UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

FACULTY OF SCIENCE

SCHOOL OF GEOSCIENCES

ASSESSMENT OF GROUNDWATER POTENTIAL OF THE KALAHARI AQUIFERS IN KAVANGO EAST AND WEST REGIONS, NAMIBIA

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DECLARATION

The work contained in this research report is my own and all other material contained here has been acknowledged. It is submitted to the University of the Witwatersrand, Johannesburg, South Africa in partial fulfilment of the Masters of Science Degree in Hydrogeology and has not been submitted to any university for any other degree or examination.

Signed ________________on the 5th day of November 2021 at Windhoek

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

DWA Department of Water Affairs

BGR Bundesanstalt für Geowissenschaftenund Rohstoffe

CEBLMWL Cuvelai Etosha Basin Local Meteoric Water Line

CMB Chloride Mass Balance

CEB Cuvelai Etosha Basin

MAP Mean Annual Precipitation

Mbgl Meters below ground level

Mm/a millimetres per annum

AAP Annual Average Precipitation

SACS South African Committee for Stratigraphy

SMOW Standard Mean Ocean Water

TU Tritium Units

KE Kavango East

KW Kavango West

GSN Geological Survey of Namibia

1 INTRODUCTION

1.1 Introduction

Studies on groundwater resources can sometimes be overlooked in regions with freshwater being used as the core water supply. Even with groundwater known to be a precious commodity, the ease with which one can obtain surface water can result in groundwater being rarely prioritized. This often results in such regions not having any groundwater management strategies in place. In addition sustainable yields when considering groundwater abstractions are often not enforced, the understanding of the importance of the sustainable management of groundwater is usually lacking. Studies of the groundwater resource including estimations of the groundwater potential are often neglected, however, they are essential to ensure the management of groundwater in a semi-arid region.

To accurately determine the groundwater potential of an aquifer, one must have an understanding of the hydrogeological factors that govern the potential. The recharge estimation, the quality of the groundwater, the geology of the area are among some of the important controlling factors to be examined in the determination of the groundwater potential of an area (Christelis & Struckmeier, 2011).

The Kavango West and East regions are situated in north-eastern Namibia and are classified to be having a semi-arid climate. The perennial Okavango River bounds the Kavango West and East regions in the northern border. The rural area occupants are centred along the river and use the river as their primary water source (Water Survey Botswana (Pty) Ltd, 2011). Despite that, inhabitants living further from the river still depend on groundwater as their main water source (Mendelsohn, 2009).

In addition, throughout the African continent, drought is considered to be the main form of natural disaster, inflicting devastating effects on local communities and thus becoming a great concern (Calow et al., 2010). The Kavango West and East regions are no exception. More drought relief boreholes are being drilled to sustain communities. This, in essence, increases the dependency of the inhabitants on groundwater. Even though the aquifers in the regions are being utilized, they are understudied. This in itself presents a gap that, the potential of the groundwater resource is not known. Previous investigations on the hydrogeology of the area were carried mainly by the German-Namibia Groundwater Project in 1991 (Department of Fisheries and Water, 1991), focusing on the borehole yield, rest water levels, hydrochemistry, and some groundwater water flow directions. These studies are so far insufficient for confidently determining the potential of the Kalahari aquifer(s) within the regions.

To implement sustainable groundwater utilization, a thorough understanding of the geology, geomorphology, and lineaments of an area is required. Therefore, groundwater potential information can be used to identify locations that are suitable for the extraction of potable water (Vijith, 2007).

1.2 Problem Statement

Limited studies were carried out on groundwater in the Kavango West and Kavango East regions. Even though the aquifers are being utilized, no management strategy exists for the regions. Studies on the behaviour of the aquifers, the potential of the resource, composition of isotopes, and other hydraulic parameters that are, therefore, important to ensure the management of groundwater in the regions have not been thoroughly studied. The Kavango West and East regions are also known to have a low density of boreholes and low abstraction rates, but this does not necessarily imply that the aquifers are not under stress due to over-abstraction. Moreover, failure of boreholes is also recorded in the area, mainly due to poor design and maintenance of the boreholes.

1.3 Aims and Objectives

The main aim of this study is to gain an insight into the factors that control the groundwater potential of the Kalahari aquifers in the Kavango West and East regions, determine the groundwater potential of the Kalahari aquifers, subsequently adding to the knowledge base of the study area and possibly contribute a better and more sustainable utilization of the water resource in the regions.

To assess the groundwater potential, the study includes the following specific objectives:

- To determine the hydraulic parameters of the Kalahari aquifers i.e. storativity/specific yield, saturated thickness.

- To estimate recharge amounts for the Kalahari aquifers and probable recharge mechanisms in the study area.

- To establish the groundwater potential of the Kalahari aquifers.

2 DESCRIPTION OF THE STUDY AREA

2.1 Location

The study area is located in northeastern Namibia. It is bounded by the perennial Okavango River on its northern border and shares boundaries with neighbouring Botswana and Angola. The regions share internal borders with Zambezi, Ohangwena, Otjozondjupa, and part of Oshikoto region (Figure 2.1). The Kavango West and East regions are relatively flat covered by the Kalahari sand and slope gently towards the Okavango River in the northern direction (Department of Fishery and Water, 1991). Geographically, the study area can be found approximately between 17° 20'- 19°12' S and 18° to 22°35' E and covers a total area of nearly 48 742 square kilometres. From the major towns, the study area is located at about 500 to 700 Km northeast of Windhoek- the central business district of Namibia, it comprises the town of Rundu, which is the main town around the Kavango West and East regions.

