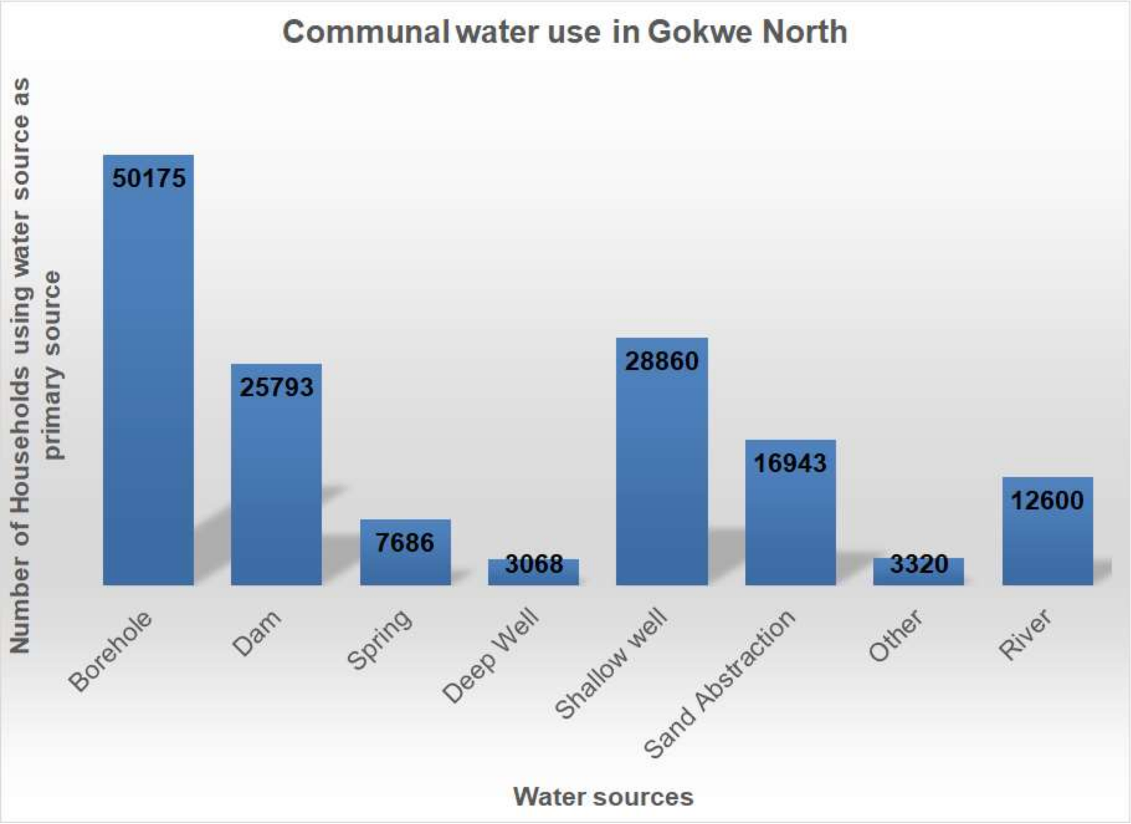

Fig 3.18 Communal dependence of different water source types in Gokwe North District (Source of data: RWIMS, 2018)

In Gokwe South District, 65 727 households (87% of the total households) use groundwater as a primary water source. As in Gokwe North the use of boreholes is very low at 53% of the total households even though it remains the predominant source as shown in Fig 3.19. Sand abstraction (17%) and shallow wells (14%) are also quite significant as primary sources in this district. Households relying on surface water constitute 13% (9939 households) of the total households in the district.

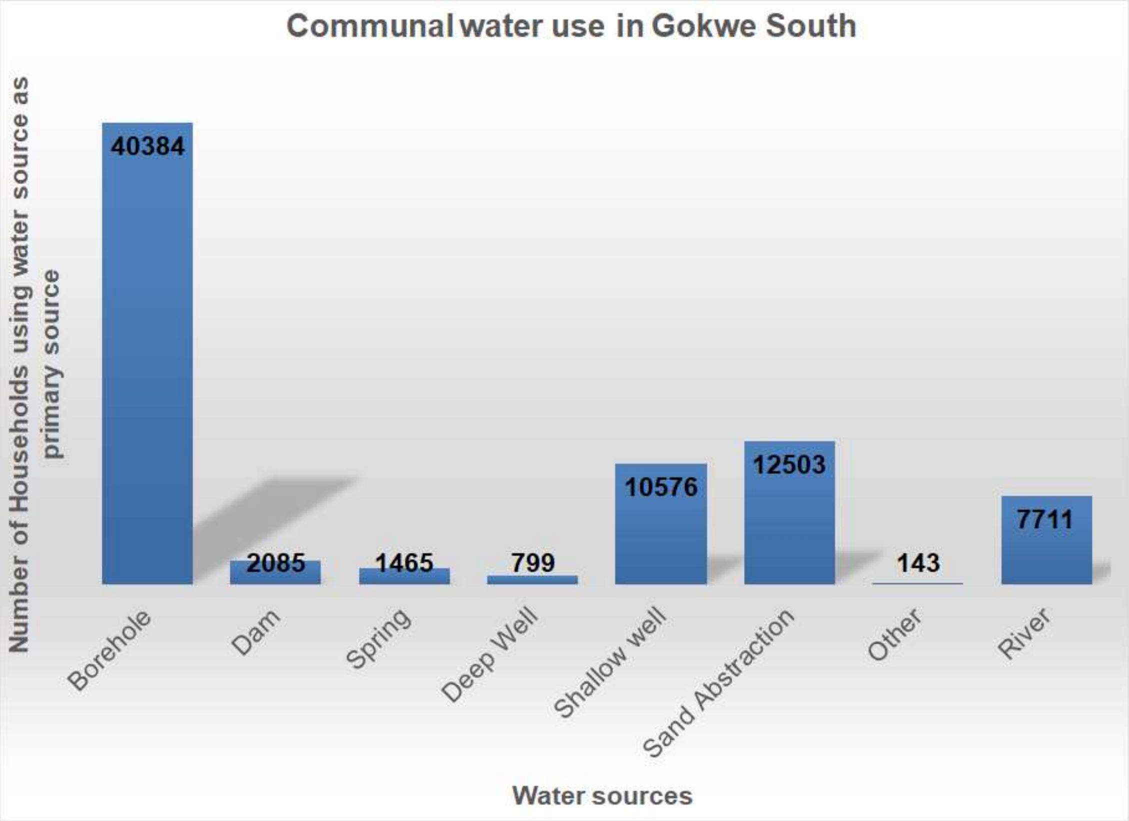

Fig 3.19 Communal dependence of different water source types in Gokwe South District (Source of data: RWIMS, 2018)

In Zvimba District, Fig 3.19 shows that ground water sources are predominant as primary sources at 87% of the total households (55 339 households) and surface water sources serve 13% of the total households (8548 households). It is also clear from Fig 3.20 that boreholes provide water to the majority of the households at 61% of the total households. A significant number of households also rely on shallow wells and deep wells as primary sources of water and very few households use sand abstraction to access water in this district.

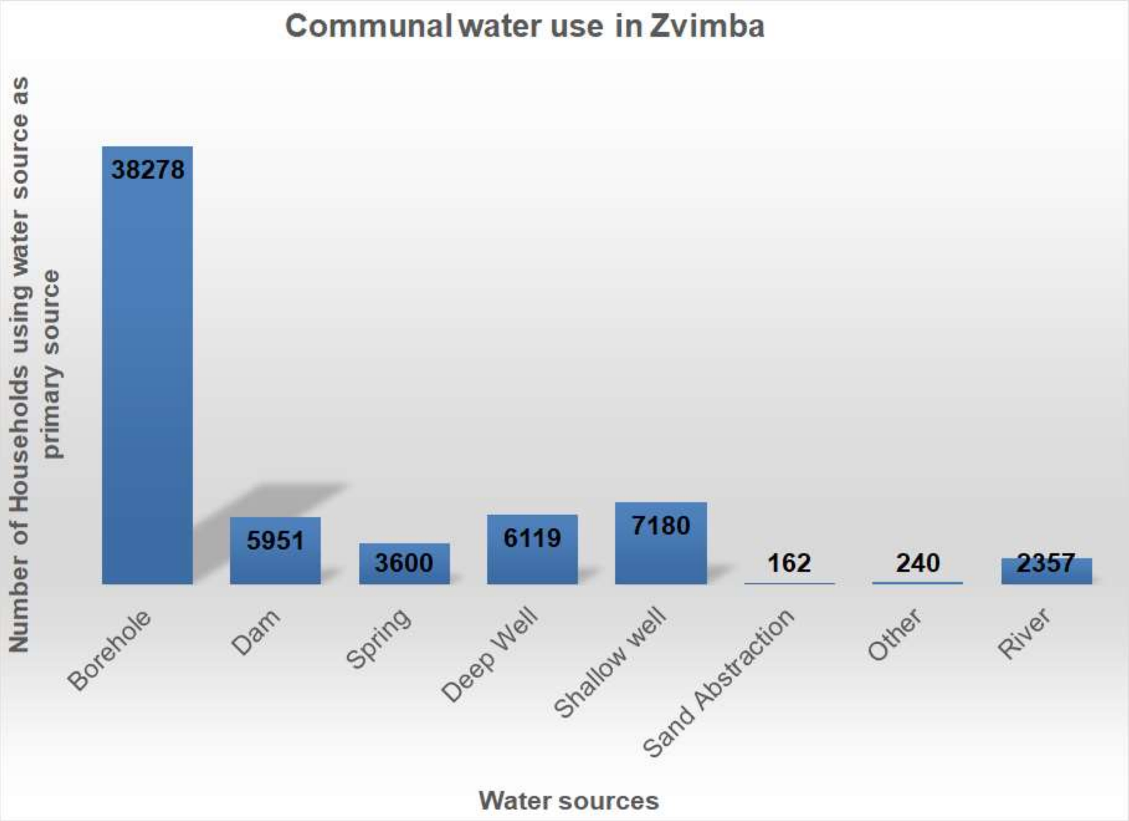

Fig 3.20 Communal dependence of different water source types in Zvimba District (Source of data: RWIMS, 2018)

The selected districts in Sanyati catchment have the least percentage households using boreholes as a primary water sources (45%) out of the four studied catchments as shown in Fig 3.21. Compared to the districts in other catchments the percentage of households using sand abstraction (10%) and shallow wells (16%) was relatively high in the districts of Sanyati Catchment, especially Gokwe North and Gokwe South districts. In total 79% of the households in the three districts depend on ground water as the primary source of water.

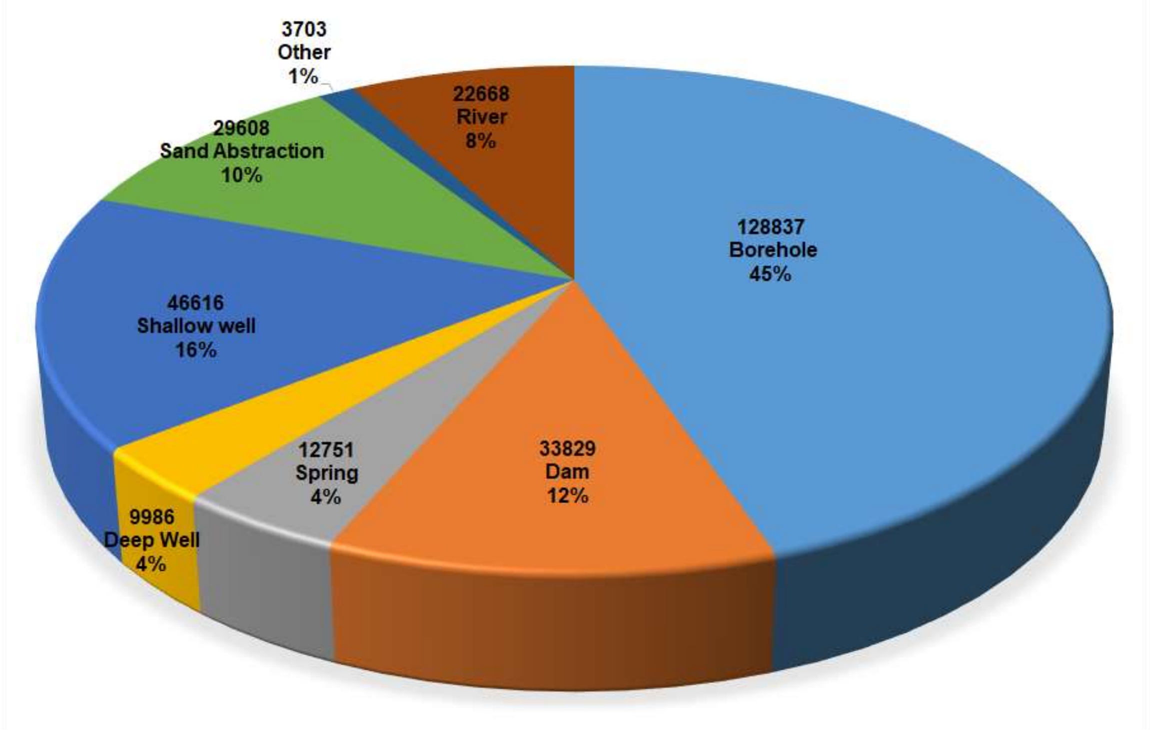

Fig 3.21 Percentage distribution of water source types in selected districts in Sanyati Catchment (Source of data: RWIMS, 2018)

3.1.3 Estimation of groundwater demand in the ZRB in Zimbabwe

The results of the analysis of primary water sources in the selected districts of the four catchments in the ZRB in Zimbabwe indicated that on average 83% of the total households in the thirteen districts depend on groundwater as a primary source of water, which concurs with findings from literature that more than 80% of the population in the basin depend on groundwater (Euroconsult Mott Macdonald, 2007). A study by Svubure et.al, (2011) in Lupane district revealed that on average the daily water demand per capita was 112 litres for domestic, gardening and livestock watering requirements.

Fig 3.22 shows the population distribution in the ZRB in Zimbabwe and the population varies from 1000 people to 1 461 000 people. Assuming the daily water demand per capita determined by Svubure et.al, (2011) of 112 litres, total water demand in the ZRB in Zimbabwe can be estimated as ranging from a minimum of 112 m^3 per day to a maximum of 163 632 m^3 per day for the population distribution presented in Fig 3.22. Applying the 83% factor for the population depending on groundwater resources, the water demand for groundwater can be estimated as ranging from 92.96 m^3 per day to 135 815 m^3 per day.

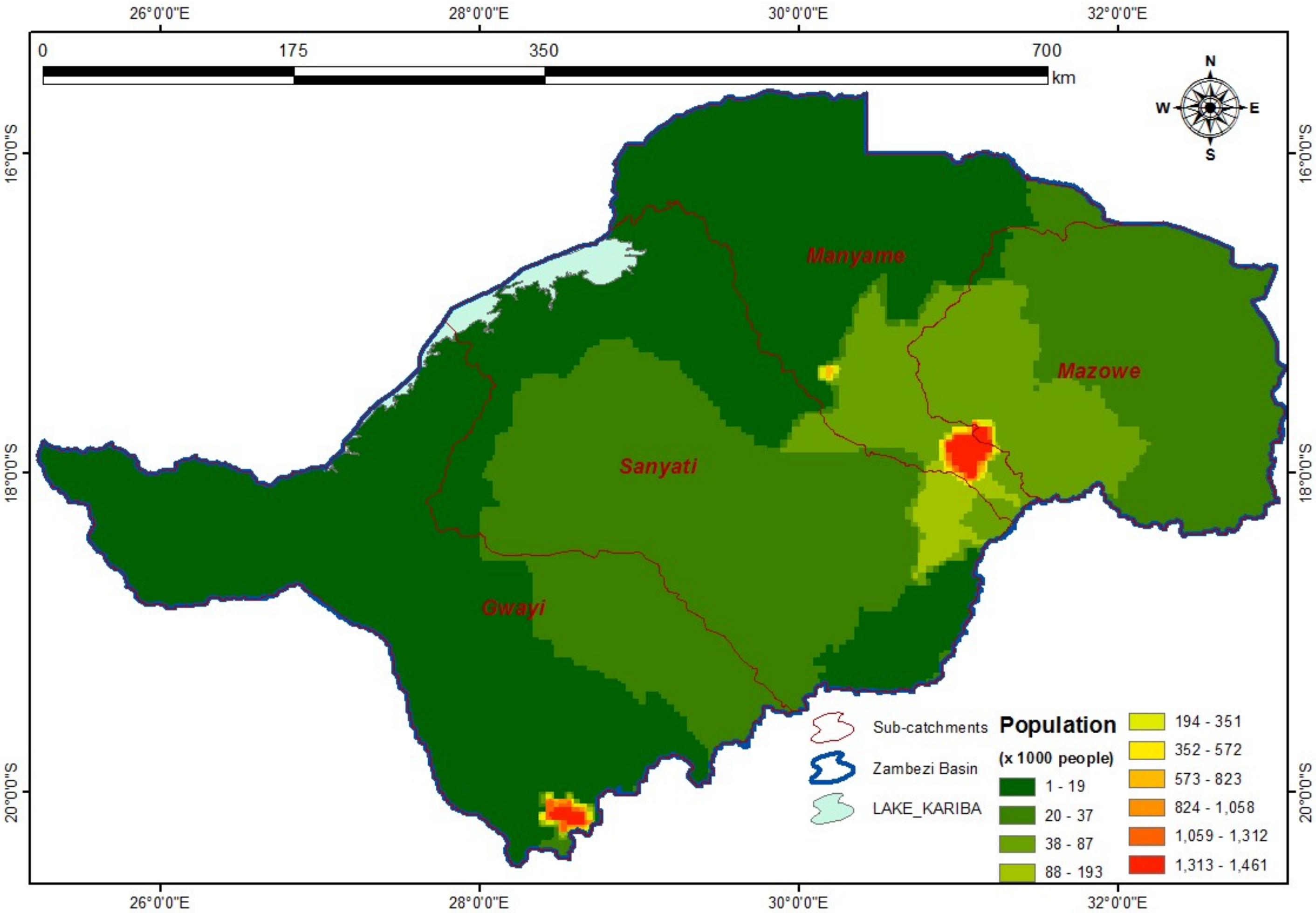

Fig 3.22 Population distribution in the ZRB in Zimbabwe (Source of data: Zimstat, 2012)

3.2 Groundwater availability in the ZRB in Zimbabwe

3.2.1 Estimating recharge for the ZRB in Zimbabwe

Good estimates of the recharge rate in the aquifer units are required to estimate the water that can be safely extracted from ground water sources in the ZRB. In data scarce areas, various techniques have been used to estimate recharge to aquifers. One of the methods that may be applied is to estimate the recharge as a proportion of the precipitation. Bonsor and MacDonald (2010) found a strong linear relationship between rainfall and recharge ($R^2 = 0.73$) in basement aquifers and in regions with rainfall higher than 500 mm/year, but a nonlinear relationship in sedimentary aquifers. Due to the high potential evapotranspiration of up to 2000 mm in the low lying areas (FAO 2016), groundwater recharge occurs mainly during high intensity rainfall events (De Vries and Simmers, 2002). As such, total annual rainfall may not be a good predictor of annual recharge for parts of the Zambezi basin (Wang et al., 2010).

Recharge estimation studies within the sub basins are few, and according to the SADC GMI database, the recharge rate for the country is 20-100 mm per annum. Sibanda et al. (2009) estimated recharge of the Nyamandlovu aquifer to be 15-20 mm per year based on the chloride mass balance method, water-table fluctuation method, Darcian flownet computations and groundwater modelling. This value is equivalent to just 2.7 – 3.6 % of the annual precipitation of the area. Therefore, in the absence of recharge studies for this area, recharge values were estimated from the WetSpass Model.

The recharge for the ZRB in Zimbabwe was estimated using WetSpass Model presenting the Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001). It is a physically based model for the estimation of long-term average spatial patterns of groundwater recharge, surface runoff and evapotranspiration employing physical and empirical relationships.

Inputs for this model include grids of landuse, groundwater depth, precipitation, potential evapotranspiration, wind-speed, temperature, soil, and slope where by parameters such as land-use and soil types are connected to the model as attribute tables of their respective grids (Batelaan and De Smedt, 2007).

The total water balance of a given area is thus calculated as the summation of the water balance of each raster cell as below:

$$ET_c = a_v ET_v + a_s E_s + a_o E_o + a_i E_i$$

$$S_c = a_v S_v + a_s S_s + a_o S_o + a_i S_i$$

$$R_c = a_v R_v + a_s R_s + a_o R_o + a_i R_i$$

Where: the index c refers to raster cell, with ET_c, S_c and R_c [L] respectively, the total evapotranspiration, surface runoff and recharge in a raster cell and a_v, a_s, a_o and a_i respectively the vegetated, bare soil, open water and impervious area fractions of a raster cell.

In this study, the model was applied over a period of 20 years, based on the availability of data particularly the groundwater levels. Fig 3.23 shows the average estimated direct recharge in the ZRB in Zimbabwe. From the model, the average recharge annually ranges between 90-240 mm. In general, high values of groundwater recharge are observed in the bare-and cultivated land with permeable sandy and loam soils and with highly fractured sandstones in the western regions. Areas with shallow groundwater depth and surface water normally have low recharge because the subsurface is high saturated.

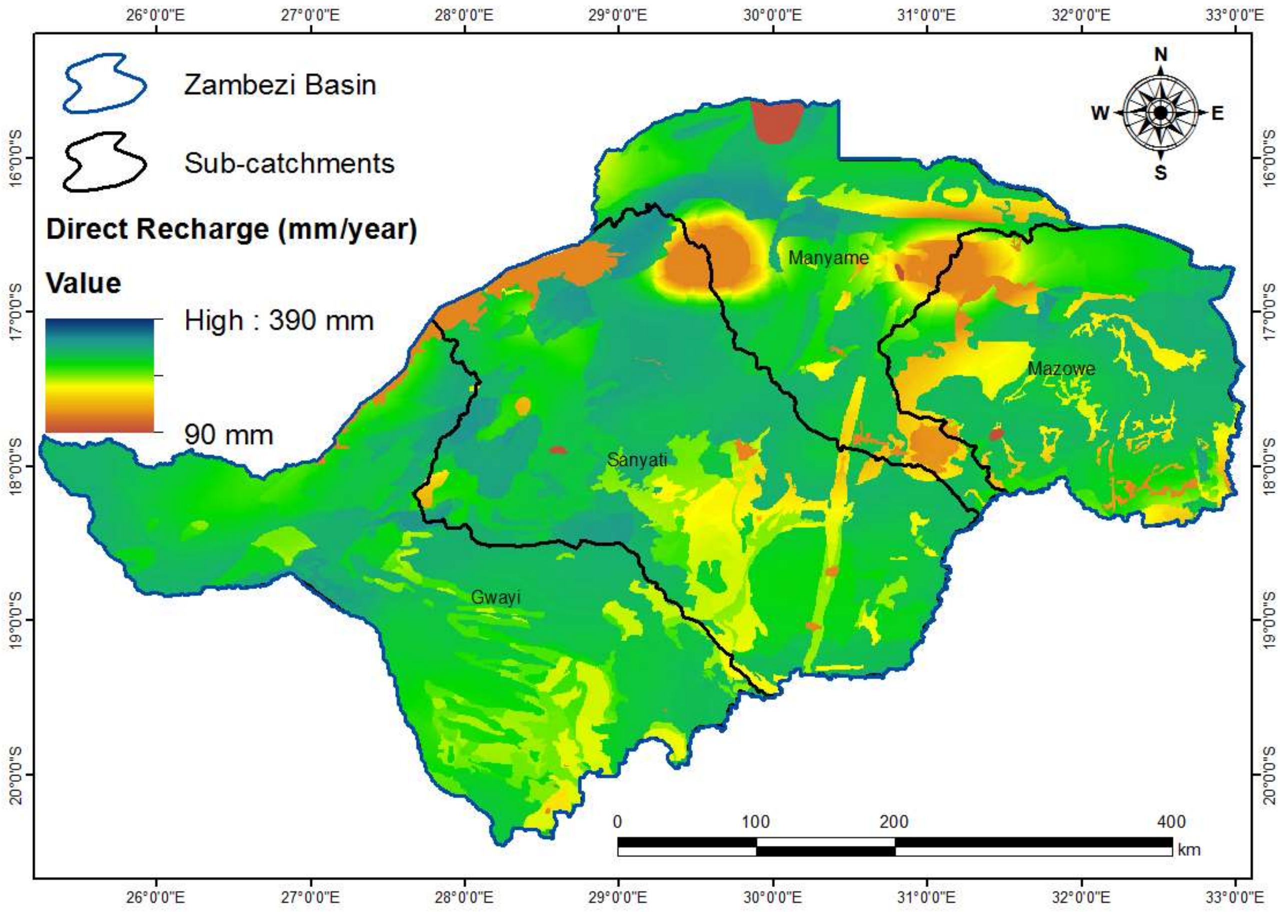

Fig 3.23 Direct recharge map for ZRB in Zimbabwe estimated from WetSpass model.