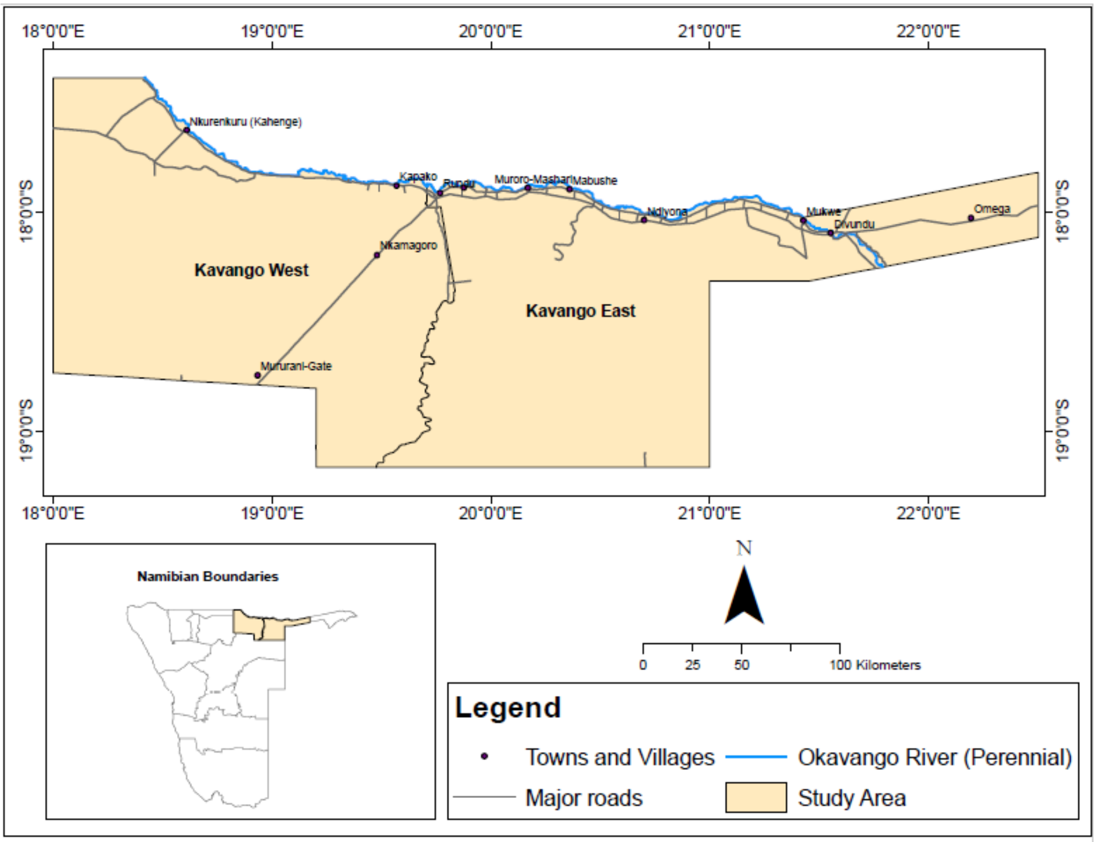

Figure 2.1: Locality map of the study area

2.2 Climate

The Kavango West and East regions have a hot semi-arid or steppe climate. They are characterized by values of precipitation that are below the potential evaporation rates with average rainfall in the area ranging between 450-600 mm annually. The annual average precipitation in the last 78 years of the AAP is 570 mm (Figure 2.2). The regions, however, receive more rainfall compared to the neighbouring areas to the south and west of the regions. The regions are characterized by the absence of rain during winter and part of spring with most of the rain falling mainly during the summer months (December to March) (Mendelsohn & Obeid, 2001; Burke, 2002; Ministry of Land and Resettlement, 2015). During summer, rainfall is related to the southward movement of the Inter-Tropical Convergence Zone (ITCZ). The general rainfall trend in the country decreases generally from north to south and south to the west direction (Burke, 2002).

Mean maximum temperatures are highest during summer months, ranging between 32 °C and 35 °C, with October being the hottest month, while winter months (May to August) records mean minimum temperatures between 5°C and 10 °C. Evaporation in the regions is highest during September and October when the temperatures are highest in the regions. An evaporation rate of 1950 mm/a is recorded in the Kavango West and East region which is four times higher than the average rainfall (Water survey Botswana (Pty) Ltd, 2011).