An analysis of the groundwater-surface water connectivity show that many of the rivers in the different sub-basins are non-perennial with very little base flow contribution to the overall surface runoff. Estimates of base flow indices were made by ZINWA (2006), using the smoothed minima techniques as demonstrated by Bullock et al. (1997) and Mazvimavi et al. (2004). Within the ZRB in Zimbabwe, base flow indices range from 0.05 to 0.40. The highest base flow indices, which indicate the highest groundwater contribution to surface water, were recorded in the alluvial deposits of the Gwayi catchment and the upper regions of both the Manyame and Mazowe catchments.

3.2.2 Estimating safe yield for the ZRB in Zimbabwe

Safe yield may be defined as the accomplishment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge (Sophocleous and Sawin, 1997). Safe yield may also be defined as the maximum abstraction of an aquifer that does not exceed the recharge from precipitation and surface water infiltration. However, this definition of safe yield ignores the fact that over long periods under equilibrium conditions, natural recharge is balanced by discharge from the aquifer into streams, springs and by evapotranspiration (Sophocleous, 2000). Consequently, if abstraction equals recharge, eventually streams, marshes and springs may dry up. According to Sophocleous (2000), groundwater losses can be accounted for by making the safe yield slightly less than the average annual recharge. Maxwell et al., (2012) suggest that provision be made for losses and natural ecosystem maintenance requirements by estimating safe yield to be less than annual recharge by a factor of safety of 0.6.

As Fig 3.24 shows, borehole yields in the ZRB in Zimbabwe range from 105,000 litres/day in the basement aquifers (Manyame and Mazowe Catchments) to over 2,000,000 litres/day in the dolomite aquifers (Sanyati Catchment). High yields are also obtained in the Gwayi catchment within the sands and sandstone.

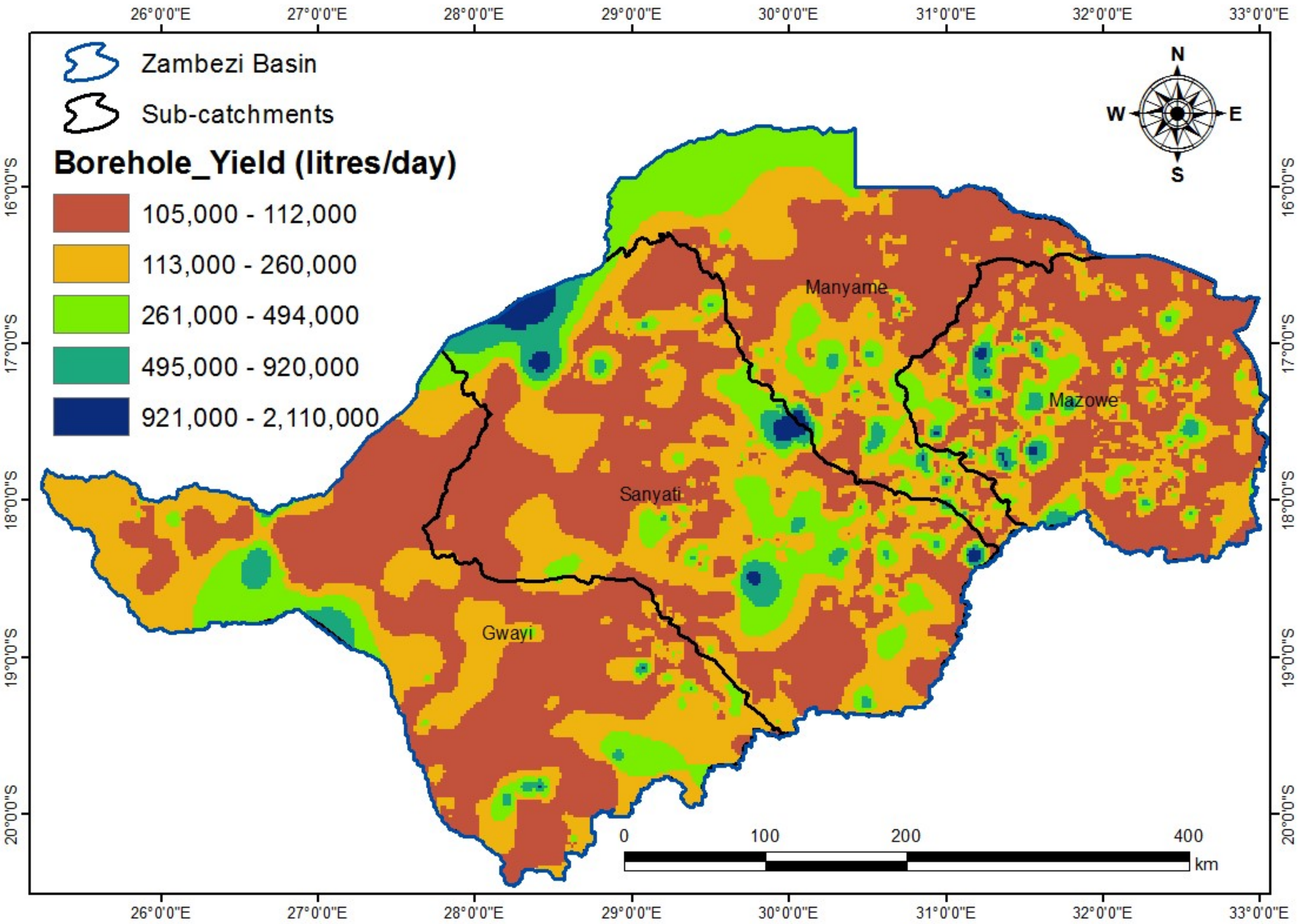

Fig 3.24 Borehole Yields in the Zambezi River Basin in Zimbabwe (Data Sourced from SADC-GMI, 2010)

3.3 Water-Energy-Food-Energy nexus perspective of groundwater availability vs groundwater demand in the ZRB in Zimbabwe

An analysis of the availability of groundwater was surrogated by borehole yields which are dependent on the recharge of the aquifers. The yield of boreholes in the ZRB in Zimbabwe was estimated as ranging from 105 m^3 per day to 2110 m^3 per day (Fig 3.24). The analysis of demand for groundwater was estimated using population distribution in the ZRB in Zimbabwe and was estimated to range from 92 m^3 per day to 135 815 m^3 per day depending on the population in the area. Comparison of the borehole yields and the estimated demand show that the available groundwater is not adequate for the needs of the population in the ZRB in Zimbabwe. However the analysis of primary water sources in the selected districts revealed that ground water can be accessed through boreholes, deep wells, shallow wells, springs and sand abstraction and the estimated quantity of available groundwater was only from the yield of boreholes and groundwater can be accessed by other means and be available to satisfy the demand.

From a Water-Energy-Food-Ecosystem nexus perspective, availability of groundwater is related to the modes of accessing the groundwater as energy is required to access the groundwater. Most rural communities use boreholes, deep wells, springs (where available) and shallow wells for primary water as the technology of accessing the water only requires mechanical energy of the person accessing the water. For sand abstraction to yield reasonable amounts of water there is need for more sophisticated pumping systems requiring energy sources such as electricity or fuels, therefore this method of accessing water is only restricted to communities who can get funding for such technologies.

In the ZRB in Zimbabwe, water has multiple uses which include the generation of electricity at Kariba dam. Recent periodic droughts that hit the basin in the past few years had an impact on the generation of electrical energy at the dam. According to Hamududu and Killingtveit (2016) hydropower generation declined in 2015 in the basin due to drought. With a specific focus on Kariba dam, the potential annual electrical power generation was reduced by more than 50 percent in 2015 (ZAMCOM 2016). The droughts have made the Zambezi River Authority (ZRA) to reduce water allocations to the Zimbabwe Power company (ZPC) from 19 billion cubic metres to 16 billion cubic metres for 2019. According to ZPC, the move was to enable the plant to be operational until next rainy season (New Zimbabwe 9 May 2019). In light of this, it can be noted with concern that recurring droughts in the ZRB in Zimbabwe have a negative effect on water availability in the basin’s reservoirs which in turn influence energy production. Reduced electrical energy production at Kariba dam has an effect on food production which is a component of the WEFE nexus. Agriculture has an important role in the ZRB Zimbabwe and is central to the livelihoods of the rural poor (World Bank 2008). Food production primarily through agriculture is hampered due to lack of electrical energy that is required for irrigation. Groundwater for irrigation has to be pumped from the source and onto the fields. The crops at risk are the winter crops such as wheat which sorely rely on irrigation. With the country’s power utility company Zimbabwe Electricity Supply Authority (ZESA) Holdings introducing a massive daily 17-hour electrical energy load-shedding programme (The Independent, 5 July 2019), most farmers were adversely affected. In the basin, electrical energy is also required to produce agricultural inputs such as seed, fertilisers and agrochemicals (ZAMCOM 2017). Industries in the ZRB, Zimbabwe currently (2019) are not able to produce these agricultural inputs at their full capacity due to the long load shedding periods. Therefore the availability of groundwater in the ZRB in Zimbabwe for food production and other community needs depends on the availability of energy which in turn depends on availability of water resources.

4.0 ASSESSMENT OF VULNERABILITY OF THE GROUNDWATER IN ZRB IN ZIMBABWE TO CONTAMINATION

4.1 Baseline Conditions of Water quality in ZRB in Zimbabwe

Generally data on ground water quality is pertinent as it determines the suitability of the available ground water for intended uses. Since ground water in the ZRB in Zimbabwe is the major source of domestic water in rural areas and growth points, water quality data is fundamental in safeguarding human health. This is also of importance as urban areas in the basin have in the recent years increased their demand of ground water. Regarding ground water sources in urban areas, water quality is of interest due to various urban activities that render the water source vulnerable to pollution. The concentration of industrial, agricultural and social activities within the Zambezi River Basin in Zimbabwe makes it of prime importance to the country. However, these activities are a potential source of contaminants of groundwater resources. Groundwater contamination has become one of the serious environmental problems in the world because once polluted it is very difficult to remediate (Samake et al. 2011). Despite the importance of ground water quality data, in the ZRB in Zimbabwe such information is limited. Literature has shown that data on water quality is mainly on surface water sources.