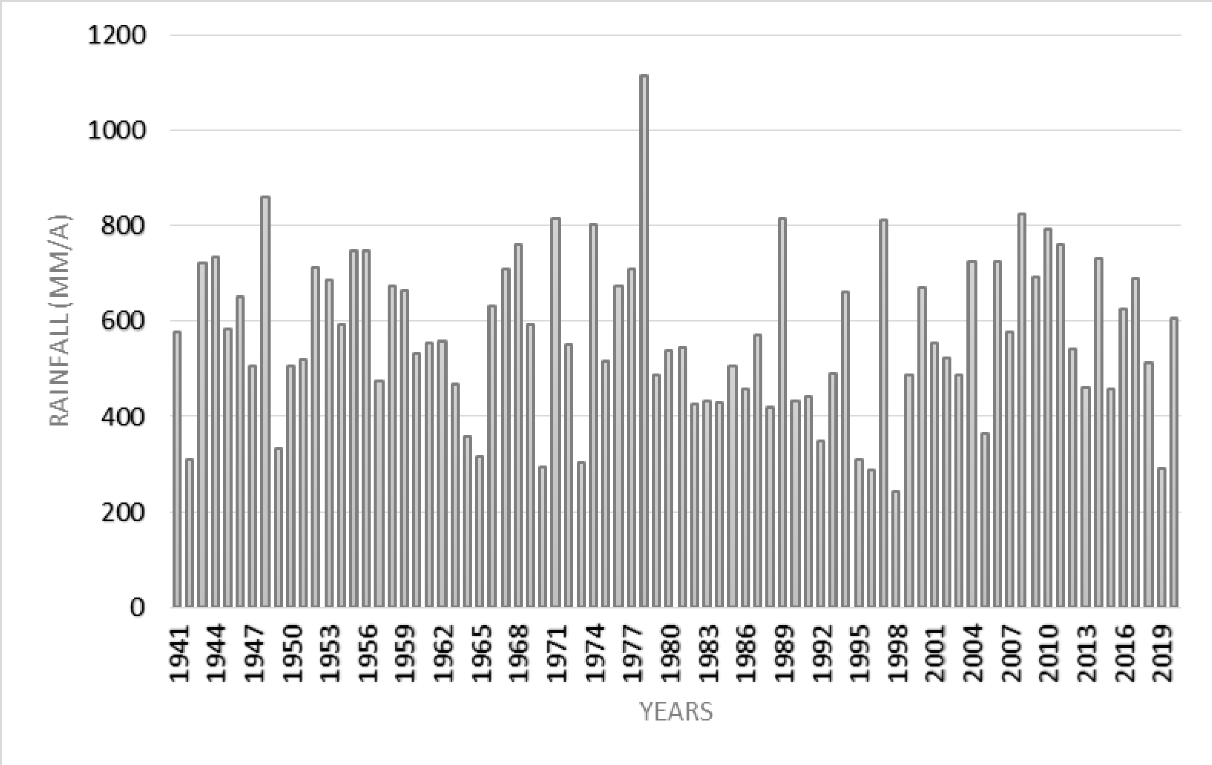

Figure 2.2: Annual rainfall in the study area (data source Namibia Meteorological Service)

2.3 Geomorphology

Present southern Africa's geomorphology is mainly contributed by the breakup of Gondwanaland together with the tectonic processes that are associated with this event. Furthermore, the landscape is majorly influenced by the continuing episodes of uplifting, rifting, volcanism, warping, and erosion, and subsequent denudation due to the creation of new base levels (Bertram & Broma, 1999).

The Kavango West and East regions are characterized by a flat plane that is covered by the Kalahari sand. The flat surface of the region has elevations that vary from 1200 m in the central-southern part to 1150 m in the northwestern corner (Figure 2.3), and 1000m in the northeast at Andara on the western borders of the now Zambezi Region (Department of Water, 1993). The sand cover in the regions is often associated with the inactive longitudinal dunes and major ephemeral rivers i.e. the Omatako Omuramba River that flows from the Khomas highlands and connects to the Okavango River. The sand dunes are dominant in the eastern part of the region and strike in the east-west direction. These dunes were deposited under a much drier climate than the present climate and are now stabilized by vegetation that is dominated by savannah and woodlands, though some areas were observed to have reactivation of dune tops (Klock, 2001; Soils & Simmonds, 2009). The Okavango River, separating Namibia from Angola on the northern side of the Kavango West and East region is the only permanent surface water. The perennial river originates in the humid Angolan highlands, flowing southeast and draining into the Okavango Delta of Botswana. Close to the Okavango River flood plains, dry banks, and backwaters are observed. The dry banks are filled with calcrete deposits that are overlain by dune sand. The active and passive flood plains are filled with sand similar to that of the dunes.