The natural ground water quality in the ZRB in Zimbabwe like the rest of the country is generally considered to be of good quality. The natural localized areas with poor groundwater quality are associated with poor groundwater circulation in confined aquifers, poor recharge in arid areas and hyper-saline paleo-groundwater (Ministry of Environment Water and Climate, 2014). In the ZRB, Gokwe North and Hwange districts have geogenic groundwater fluoride. According to the Ministry of Environment Water and Climate (2014) salinity in the ZRB in Zimbabwe is presumably associated with deep groundwater in the escarpment fault zone and in the deep Kalahari in north west Zimbabwe, likely related to the evaporate sequences in the Kalahari beds.

Apart from the natural causes of ground water pollution in the ZRB in Zimbabwe, numerous anthropogenic causes also exist. In major cities such as Harare and Bulawayo, ground water utilization is high in areas not connected to municipal water supply systems. Previously nonconnection of households and establishments to municipal water supply was mainly found in informal settlements. However, this is now also a characteristic of many new planned settlements. In these areas bacteriological contamination of ground water sources is a challenge due to high usage of on-site sanitation systems such as pit latrines. The use of other onsite sanitation systems such as septic tanks has also contributed to groundwater pollution especially where the stand sizes are small and where the sanitation systems are wrongly sited in relation to groundwater sources. A study by Sinandima (2013) showed that ground water quality in Epthworth- Harare was attributed to poor sanitation practices and indiscriminate dumping of solid waste. The study results on microbial water quality indicated that the water was generally unfit for drinking according to the WHO guidelines.

In urban areas groundwater quality is also under threat from wastewater pipes bursts. In Bulawayo, total coliforms and faecal coliforms which pose a threat to human health were found in 27% and 8% respectively of the sampling sites drawn from the Matsheumhlope basement aquifer (Mangore and Taigbenu 2004). Recently the cholera cases in Harare in September 2018 were also blamed on wastewater pipes bursts which contaminated ground water sources exposing people to water borne diseases. In the upper part of Manyame catchment, field evidence has revealed that bacteriological contamination of ground water sources in rural areas (Chihota Communal Lands) is from pit latrines (Dzwairo et. al. 2006). This could be the case with other rural settings in the basin.

Indiscriminate solid waste disposal in urban cities in the ZRB in Zimbabwe is also another source of groundwater pollution. Even where dumpsites are designated, most of them are poorly constructed and poorly managed without impermeable linings and leachate collection as well as treatment facilities (Ministry of Environment Water and Climate, 2014). Sinandima (2013) noted that the use of dumpsites in Epworth was a threat to ground water quality in the area. In the Upper Manyame Catchment, Misi et al (2018) concluded that samples of ground water which were characterized by metallic compounds suggested pollution from mineral dissolution into aquifers from sources such as dumpsites. This was evidenced by samples which were collected from boreholes close to Golden Quarry Dumpsite. The impact of dumpsite leachate on groundwater quality was also noted by Love et al (2006). Poor solid waste management practices such as illegal dumpsites and poorly engineered and decommissioned landfills are also another major source of groundwater pollution in urban areas (Kibena et al., 2013). Furthermore, in major urban centres such as Harare and Bulawayo, the mushrooming of unserviced settlements is posing a threat on groundwater sources. This is because, these settlements rely on onsite sanitation systems such as pit latrines and in some cases poorly designed septic tanks there by affecting the biological quality of groundwater sources (Sinandima 2014; Vushoma 2016).

In the ZRB in Zimbabwe, patchy sources of information available show that industrial activities have a negative impact on ground water quality. Industries generate effluent and other toxic waste and in many cases such waste is not properly treated. Chemical industries, such as Chemplex and ZimPhos in Harare, leather tanneries in Harare and Bulawayo, and industries that use large volumes of water and discharge bulk effluent back into the drains, such as the dairy industry, all contribute to groundwater quality degradation (Ministry of Environment, Water and Climate, 2014). Nhapi and Tirivarombo, (2004); GoZ, (2011); and Masere et al.(2012) observed that partially treated effluent, sewer leakages and industrial effluent are major sources of ground water pollution in Harare (Manyame) while similar findings were also revealed by Mukumbuzi (2018) in Bulawayo (Gwayi).

With a focus on the mining industry, most mines have open shafts, waste rock dumps and tailings dams with exposed sulphide minerals, making them susceptible to Acid Mine Drainage (AMD). AMD is the formation and movement of highly acidic water rich in heavy metals, caused by the weathering of pyrite (Gray 1997). Whenever pyrite is exposed to air and water (leading to oxidation and hydrolysis), it produces sulphuric acid which in turn dissolves heavy metals in the rock, hence it is characterized by high concentrations of dissolved heavy metals, sulfates and low pH (Gray 1997). When these are in solution they are mobilized to enter the surface and groundwater sources thereby threatening water quality. In the ZRB, Gwayi catchment in particular Hwange district has its ground water sources vulnerable to AMD. In a study done by Mucheriwa (2016), water in Deka River in Hwange was found to be an environmental hazard as it was above the Environmental Management Agency standards and using US EPA standards it was concluded that Deka River is severely impacted by AMD. Although the study focused on surface water, in the absence of ground water quality data, the quality of the surface water source can be used as a proxy of the ground water quality considering the phenomenon in question.

In Mazowe and Sanyati catchments groundwater is also under threat from mining activities although the ground water quality data is not available. For example the high prevalence of artisanal gold miners in the Sanyati catchment has potential negative impacts on ground water quality coupled by high usage of mercury and cyanide as well as poor environmental management practices. In the Mazowe catchment the existence of the Trojan Nickel Mine, Shamva Gold Mine, Mazowe Gold Mine among others should not be underestimated as potential sources of ground water pollution. In these areas studies done by Ravengai et al (2005) and Lupankwa (2006) showed the impact of the mining activities on surface water sources in rivers such as Yellow Jacket and Mazowe and Pote. In the Upper Sanyati catchment, water samples from boreholes located in areas where mining, mineral processing and agricultural activities recorded high values above WHO standards of toxic metals (Madebwe et al 2015).

Intensive agricultural practices are also widespread in the basin which pose imminent threats to groundwater resources since some of the agricultural activities are located close to wells and boreholes. It was revealed by UNEP (2006) that increased use of pesticides and fertilizers, to increase food production significantly increase groundwater pollution. Mining towns in the basin such as Shamva, Bindura, Mazowe and Hwange also pollute ground water sources due to Acid Mine Drainage (AMD). Evaluation of more than fifty mine dumps within the Zambezi Basin, Zimbabwe, suggests that the major environmental risks come from release of acidity, arsenic, zinc, copper, cobalt and nickel into soils and streams draining the dumps. This was confirmed by detailed case studies on six mines, which showed cases of ultra-acidic mine drainage (Iron Duke), controlled acid mine drainage (Arcturus), significant transition metal releases (Madziwa, Mvuma and Trojan), and problems with antimony (Beatrice) and arsenic (Athens) (Love et al., 2006). In addition, recent studies in Hwange by CNRG (2017) show that coal mining by Hwange Colliery, Makomo, Chilota, WMK & Coalbricks mines has resulted in the contamination of ground water sources. AMD produced by the leaching of sulphide minerals present in the coal has had a direct impact on drinking water quality, as it has become too acidic and is not suitable for domestic use (CNRG, 2017). The same study also revealed that, the erosion of stockpiles at Chilota mine has led to sedimentation at the nearby Dheka River and coal dust settling on surface water leaches into ground water sources. Rural areas in the basin rely on onsite sanitation systems which also affect ground water sources. This has been a challenge where the sanitation facilities are poorly sited and where water tables are high.

Given that ground water constitutes a significant portion of water sources in the basin, conservation and protection of these water resources is of central importance in Zimbabwe. To promote effective groundwater resource planning and management, knowledge of groundwater vulnerability to pollution and any vulnerability information is essential. This chapter aims to assess the vulnerability of the groundwater in ZRB to contamination. Although data availability is a challenge in the basin, the existing limited data was used to derive a generalised assessment of groundwater vulnerability in the basin.

4.2 Ground Water Vulnerability

All aquifers are vulnerable to contamination to a greater or lesser extent and in either short or long term (Maia and Cruz 2013). For this reason, the establishment of a surveillance network for monitoring the extent of aquifer pollution, through aquifer vulnerability assessments, becomes key to effective groundwater protection (Morris et al., 2003). The concept of groundwater vulnerability to contamination was introduced in the 1960s in France (Alwathaf, 2011). Kuisi et al. (2014), defined groundwater vulnerability as a measure of the risk placed upon groundwater by human activities and the presence of contaminants. Groundwater vulnerability to contamination is based on the concept that the physical environment can provide protection to groundwater against natural and human impacts with respect to contaminants in the groundwater (Baalousha, 2006). Foster et al. (2013), defined “specific vulnerability” as accounting for anthropogenic activities that cause contaminates to reach the subsurface and “intrinsic vulnerability” as natural risk to contamination based on the physical characteristics of the environment. According to Eskom (2014), when natural factors provide little protection to shield groundwater from contaminates groundwater vulnerability becomes high and when natural factors provide good protection, little contamination will occur hence groundwater vulnerability is low.

Groundwater vulnerability analyses and delineates areas which are more susceptible to contamination, hence assisting in the remediation, protection or prevention of further groundwater degradation (Foster et al., 2002). In light with this, direct regulatory, monitoring, educational and policy development efforts can be prioritised to those areas where they are most needed for the protection of groundwater quality (Foster et al., 2002). Highly sensitive zones can then be targeted as opposed to applying universal protection measures to an entire aquifer (Maia and Cruz, 2013). In ground water vulnerability assessment, the development of vulnerability maps is useful for prioritization of areas for protection, community education and development of risk assessments.

4.3 Methods of assessing vulnerability of groundwater to contamination

Groundwater vulnerability assessment involves the spatial distribution of contamination occurrence in an area but does not specify the actual pollutant that could contaminate the groundwater aquifer (Saatsaz et.al, 2011). Localised vulnerability assessment involves monitoring groundwater quality for specific pollutants. Where the area of interest is a river basin, these localised methods become expensive and cumbersome, therefore aquifer vulnerability mapping techniques become more applicable (Jang et.al, 2017). Researchers have developed several groundwater vulnerability assessment methods which are divided into three categories. The three categories are overlay and index methods, methods employing process-based simulation models and statistical methods (Anthony et al., 1998). Of all the methods that are available, the DRASTIC model which falls under the overlay and index category, is the most popular vulnerability mapping method. The Model was used in South Africa (Musekiwa and Majola, 2013), Nigeria (Omosuyi and Oseghale, 2012), Canada (Liggett and Talwar, 2009) and Zimbabwe (Vushoma, 2016 and Misi, 2016), among other countries. DRASTIC is an acronym for Depth to water table, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and Conductivity.

The DRASTIC mapping model allows the pollution potential of any area to be evaluated systematically using existing information. It can spatially and comparatively display areas of low and high vulnerability with respect to the potential to pollute groundwater, making it an important tool for groundwater planning and decision making (Aller et al. 1985). Vulnerability to contamination is a combination of hydro-geologic factors, anthropogenic influences, and sources of contamination in any given area. The DRASTIC system focuses only on those hydro-geologic factors that influence groundwater pollution potential. The system consists of two major elements: the designation of hydrogeologic settings, and the superposition of a relative rating system to determine pollution potential. In order to reflect the relative importance of these parameters (Depth to water table, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and Conductivity), weights in the scale of 1–5 are assigned to each of these parameters (Kumar et al., 2014). In addition, the seven hydrological parameters are also assigned ratings in the range of 1-10.

4.4 Assessment of Groundwater vulnerability in the ZRB in Zimbabwe

For the ZRB in Zimbabwe where data availability was a challenge, the DRASTIC model was applicable since it can be used even where data is limited (Piscopo, 2001). Therefore, in this study available data was used to come up with a generalised ground water vulnerability assessment for the ZRB, Zimbabwe.

4.4.1 Model inputs

The inputs to the DRASTIC model used in the assessment of groundwater vulnerability in ZRB in Zimbabwe are described in Table 4.1. The sources of data for the inputs are also indicated in Table 4.1.