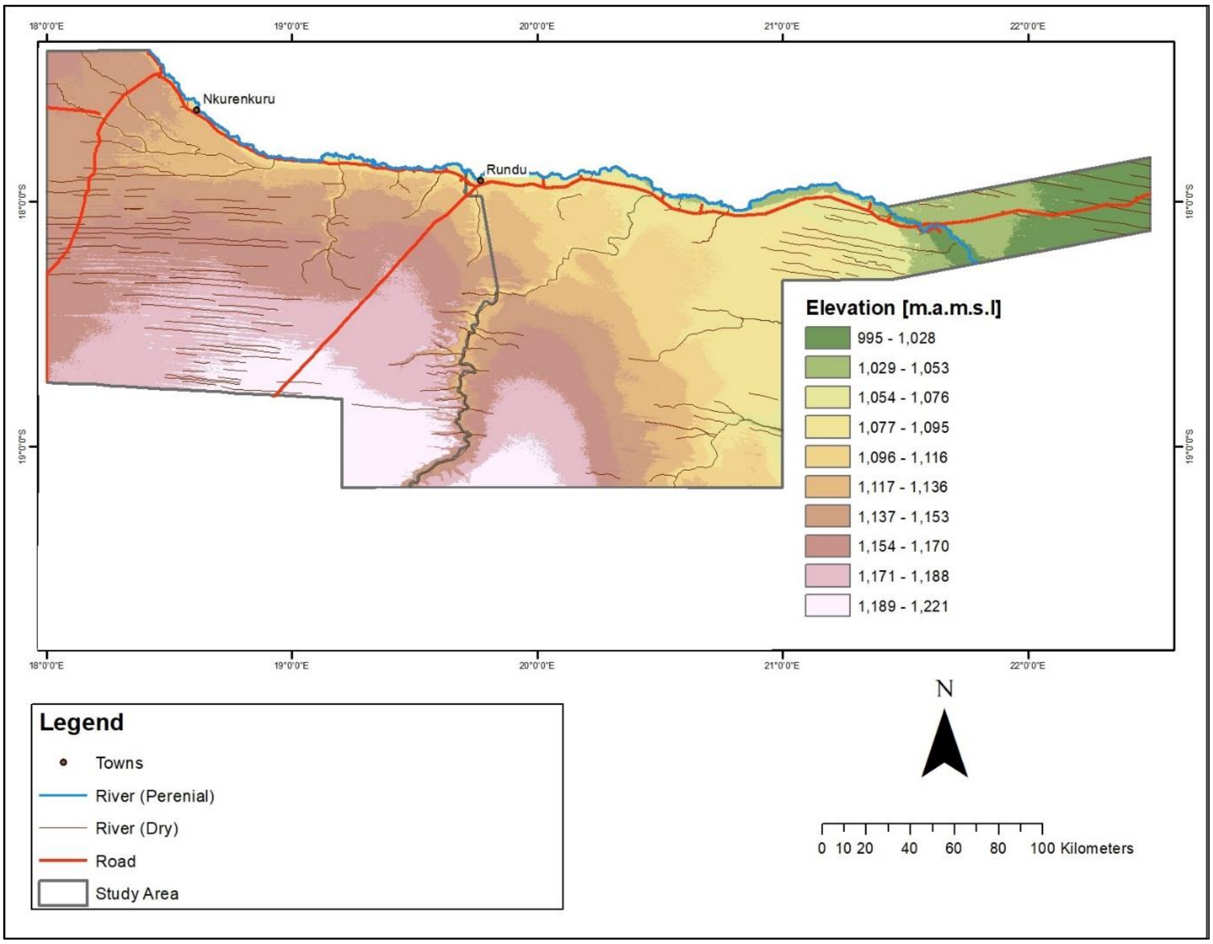

Figure 2.3: Elevation of the Kavango West and East region

2.4 Geological and Hydrogeological review

2.4.1 Geology

The Kavango West and East regions fall within the Okavango Basin, this forms part of a much larger Kalahari Basin. This basin covers most of the eastern and northern parts of Namibia extending into Angola, Botswana, and South Africa. The Kalahari basin is filled with the Kalahari Group deposits which are overlying basil rocks of the Damara Sequence and the Karoo Supergroup (Biwac, 2002), see Table 2.1.

The Damara Sequence consists mostly of quartzites of the Nosib Group, some dolerite dikes, and sills as well as granitic rocks. Most of the Damara appears to be structurally deformed intensively (Department of Water Affairs, 1993). Quartzites are exposed on the eastern side of the Kavango East region, these rocks formed from sediment deposits in the rift valley (Soils & Simmonds, 2009).

According to Miller (2008), from the study area, the Aeolian Etjo Formation sandstone and the overlaying Karoo basalts (Rundu Basalt Formation) are the only known units of the Karoo Supergroup. The basalts are red at the top of the succession due to the pre-Kalahari weathering and darker purplish-grey to dark red in the deeper parts. However, these basalts are rarely exposed in the study area due to the extensive coverage of the Kalahari sediments, their existence is known mainly from the aeromagnetic surveys and water and mineral exploration boreholes (Miller, 2008). Hegenberger (1982) assumed that the entire study area is underlain by the Karoo basalts.

The Kalahari succession was deposited over deeply dissected pre-Kalahari terranes, filling end-Cretaceous interior basins of central and southern Africa. The basin covers mainly southern Botswana, southeastern Namibia, and parts of the Northern Cape Provence in South Africa (Miller, 2008).

The Kalahari Group sediments fill the entire Okavango Basin, covering most of the study area (see Figure 2.4). The basin fill is made up of largely unconsolidated to semi-consolidated clay, sand, and gravel (Biwac, 2002). Albat (1978) described a three-fold Kalahari Group and subdivided it into the Kalahari, Tsumkwe, and the Omatako Formations. Sacs (1980) adopted the subdivision by Albat (1978), however, he renamed the Kalahari into Eiseb Formation which is used in this study (Table 2.1). The Omatako Formation which is the uppermost recent unit consists of unconsolidated windblown sand, this unit also consists of sand that was deposited or reworked under fluvial conditions. The middle Kalahari Group, the Eiseb Formation is mostly fluvial sand with minor aeolian deposit. The lower Kalahari is of the late Cretaceous age, named the Tsumkwe Formation by Albat (1978). Even though poorly understood, it comprises conglomeratic, red clayey sand that has carbonate cement (Department of Fishery and Water, 1991; Klock, 2001; Biwac, 2002; Christelis & Struckmeier, 2011). The three Kalahari Groups are overlain by the Kalahari sand (Table 2.1).