Table 4.1 Model inputs used to compute the Drastic Vulnerability Index for ZRB in Zimbabwe

Parameter	**Source**
Topography, DEM	• Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topography Mission (SRTM).
Landuse	• Landsat 8 • DIVA-GIS (https://www.diva-gis.org)
Groundwater level	• IGRAC (International Groundwater Resources Assessment Centre)
Depth to water	• SADC GMI
Soil	• Geological Survey of Zimbabwe
Rainfall	• The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (https://globalweather.tamu.edu/) • Meteorological Services Department of Zimbabwe
Wind speed	• The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (https://globalweather.tamu.edu/) • Meteorological Services Department of Zimbabwe
Temperature	• The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (https://globalweather.tamu.edu/) • Meteorological Services Department of Zimbabwe
Potential evapotranspiration	• Calculated using Thornthwaite Formula and Penman-Monteith
Runoff	• WetSpass - Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001)
Recharge	• WetSpass - Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001)
Runoff	• WetSpass - Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001)
Actual evapotranspiration	• WetSpass - Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001)
Interception	• WetSpass - Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001)

The model inputs were processed in GIS using ArcMap 10.3.1 software to create the Drastic Vulnerability Index map. The numerical index was derived from ratings and weights assigned to each of the six model parameters. In this report, the vulnerability index is depicted in thematic maps with areas classified as low or high vulnerability. The DRASTIC Vulnerability index (DVI) was calculated as the sum of product of ratings and weights assigned to each of the parameters on the scale of 1 to 10 and 1 to 5 respectively. Weights and ratings were assigned to each of the seven parameters according to the guidelines from previous studies such as Saatsaz et.al (2011). The weight of each parameter denotes the importance of the parameter in determining the vulnerability of the aquifer. The weights range from 1 to 5 where, 1 is least significant and 5 is most significant. Higher values depict greater vulnerability to groundwater contamination. The DRASTIC indices were calculated by multiplying weight and rating for each DRASTIC parameter, then computed using linear summation according to Equation (Eq4.1) (Aller *et al.,* 1987).

$$DVI = 5D_r + 4R_r + 3A_r + 2S_r + T_r + 5I_r + 3C_r \qquad \text{Eq4.1}$$

Where;

Dr = Rating for the depth to water table

Rr = Rating for aquifer recharge

Ar = Rating assigned to aquifer media

Sr = Rating for the soil media

Tr = Rating for topography (slope)

Ir = Rating assigned to impact of vadose zone

Cr = Rating for rates of hydraulic conductivity

4.4.2 Depth to water

The static water level map was converted to raster format. The raster dataset was then reclassified according to the categories shown in Table 4.2. Each static water level was assigned a DRASTIC rating as depicted in Table 4.2. The depth to water is related to the travel time within the aquifer media, the greater the depth the greater the attenuation of contaminants from the surface.

Table 4.2 DRASTIC rating for depth to water in the ZRB in Zimbabwe

Static water Level (m)	**Rating**	**Weight**	**Total Weight**
0 - 2.5	10	5	50
2.5 – 4	7		35
4 – 6.5	5		25
6.5 – 9	3		15
>9	1		5

(Ratings and weights assigned according to guidelines from Saatsaz et.al (2011)).

4.4.3 Aquifer Media

In the absence of borehole logs in the basin, the aquifer media was assumed to be closely related to the surface geology. The geological map (Fig 2.3) was converted to raster format then reclassified according to the geological era. Figure 4.1 shows the dominant geological groups that were used as proxy for aquifer media. As Figure 4.1 shows, the Gwayi Catchment is dominated by recent cover rocks such as red grit, sandstone, siltstones and alluvium. Mazowe Catchment and the southern parts of Manyame and Sanyati Catchments are almost entirely covered by the older intrusive gneisses and paragneisses.

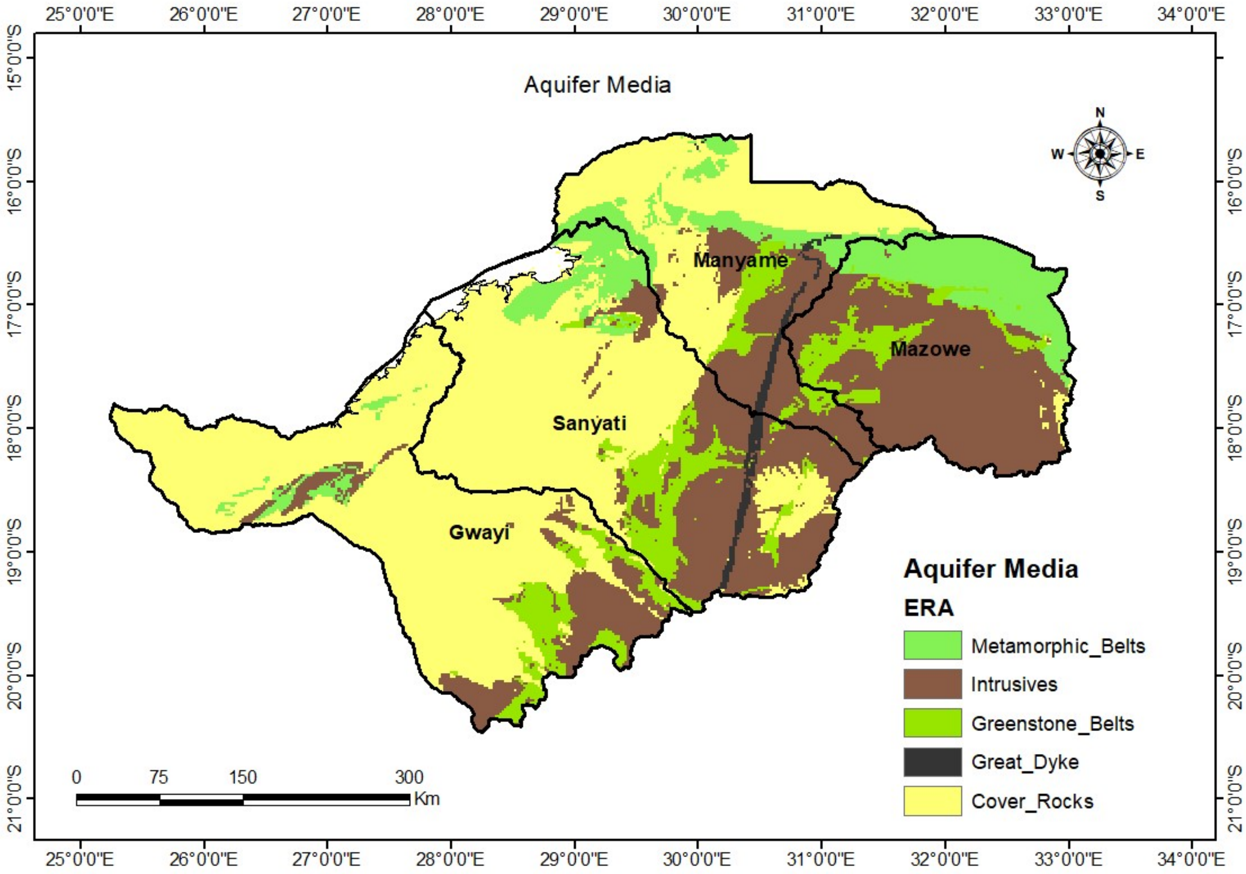

Fig 4.1 Aquifer media in the Zambezi Basin (generated from Fig 2.3)

The ratings for the different rock types presented in Fig 4.1 were assigned as shown in Table 4.3. A higher rating was assigned to the cover rocks while the intrusive rocks were assigned a low rating as they are generally impermeable unless weathered.

Table 4.3 Drastic rating for aquifer media in the ZRB in Zimbabwe

Geological group	Rating	Weight	Total Weight
Cover Rocks	9	3	27
Intrusive	1		3
Greenstone belt	3		9
Metamorphic Belts	3		9
Great dyke	1		3

(Ratings and weights assigned according to guidelines from Saatsaz et.al (2011)).

4.4.4 Soil Media

Soil media influences the rate of infiltration of contaminants into the underlying saturated zone. The thickness of the soil layer also impacts the processes that attenuate contaminant transport in the vadose zone. The soil were classified in terms of textural classes in the Soil Survey Manual, (1951). Fig 4.2 is showing the textural soil map of the ZRB in Zimbabwe produced from analysis of the soil profiles done by Thompson, (1965) and the geological data.

The DRASTIC rating and weighting of soil media in the basin is shown in Table 4.4 highlighting the soil groups and soil types.

Table 4.4 Drastic rating for soil media in the ZRB in Zimbabwe

Soil Group	Soil types	Rating	Weight	Total Weight
Haplustalfs	Clay loams, clay silt	2		6
Kanhaplustalfts	Fine sandy loam, loamy sand	3		9
Ustorthents	Coarse sand	5		15
Rhodustalfs	Granular clay	1		3
Ustipsamments	Kalahari Sands	5		15
Pellusterts	Silty clay	2		6
Haplustox	Loamy sands	3		9
Haplustults	Coarse sands	5		15
Ochraqualfs	Grey coarse sands	8		24

(Ratings and weights assigned according to guidelines from Saatsaz et.al (2011)).

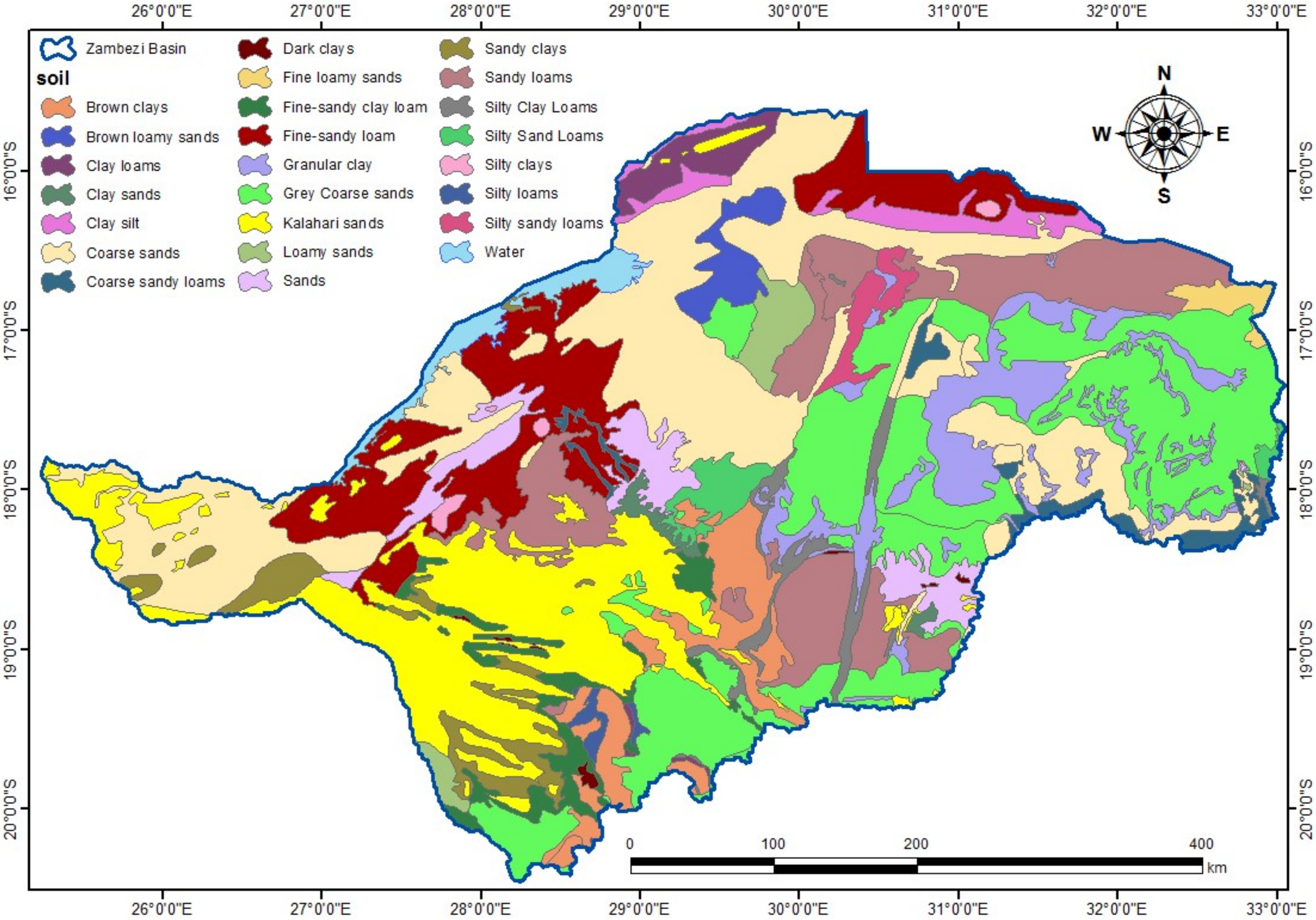

Fig 4.2 Soil types in the Zambezi Basin (Reclassified from Thompson, 1965)

The soil map was converted to raster format then reclassified according to Zimbabwe Soil Classification groups and Soil Great group as shown in Fig 4.3.