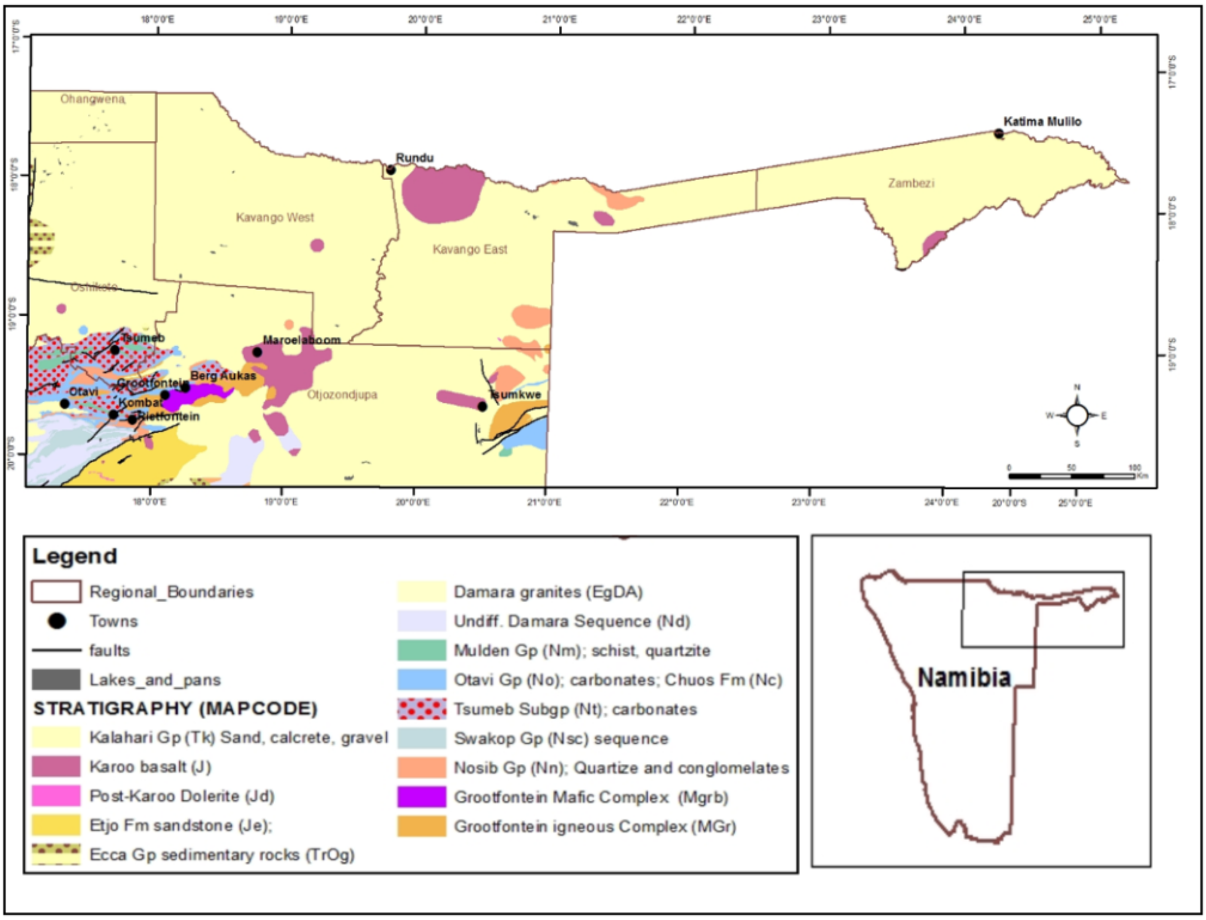

Figure 2.4: Geology of the study area (data source GSN)

Table 2.1: Geology and Stratigraphy of the Kavango West and East Region, modified from (Biwac, 2002)

Age	Sequence/Group		Formation	Description	Distribution in the study area
Recent	Kala hari	Upper	'Kalahari Sand'	thin aeolian sands and loamy, calcareous soil with crusts of ferricrete and calcrete	regional covering to all older rocks
to			Omatako	ferricrete and ferruginous sandstone	borehole intersections only
		Middle	Eiseb	thick layered, light-coloured, sandy silcrete and calcrete, conglomerate bands in the middle unit	borehole intersections only
Late Cretaceous (64 – 0 m.y.)		Lower	Tsumkwe	Reworked sandy to clay-rich conglomerate, poorly sorted basal scree with calcareous cement; minor mudstone	borehole intersections only
Cretaceous (180 - 60 m.y.)	Karoo		Kalkrand	Plateau Basalt	borehole intersections only, e.g.: Omatako/Kavango river area near Rundu, south of Andara and northeast of Mangetti block
Early Namibian (900 m.y.)	Damara/Nosib		Duruchaus	Fine-grained greyish to brown, feldspathic quartzites with interbedded sandy shales	Nhoma, Andara, and Popa Falls area

2.4.2 Hydrogeology

In the study area, the geographic coverage and systematic hydrogeological investigations of the Kalahari Group are limited, this is due to factors like the lack of mineral interest and the area sparsely inhabited (Wanke & Wanke, 2007).

According to Biwac (2002), Department of Fishery and Water (1991), and Christelis & Struckmeier (2011), two aquifer systems exist within the study area, the primary sand and sandstone aquifers of the Kalahari Group and the fractured and weathered aquifers of the pre-Kalahari bedrock (Figure 2.5).

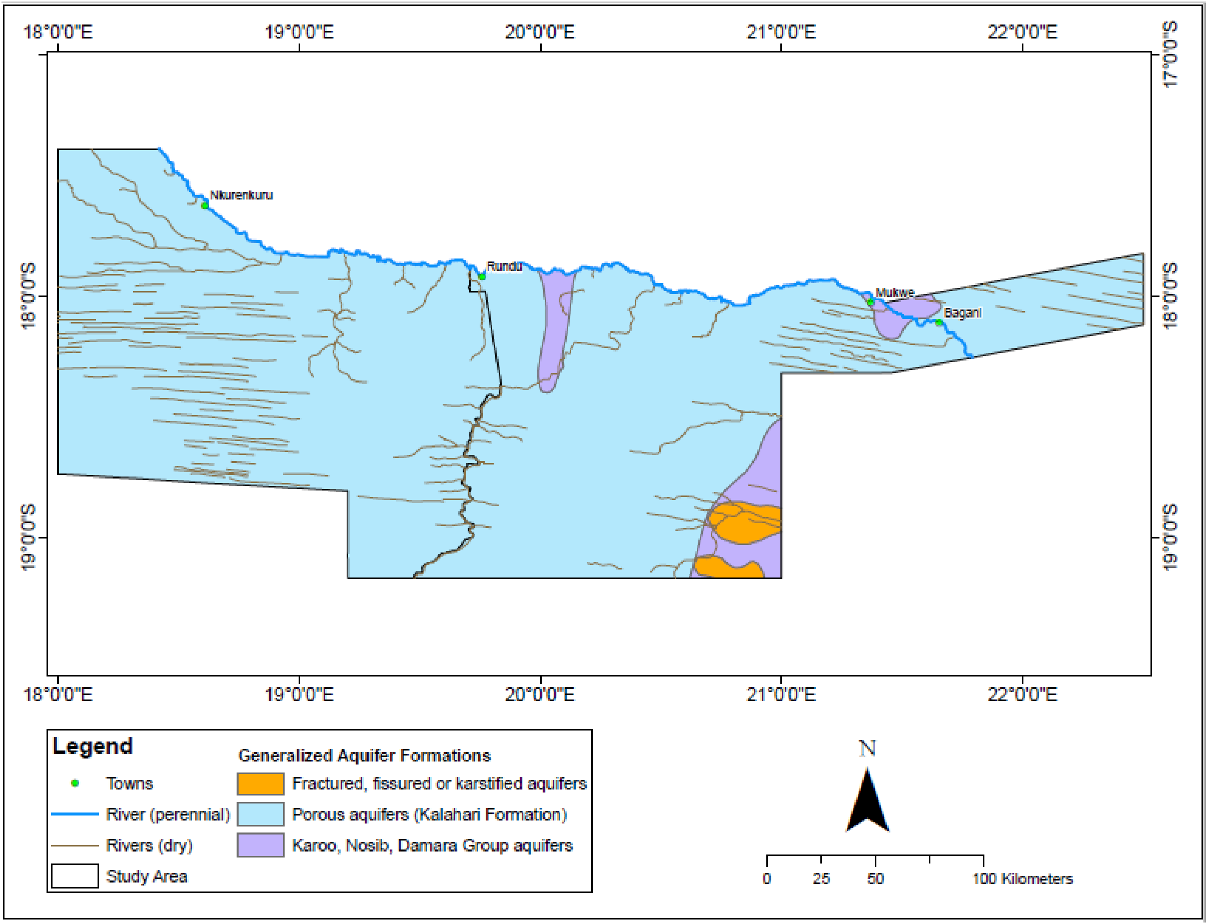

Figure 2.5: Aquifer types in the study area (data source, DWA)

Over 100 borehole completion reports were thoroughly studied to determine the distinction between the Kalahari Group sediments and division according to Albat's (1978) subdivision. Three aquifer units of the Kalahari are observed in the study area (Table 2.2). The top Kalahari aquifer is largely composed of aeolian sand mainly of fine and silty . The upper Kalahari aquifer is the least extensive formation in the study area (Namibia groundwater development consultants, 1993). It is also categorized by a low energy drainage nature which is presented in the fine and silty sediments and is, therefore, not appreciated as an aquifer. There are several places in the study area with uplifted local streams by igneous impalements, at these places, the upper Kalahari is then considered as a local aquifer (HMRW cc, 2019).

The main regional aquifer is recognized as the middle Kalahari aquifer (Eiseb Formation), composed mainly of medium sand and sandstone layers. Albat (1978), noted that the formation has Kalahari rocks that are made up of alternating silcrete and carbonate rocks formed during a fluctuating climate where periods of higher rainfalls were followed by arid climates. The middle and the lower Kalahari aquifers both appear to be extensive in the entire study area. The lower Kalahari aquifer (Tsumkwe Formation) has a matrix made up of fine to very fine-grained sand, commonly with some silt and clay. Angular to sub-rounded, poorly sorted fragments of the country-rock are also commonly found within the matrix. In several places of the study area, the fragmented matrix is concentrated at the basal contact. The sediments of middle and low Kalahari form a permeable layer that is almost continuous, and yields between less than 1 m^3/h to 70 m^3/h can generally be abstracted from boreholes (Biwac, 2002; Christelis & Struckmeier, 2011).

Even though there is a large Aeolian upper Kalahari deposit (Omatako Formation), this formation is not appreciated as an aquifer (HMRW cc, 2019) and was, therefore, not included in this study. This study focuses on the middle and lower units of the Kalahari Group sediments.

Table 2.2: Aquifers found in the study area (source Biwac, 2002 and HMRW cc, 2019)

GROUP/SEQUENCE		**STRATIGRAPHIC UNIT**	**DESCRIPTION**	
Kalahari			**Nature Type**	**Aquifer Potential**
	Upper	Fine and Silt sediments	Aquitard/ Leaky aquifer	Low Yield, Locally high Yielding
	Middle	Sandstone, Sand & Clay	Aquifer	Low Yielding
	Lower	Marl and Clay	Confining Layer	None
		Conglomerate & Gravel	Aquifer	High Yielding
Karoo		Basalt/Sandstone	Aquitard/Weathered	Conditional
Damara		Schist/Quartzite/Dolomite	Aquitard/Fractured	Conditional

In the study area, the flow direction of both groundwater and surface water is south to the north, north-easterly direction towards the Okavango River. It should be noted that surface water does, however, locally pond during the rainy season. In Biwac (2002), three main flow regimes and 1 sub-flow regime were identified based on the available piezometric data. Figure 2.6 is a piezometric map of the Kavango regions. The three flow regimes are further explained below.

Regime 1

- Located in the south-southwestern part of the Kavango West region.