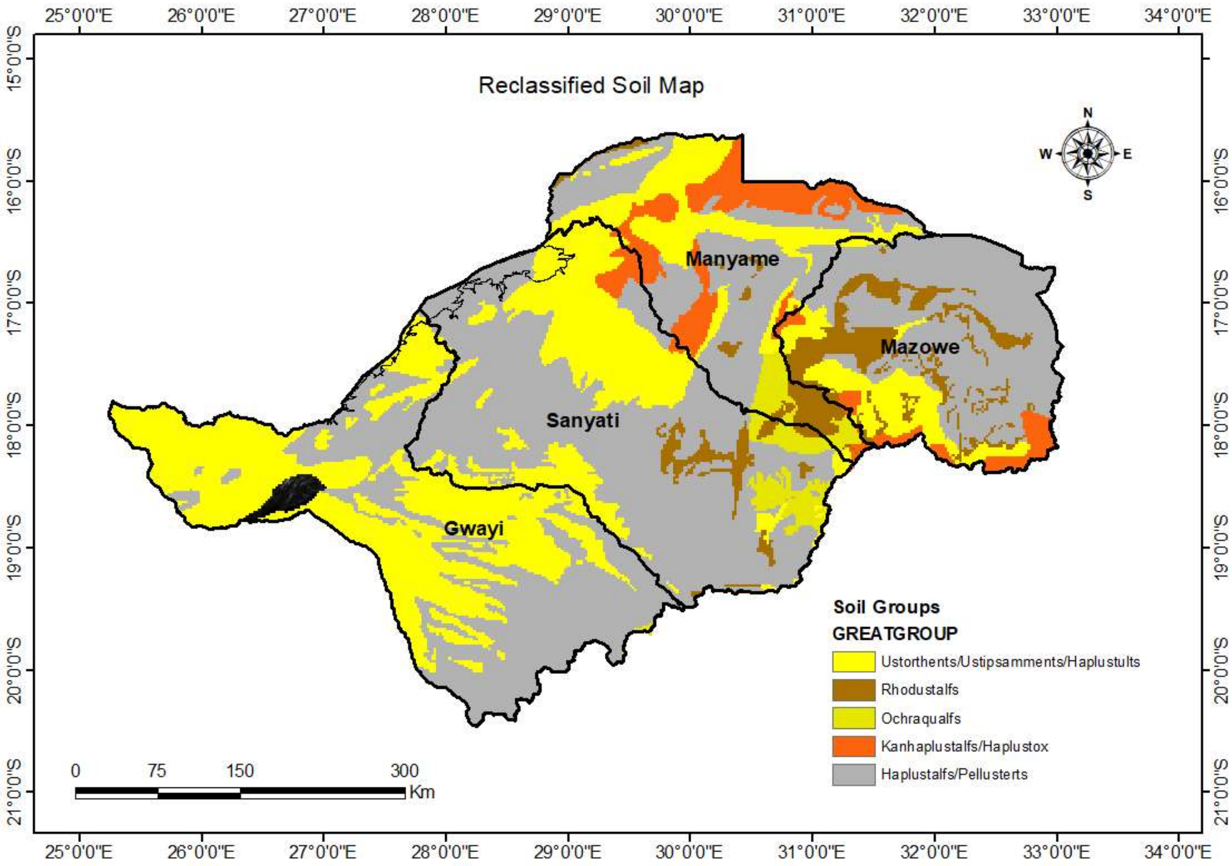

Fig 4.3 Major soil groups in the ZRB in Zimbabwe

4.4.5 Topography

In areas with gentle slope water may remain stagnant on the surface for a while allowing greater infiltration or recharge of water and thus a greater potential for contaminant migration. The digital elevation model was derived from SRTM data of the Zambezi basin. The slope of the area was derived with the 3D analyst tool. The digital elevation model that was used for the input to the model is shown in Fig 4.4.

4.4.6 Impact of the Vadose Zone

The vadose zone controls the path of contaminant particles to the aquifer system (Chitsazan and Akhtari, 2009). The media controls the attenuation process due to geological characteristics. Contaminant attenuation processes also occur within the unsaturated zone. The ratings are similar to the previously applied ratings for soil media. The DRASTIC Weighting for this parameter is 5.

4.4.7 Hydraulic Conductivity

The ratings and weight for hydraulic conductivity are shown in Table 4.5. Values range from 3m/day-380 m/day. The higher the hydraulic conductivity, the more vulnerable the aquifer to contamination.

Table 4.5 Drastic Rating for hydraulic conductivity in the ZRB in Zimbabwe

Hydraulic Conductivity (m/d)	**Rating**	**Weight**	**Total Weight**
0-7	1	3	3
7-16	3		9
16-32	5		15
32-70	7		21
70-150	9		27
>150	10		30

(Ratings and weights assigned according to guidelines from Saatsaz et.al (2011)).

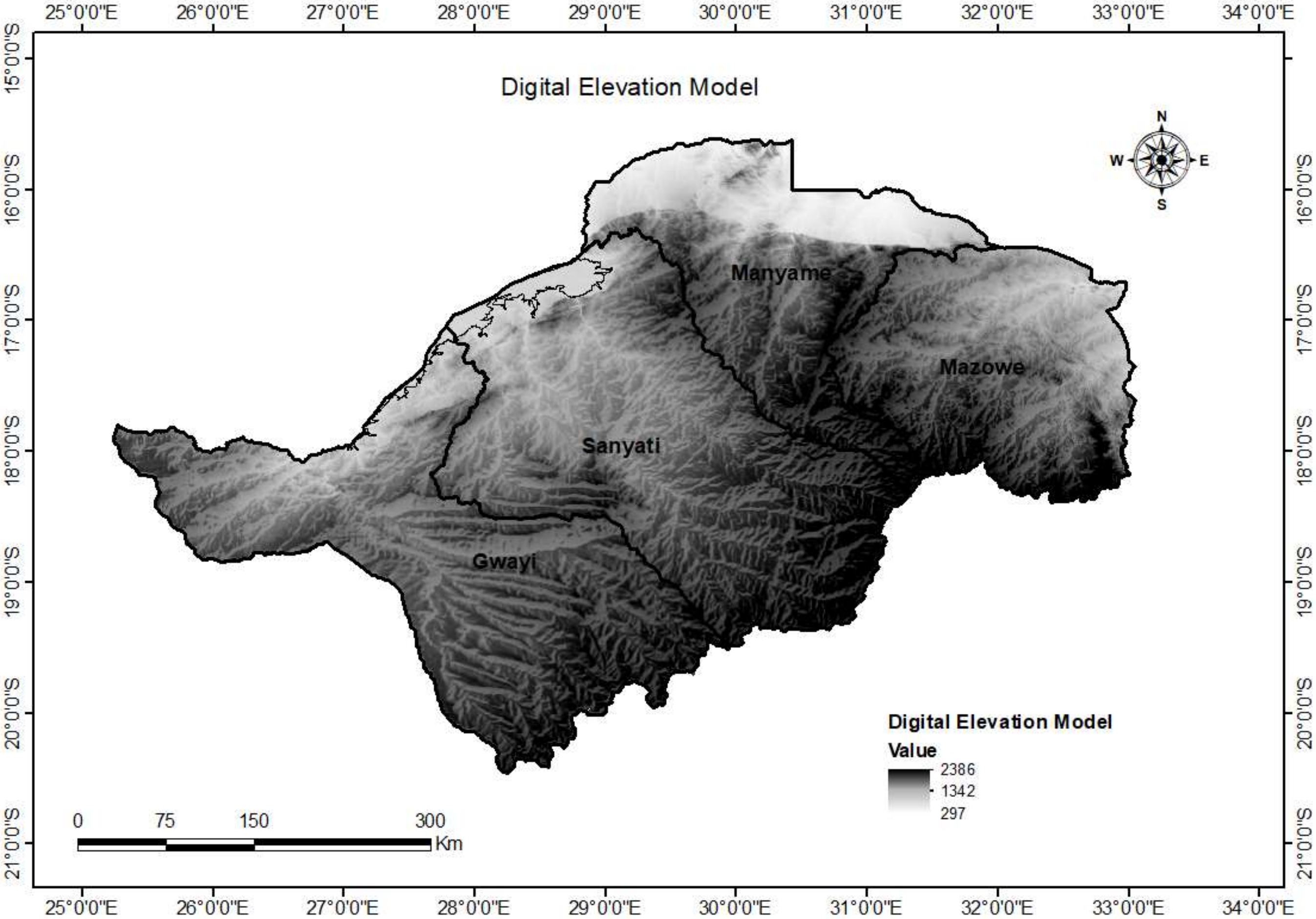

Fig 4.4 Digital Elevation Model for the ZRB in Zimbabwe

4.5 DRASTIC Vulnerability Index (DVI)

The DRASTIC Vulnerability Index map of the ZRB in Zimbabwe is shown in Fig 4.5. The model results depict high vulnerability to contamination in the Gwayi Catchment. A combination of high hydraulic conductivity of alluvial sands and shallow water table provide a favourable passage for contamination. The DRASTIC Vulnerability Index of the ZRB in Zimbabwe ranges from 23 to 138.

From the outset, Aller et al.(1987) did not prescribe vulnerability classification ranges, but left it to the discretion of the user to interpret the vulnerability index based on field knowledge and hydro geological experience (Gogu et al., 2003). A suggested vulnerability index classification system has five classes of vulnerability: very high vulnerability (vulnerability index >199), high vulnerability (160–199), moderate vulnerability (120–159), low vulnerability (80–119), and very low vulnerability (<79) (Gogu et al., 2003).

According to Liggett and Talwar, (2009), there are suggested action plans for the three vulnerability classes in this basin. For the Very Low Vulnerability area preparation of a standard format hydro geological report, showing hazards and risk to groundwater or the environment would be sufficient. Low vulnerability areas require limited site investigation with monitoring, testing, and delineation of flow system in addition to desk study. The medium vulnerability area warrants detailed site investigation and ongoing monitoring and protection.