- Shows a northerly flow trending towards the basin axis and onwards to the Okavango River and towards the Omuramba Mpungu.
- Flow is driven by recharge from south of the Mangetti Block.
- Two recharge sources were identified, firstly groundwater from the Otavi Mountains north of Grootfontein and secondly from calcareous Kalahari sediments between Abenab and the Kavango West regional border.
- A Shallow gradient of 0.0003.

Regime 2:

- Located in the north-western part of the Kavango West region.
- North-south flow towards the Okavango River and the Omuramba Mpungu
- Recharge suggested being from the upper catchment area in Angola.
- After recharging from Angola into the aquifer, the flow direction of the groundwater is then changed and directed into the Omuramba Mpungu and eventually into the Okavango River.
- Flat gradient.

Regime 3:

- Covers the major part of the study area, located on the eastern part of the study area.
- Recharge from northwest of Tsumkwe causes radial flow towards the Eiseb, Omatako, and the Okavango River.
- The Damaran meta-sediment outcrops in the Kaudom Park and near the Okavango River at Andara act as groundwater sinks rather than recharge zones.
- A Shallow gradient of 0.0003.

Sub-regime 3a

- Localized shallow Kalahari aquifer southwest of Rundu.

- Radial flow from a central recharge zone.

According to Biwac (2002), a dis-connectivity within the two Kavango regions is introduced by the flow systems resulting in a lack of mixing of water between different areas of recharge before joining the Okavango River flow system, even though the final general flow ends up in the Okavango River.

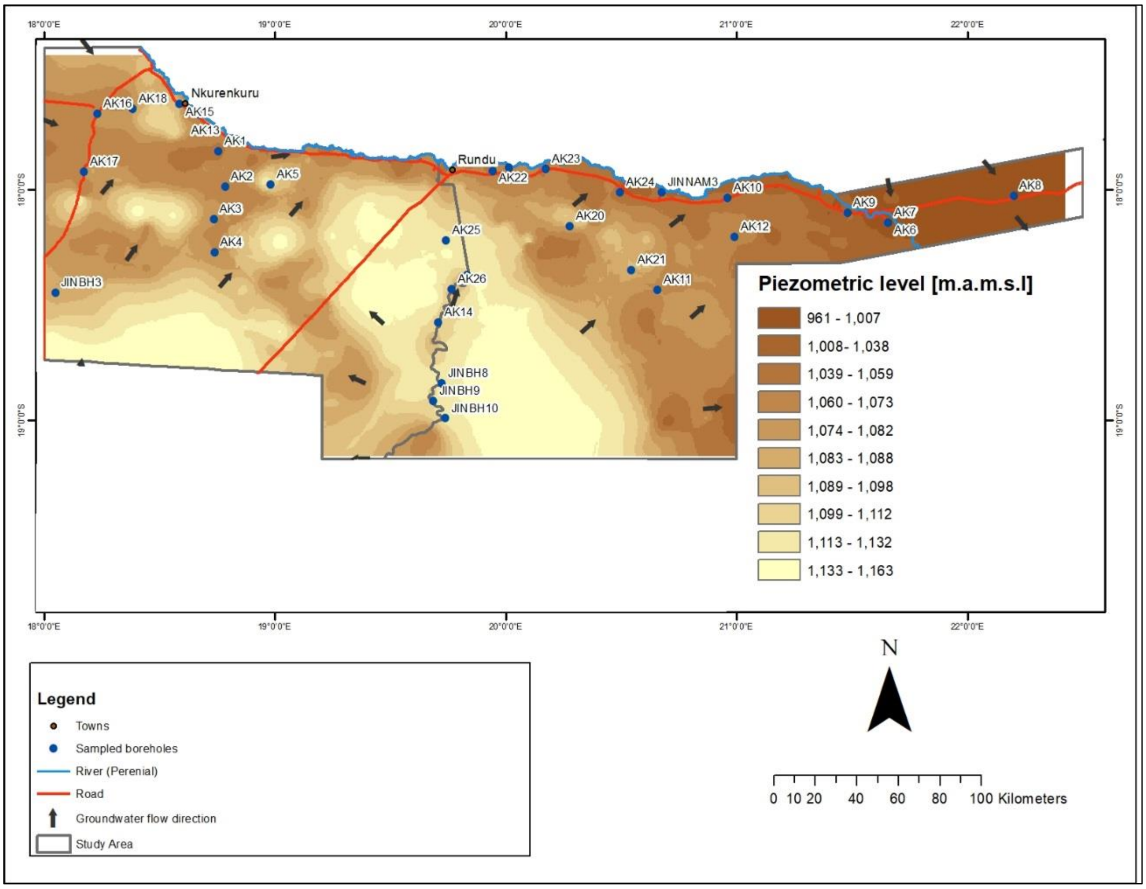

Figure 2.6: Piezometric map (data source, DWA)

The groundwater flow gradient suggests that the Okavango River is not a recharge source. However, in Botswana, where a similar groundwater gradient towards the Okavango River exists, recharge from the river is indicated within its floodplain (Biwac, 2002; Christelis & Struckmeier, 2011). Besides, this study has noted that the Okavango River is both gaining water from the aquifer and losing water to the Kalahari aquifers.

The depth of the lower Kalahari aquifer cannot be estimated even though the gravity sediments which are conglomerates or tillites of the Dwaka Formation mark the onset of the Karoo Supergroup rocks. The fluviatile gravels and conglomerates mark the onset of the Kalahari Group rocks (Figure 2.7). The lower Kalahari aquifer is assumed to produce more water than the top two Kalahari aquifers beside the fractured quartzites and dolomites/limestones of the Damara Sequence (HMWR cc, 2019).