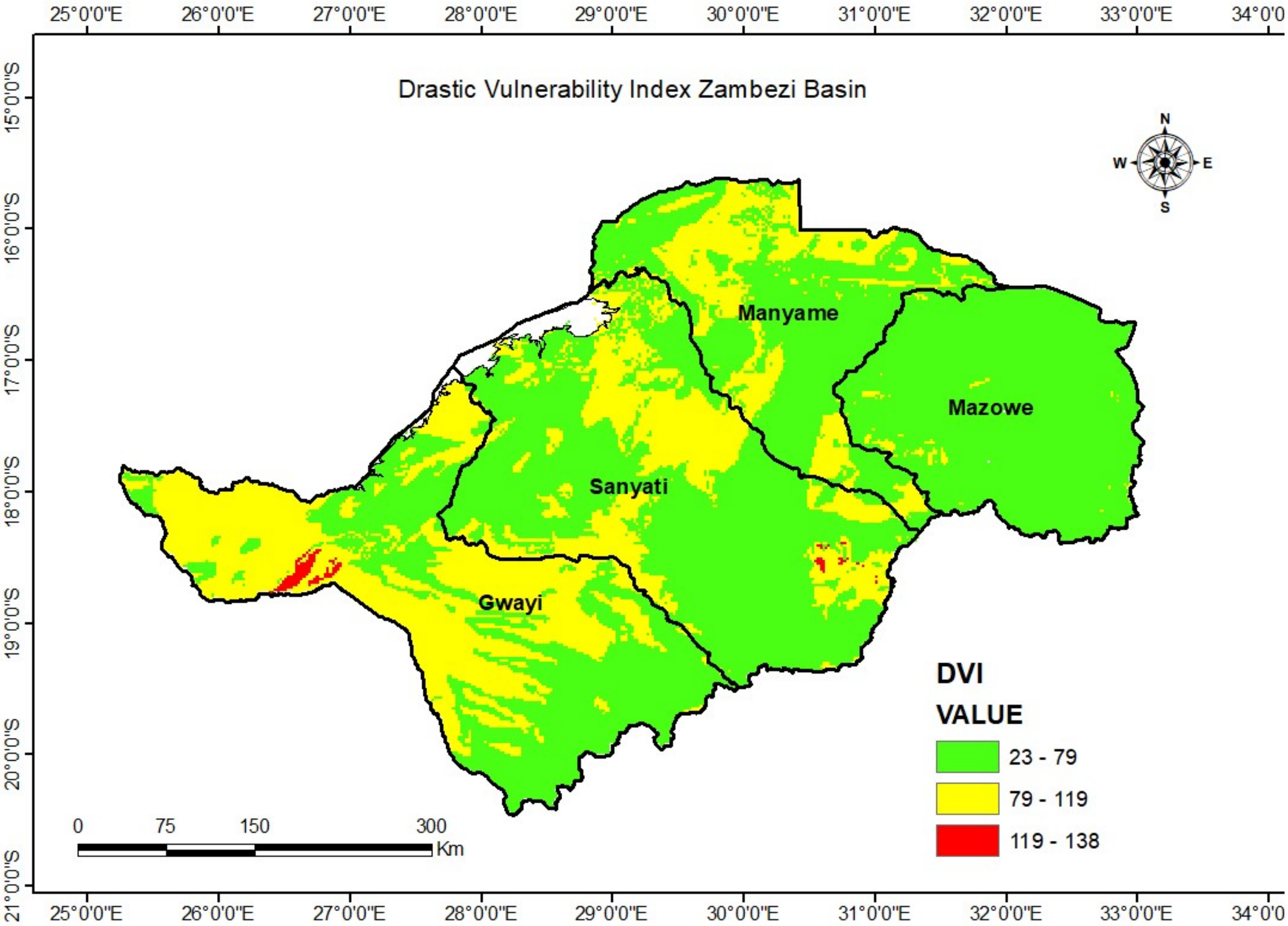

Fig 4.5 DRASTIC Vulnerability Index of the ZRB in Zimbabwe

4.6 Vulnerability of the groundwater to contamination and implications for WEFE nexus

The quality of the groundwater resources should render the water suitable for domestic, agriculture and other uses. The generalized vulnerability assessment shows that the groundwater in Zambezi River Basin in Zimbabwe is low to moderately vulnerable to contamination. The areas of moderate vulnerability such as Hwange in the Gwayi catchment are characterized by mining activities which are potential threats to the quality of the groundwater resources. The vulnerability assessment informs the WEFE nexus in that water for food and domestic use must be of acceptable quality and when this quality is compromised energy is required in treating this water to acceptable standards.

In the ZRB Zimbabwe, natural ecosystems play an important role in the fresh water supply to population, hence their inclusion in the nexus. However, due to a number of anthropogenic activities in the basin the natural ecosystems are under threat. Rapid urbanisation in major cities such as Harare have resulted in the construction of houses and industries on wetlands. This is against the background that wetlands are crucial in ensuring the capacity of ecosystems to purify water and reduce the vulnerability of the groundwater to contamination. In a study done by Mucheriwa (2016), Deka River in Hwange was severely impacted by AMD which affects the availability of surface water by aquatic ecosystems, industries as well as domestic users as well as the increased vulnerability of the groundwater to contamination by infiltration.

Unsustainable harvesting of woodfuel resources in the ZRB Zimbabwe also has disrupted the natural ecosystem. According to FAO (2014) disruptions to ecosystems, through unsustainable harvesting of woodfuel resources, will consequently impact the local availability of water. At the same time, a decreasing availability of water contributes to a decrease in woodfuel resources, therefore have multiple impacts on the nexus. Therefore, under the WEFE nexus there is need for suitable energy schedules and planning from hydropower facilities that cooperate with improved irrigation techniques and smart crop arrangements together with efficient energy use by industries and a holistic approach in planning and management of ecosystems in the ZRB Zimbabwe.

5.0 CONCLUSION

5.1 MAJOR BASELINE FINDINGS IN ZRB IN ZIMBABWE

5.1.1 Multi-scale groundwater hydrology baseline database at ZRB and Zimbabwe scale

- The geology of the Zambezi River basin in Zimbabwe is very well documented.
- However there is not enough data on aquifer properties such as their extent.
- The productivity of the ground water sources in the basin depend very much on the geology in the area and hence vary across the different catchments of the river basin as the geology varies.

5.1.2 Baseline conditions database on water demand vs. availability and quality

- The ZRB in Zimbabwe is generally rich in ground water resources.
- There is a high demand of groundwater in the ZRB in Zimbabwe as the communities in the basin are predominantly rural. An analysis of selected districts in the ZRB in Zimbabwe reveal that on average 82.5% of the households in the selected districts rely on groundwater as a primary source.
- Generally there is not enough data on groundwater quality in ZRB in Zimbabwe to inform suitability for human consumption and promote food production in the basin.
- Access to the groundwater resources is through boreholes and mechanical pumps are used in most cases in the rural communities (54% usage in the selected districts) except on commercial farms, National Parks and private urban homes where energy sources such as solar energy, fossil fuels (diesel, petrol) and electricity are used.
- The type of energy used to pump the ground water as well as its availability have a direct bearing on the amount of food produced from irrigated agriculture in the small scale and large scale commercial farming areas in the ZRB.

5.2 Assessment of vulnerability of the groundwater to contamination

- The generalized vulnerability assessment shows that the groundwater in Zambezi River Basin in Zimbabwe is low to moderately vulnerable to contamination.

- The areas of moderate vulnerability such as Hwange in the Gwayi catchment are characterized by mining activities which are potential threats to the quality of the groundwater resources.

5.3 Water-Energy-Food-Ecosystem (WEFE) nexus across the Zambezi River Basin in Zimbabwe

- Generally access to water, food, energy and ecosystem (WEFE) services are the four crucial elements for human well-being and they are intrinsically linked in the ZRB in Zimbabwe.
- The demand for water, energy, food and ecosystems services and goods is expected to increase in the whole ZRB due to demographic changes, economic growth and climate change.
- From a WEFE nexus perspective, availability of groundwater in the ZRB in Zimbabwe is related to the modes of accessing the water from the aquifers as energy is required to access the groundwater.

REFERENCES

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J. and Hackett, G. (1985) DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential using Hydrogeologic Settings, Environmental Protection Agency Report, NWWA/EPA Series EPA-600/2-87-035

Alwathaf, Y., Mansouri, B.I., (2011). Assessment of Aquifer Vulnerability Based on GIS and ARCGIS Methods : A Case Study of the Sana'a Basin (Yemen). Journal of Water Resource and Protection, 3: 845-855.

Anthony, J.T., Inkpen, E.L. and Voss, F.D. (1998). 'Assessing groundwater vulnerability using logistic regression', Proceedings for the Source Water Assessment and Protection 98 Conference, Dallas, TX, USA, pp.157–165.

Baalousha, H. (2006) Vulnerability Assessment for the Gaze Strip Palestine Using DRASTIC. Environmental Geology, 50, 405-414. http://dx.doi.org/10.1007/s00254-006-0219-z

Batelaan, O. and De Smedt, F., (2007). GIS-based recharge estimation by coupling surface-subsurface water balances. Journal of Hydrology, 337(3-4), 337-355, doi: 10.1016/j.jhydrol.2007.02.001"

Batelaan, O. and De Smedt, F., (2001). "WetSpass: a flexible, GIS based, distributed recharge methodology for regional groundwater modelling"

British Geological Survey (1989). The Basement Aquifer Research Project. Technical Report WD/89/15. British Geological Survey, Nottingham, UK.

Bullock, A., Andrews, A. and Mngodo, R., (1997). Regional surface water resources and drought assessment. In: Southern African FRIEND. Technical Documents in Hdyrology No 15, UNESCO, Paris.

Centre for Natural Resources Governance (CNRG) (2017). Environmental Impact Assessment Report for Hwange Mining Activities. Harare, Zimbabwe. http//coalaction.org.uk/why-not coal. (Accessed15 July 2019)

Davies B. R., (1986). The Zambezi River. In Davies B. R and K. F. Walker (eds), The Ecology of River Systems. Dr. W. Junk Publishers, Lancaster, UK.

Davis R and Hirji R (2014). Climate Change and Water Resources Planning, Development and Management in Zimbabwe. An Issues Paper. World Bank

De Vries, J.J., Simmers, I., (2002). Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal, 10, 5-17.

Dzvairo, B., Hoko, Z., Love, D., Guzha, E., (2006). Assessment of the impacts of pit latrines on groundwater quality in rural areas: a case study from Marondera District, Zimbabwe. Phys. Chem. Earth 31 (15–16), 779–788.

FAO. (2014). Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus. Environment and Natural Resources Management working paper No. 58. Rome, FAO. 150 pp. (Accessed 6 August 2019: http://www. fao.org/3/a-i3959e.pdf)

FAO. (2016). AQUASTAT website. Food and Agriculture Organization of the United Nations (FAO). Website accessed on [2018/11/18].

Focazio, M., Reilly, T.E., Rupert, M.G., Helsel, D.R., (2002). Assessing Groundwater Vulnerability to Contamination: Providing Scientifically Defensible Information for Decision Makers. US Dept. of the Interior: US Geological Survey Circular 1224. Retrieved from: http://pubs.usgs.gov/circ/2002/circ1224/pdf/circ1224_ver1.01.pdf (Accessed 12 July 2019)

Foster, S., Hirata, R., Andreo, B., (2013). The Aquifer Pollution Vulnerability Concept: Aid or Impediment in Promoting Groundwater Protection? Hydrogeology Journal, 21, 3, 13891392.

Foster, S., Hirata, R., Gomes, D., D'Elia, M. and Paris, M., (2002). Groundwater quality protection. The World Bank. Washington, DC, USA. Retrived from: http://wwwwds.worldbank.org.pdf [Accessed 12 July 2019]

GoZ, (2011). Harare Provincial Profile. Parliament Reasearch Department, Government Printers. Retrieved from: https://www.google.com/?gfe_rd=ssl&ei=8lOXV-T6E4jEaIbeksAC#q=+Harare+Provincial+Profile [Accessed 28 June 2019].

Gray, N.F., (1997). Environmental impact and remediation of acid mine drainage: A management problem. Environmental Geology, 30, 62-71.

Hamududu, B. H. and Killingtveit, Å. (2016) 'Hydropower Production in Future Climate Scenarios ; the Case for the Zambezi River', Energies 2016, 9(7), p. 502. doi: 10.3390/en9070502.

Interconsult A/S. (1985). National master plan for rural water supply and sanitation, Volume 2.2 Hydrogeology. Ministry of Energy and Water Resources and Development, Republic of Zimbabwe.

Jang W.S, Engel B., Harbor J. and Theller L. (2017). Aquifer Vulnerability Assessment for Sustainable Groundwater Management Using DRASTIC Water, 9, 792; doi:10.3390/w9100792

Kuisi, M.A., Mashal, K., Al-qinna, M., Hamad, A.A., Margana, A., (2014). Groundwater Vulnerability and Hazard Mapping in an Arid Region: Case Study, Amman-Zarqa Basin (AZB) -Jordan. Journal of Water Resource and Protection, 6, 12, 297-318

Kumar, S., Thirumalaivasan, D., Radhakrishnan, N., (2014). GIS Based Assessment of Groundwater Vulnerability Using Drastic Model. Arabian Journal for Science and Engineering, 39, 1, 207-216.

Liggett, J.E., Talwar, S., (2009). Groundwater Vulnerability Assessments and Integrated Water Resource Management. Watershed Management Bulletin, Journal for Science and Engineering. 13, 18-29.

Love, D., Zingoni, E., Ravengai, S., Owen, R., Moyce, W., Mangeya, P., Meck, M., Musiwa, K., Amos, A., Hoko, Z., Hranova, R., (2006). Characterization of diffuse pollution of shallow groundwater in the Harare urban area, Zimbabwe. In: Groundwater Pollution in Africa: Leiden. Taylor & Francis/Balkema, The Netherlands, pp. 65–75.

Lupankwa, K., D. Love, B. Mapani, S. Mseka, and M. Meck. (2006). Influence of the Trojan Nickel Mine on surface water quality, Mazowe valley, Zimbabwe: Runoff chemistry and acid generation potential of waste rock. Physics and Chemistry of the Earth 31:789-796.

Madebwe, V., Munodawafa, A., Mudgabe, F., and Madebwe, C. (2015). Predicting heavy metal movements in Upper Sanyati Catchment in the Midlands Province of Zimbabwe. Ethiopian Journal of Environmental Studies & Management 8(5): 556 – 569, 2015.

Maia, P.H.P., Cruz, M.J.M., (2013). A New Method for Evaluating the Vulnerability of Aquifers. Science Journal of Environmental Engineering Research, 2013.

Mangore, E. and A. Taigbenu. (2004). Land-use impacts on the quality of groundwater in Bulawayo. Water SA 30:453-464.

Masere, T.P., Munodawafa, A., Chitata, T., (2012). Assessment of Human Impact on Waterquality along Manyame River. International Journal of Development and Sustainability, 1(3): 754-765.

Maxwell, A., Geophrey, A. & Kasei, R.A. (2012). Prediction of Potential Groundwater Over-abstraction: A Safe-yield Approach-A Case Study of Kasena-Nankana District of UE Region of Ghana. Journal of Applied Sciences, Engineering and Technology.

Mazvimavi, D., Meijerink, A.M.J. and Stein, A. (2004). Prediction of base flows from basin characteristics: a case study from Zimbabwe. Hydrological Sciences Journal. Vol. 49, No. 4, pp 703-715.

Metrological Services of Zimbabwe, (2015). Rainfall Data

Ministry of Environment, Climate and Water, (2014). Rapid Assessment – Identification and Characterization of Hotspots of Water Pollution and Source Degradation. Harare, Zimbabwe.

Misi, A., Gumindoga, W., Hoko, Z., (2018). An assessment of groundwater potential and vulnerability in the Upper Manyame Sub-Catchment of Zimbabwe. Physics and Chemistry of the Earth 105: 72-83

Morris, B., Lawrence, A., Chilton, P., Adams, B., Calow, R., Klinck, B., (2003). Groundwater and Its Susceptibility to Degradation: A global assessment of the problem and options for management. Nairobi: UNEP,. [Accessed 28 June 2019] Available at: www.unep.org/dewa/Portals/67/pdf/Groundwater_INC_cover.pdf

Mucheriwa, T., An assessment of Acid Mine Drainage contamination in Deka River from coal fields in Hwange and its impacts on water quality. Unpublished thesis. Environmental Science and Health Department Library, National University of Science and Technology, Bulawayo, Zimbabwe.

Mudimbo, D., Owen, R., Crane, E., Upton, K., Ó Dochartaigh, B.É. and Bellwood-Howard, I. (2018). Africa Groundwater Atlas: Hydrogeology of Zimbabwe. British Geological Survey. [Accessed 14 November 2018]. http://earthwise.bgs.ac.uk/index.php/Hydrogeology_of_Zimbabwe

Mukumbuzi A., (2019). A Snapshot Survey of Water Pollution Using Species Diversity in a Segment of a Polluted River in Bulawayo. Unpublished Thesis. National University of Science and Technology. Bulawayo, Zimbabwe.

Musekiwa, C., Majola, K., (2013). Groundwater Vulnerability Map for South Africa. South African Journal of Geomatics, 2, (4), 30-45.

New Zimbabwe. (2019) http://www.newzimbabwe.com/ power-shortages-looms-kariba. (Accessed 13 August 2019)

Nhamo L., Ndlela B., Nhemachema. C., Mabhaudhi., T., Matchaya G., (2018). The Water-Energy-Food Nexus: Climate Risks and Opportunities in Southern Africa Water (10) (567).

Nhapi, I., Tirivarombo, S., (2004). Sewage Discharges and Nutrient Levels in Marimba River, Zimbabwe. Water SA, 30(1): 107-113.

Omosuyi, G.O., Oseghale, A., (2012). Groundwater vulnerability assessment in shallow aquifers using geoelectric and hydrogeologic parameters at Odigbo, Southwestern Nigeria. American Journal of Scientific and Industrial Research, 3, (6), 501-512.

Pavelic, P.; Giordano, M.; Keraita, B.; Ramesh, V; Rao, T. (Eds.). (2012). Groundwater availability and use in Sub-Saharan Africa: A review of 15 countries. Colombo, Sri Lanka: International Water Management Institute (IWMI). 274 p.
doi: 10.5337/2012.213

Piscopo, G., (2001). Groundwater Vulnerability Map Explanatory Notes - Castlereagh Catchment, in: Conservation, Retrieved from: http://www.water.nsw.gov.au/__data/assets/pdf_file/0008/549377/quality_groundwater_c astlereagh_map_notes.pdf (Accessed 10 July 2019)

Ravengai, S., D. Love, I. Love, B. Gratwicke, O. Mandingaisa, and R. J. S. Owen. (2005). Impact of Iron Duke Pyrite Mine on water chemistry and aquatic life – Mazowe Valley, Zimbabwe. Water SA 31:219-228.

Rural WASH Information Management System (RWIMS), (2018). [Accessed 5 July 2018] [Online] Available at:http://www.ncuwash.org

Saatsaz, M., Sulaiman, W.N.A., Eslamian, S. and Mohammadi, K. (2011) ‘GIS DRASTIC model for groundwater vulnerability estimation of Astaneh-Kouchesfahan Plain, Northern Iran’, Int. J. Water, Vol. 6, Nos. 1/2, pp.1–14.

SADC-GMI (2010) for the SADC-HGM project maps, Retrieved from: SADC-Groundwater Information Portal (SADC-GIP) [Online] Available at: http://gip.sadc-gmi.org (Accessed: 23 August 2018).

SADC-WD/Zambezi River Authority, Rapid Assessment Final Report (2008): Integrated Water Resources Management Strategy for the Zambezi River Basin, SIDA, DANIDA, Norwegian Embassy Lusaka, Zambia.

Samake, M., Tang, Z., Hlaing, W., Mbue, I.N., (2011). Groundwater Vulnerability Assessment in Shallow Aquifer in Linfen Basin, Shanxi Province, China Using DRASTIC Model. Journal of Sustainable Development, 4, 1, 53-71.

Sanchez S.G (2018) The Zambezi River Basin: Water Resources Management: Energy-Food-Water nexus approach, Master's Thesis, Stockholm University, Sweden http://su.diva-portal.org/smash/get/diva2:1244639/FULLTEXT01.pdf (Accessed online 08 August 2019)

Scanlon, B. R., Healy, R. W., and Cook, P. (2002): Choosing appropriate techniques for quantifying groundwater recharge, Hydrogeol. J., 10, 18–39.

Sibanda T; Nonner JC.& Uhlenbrook S (2009) Comparison of groundwater recharge estimation methods for the semi-arid Nyamandhlovu area, Zimbabwe. Hydrogeology Journal 17: 1427–1441.

Sinandima, B. (2016). An assessment of water and sanitation practices in Parallel Housing Development Programmes (PHDP) - a case of Overspill Extension, Epworth, Harare. Unpublished thesis. Environmental Science and Health Department Library, National University of Science and Technology, Bulawayo, Zimbabwe.

Sophocleous, M.A. & Sawin, R.S. (1997). Safe Yield and Sustainable Development of Water Resources in Kansas. Kansas Geological Survey, Public Information Circular, 9, (6).

Sophocleous, M.A. (2000). From safe yield to sustainable development of water resources: the Kansas experience. Hydrogeol. J., 13, 351–365.

Sunguro S., Hans E.B., and Klaus E., (2000). Groundwater regulations and guidelines:crucial components of integrated catchment management in Zimbabwe, Paper presented at the 1st WARFSA/Waternet Symposium: Sustainable Use of Water Resources: Maputo, Mozambique (1-2 November 2000).

Svubure, O., Gumbo, T., Soropa, G., Rusere, F., Ndeketeya, A., and Moyo, D., (2011) Evaluation of the Sand Abstraction Systems for Rural Water Supply: the case of Lupane District, Zimbabwe. International Journal of Engineering Science and Technology Vol. 3 (1).

The Independent. (2019). https://www.theindependent.co.zw/2019/07/05/imf-worried-about-power-shortages/ (Accessed 13 August 2019)

Thompson, J.G. (1965). The Soils of Rhodesia and Their Classification. Doctor of Philosophy Submitted to the Department of Soil Science, Faculty of Agriculture University of Natal, Pietermaritzburg.

Tumbare M.J (2004) *The Zambezi River: Its threats and opportunities* presented at the 7th River Symposium, 1-3 September 2004, Brisbane

UNEP, (2006). Groundwater Pollution in Africa. CRC Press.Taylor & Francis, Leiden. Retrieved from: http://apps.unep.org/redirect.php?file=/publications/pmtdocuments/Groundwater_pollution_in_Africa.pdf [Accessed May 23, 2016]

Vushoma, P. Assessment of Groundwater Vulnerability in Norton Town, Zimbabwe. Unpublished Thesis. University of Zimbabwe Library, Harare, Zimbabwe.

Wang, L.; O Dochartaigh, B.; Macdonald; David. (2010). A literature review of recharge estimation and groundwater resource assessment in Africa. British Geological Survey, 35pp. (IR/10/051)

Yihdego, Z., & Hawkins, S. (2018). Cooperative Governance over the Zambezi River Basin: key findings from a legal review. Website, Blog, Social Media, The Newsletter of the DAFNE Project. Retrieved from http://dafne-project.eu/

ZAMCOM, (2017). Zambezi Watercourse Commission Integrated Water Resources Management Strategy and Implementation Plan for the ZAMCOM, SADC, SARDC, 2015. Zambezi Environment, Harare

ZAMCOM. (2019). Strategic Plan for the Zambezi Watercourse, Zambezi Watercourse Commission (ZAMCOM), Harare.

Zimbabwe Geological Surveys (2016). Geological Map of Zimbabwe

Zimstat (2012) National Report: Zimbabwe Population Census 2012, Government of Zimbabwe.

Zimbabwe Vulnerability Assessment Committee (ZimVAC) (2016). Rural Livelihoods Assessment Summary Report. Food and Nutrition Council (FNC) at SIRDC: 1574 Alpes Road, Hatcliffe, Harare.

ZINWA (2006). Assessment of Surface Water Resources of Zimbabwe and Guidelines for Planning. Department of Water Development, Zimbabwe