Boreholes are drilled almost entirely into the Kalahari aquifers in the study area, the fractured aquifers are only mainly important in areas where the Kalahari aquifers are absent. This has led to minimal studies being done on fractured aquifers. The Etjo sandstone aquifer within the Karoo Supergroup is less utilized in the area because of its depth within the study area. Therefore, this study will only focus on the Kalahari aquifers.

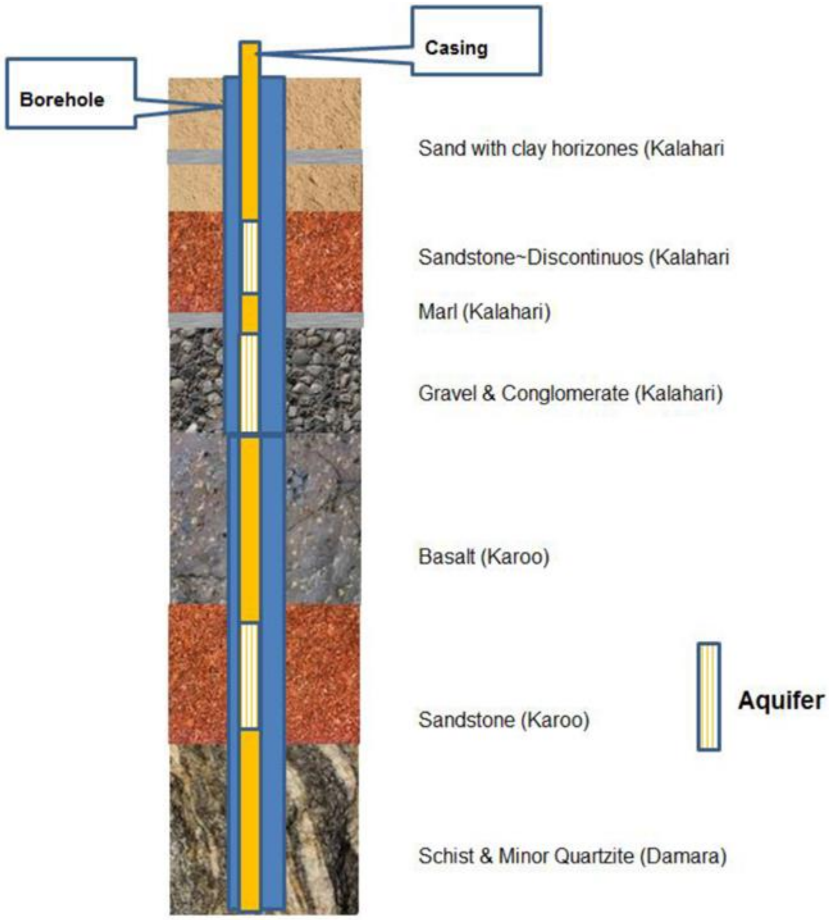

Figure 2.7: Vertical conceptual hydrogeology of the study area
(Source: HMWR cc, 2019)

3 LITERATURE REVIEW

3.1 Hydraulic Parameter of the aquifers

3.1.1 Storativity/specific yield

Knowledge of the storativity of an aquifer is essential in the determination of groundwater storage and resource potential in semi-arid and arid regions.

For a confined aquifer, storativity is defined as:

S= S_s*b

Where S_s is the volume of water released from a unit volume of a saturated material per change in the hydraulic head component normal to the surface and b is the thickness of the aquifer. In other words, storativity (S) (or storage coefficient) is defined as the volume of water released or the decrease in the volume of water that is stored in an aquifer per unit surface area per unit change in head. The values of storativity are dimensionless and can be obtained from the following equation:

$$S = \frac{Volume\ of\ water\ released\ (m^3)}{Surface\ area\ of\ aquifer\ (m^2) * \Delta H\ (m)}$$

Where ΔH is the change in hydraulic head per unit change in the head (Freeze & Cherry, 1979; Fitts, 2002; Hiscock, 2005). The volume of water extracted from an aquifer is relatively proportional to the storativity of that particular aquifer. Generally, in a confined aquifer, storativity ranges from 10^{-2} to 10^{-5}, the thicker and more compressible an aquifer is the higher the storativity while thin and stiff aquifers have low storativity (Hiscock, 2005).

As explained in Freeze & Cherry (1979); Fitts (2002); Hiscock (2005), the unconfined aquifers storage term is referred to as the specific yield (Sy) or the unconfined storage. This term is conceptually equivalent to the confined aquifers storativity (S), therefore:

S=S_Y.

Like storativity, specific yield is dimensionless. It is also said to be approximately equal to the total porosity of a rock or soil but always less since not all water drain from pore spaces, capillary forces hold some water to the mineral surfaces. However, the coarser the material, the closer S_y is to total porosity (*n).* The values of the specific yield generally range from 0.01 to 0.30. In comparison to the storativity of confined aquifers, the specific yield is usually much larger, therefore more water can be extracted in a given area from the storage of an unconfined aquifer than from the same area in a confined aquifer. When pumping in an unconfined aquifer, the values of specific yield reflects actual dewatering of pore spaces as the heads decline, the water level decrease. Pumping from the confined aquifer results mainly from secondary effects of water expansion and compaction of an aquifer caused by fluid pressure changes and not dewatering. Therefore, for an equal unit decrease in the hydraulic head in both the confined and unconfined aquifer, the confined aquifer will produce much less yield than the unconfined aquifer. The storage coefficient values are much smaller in confined aquifers than unconfined aquifers (Fitts, 2002; Hiscock, 2005).

3.1.2 Groundwater level and saturated thickness

The total volume of the groundwater stored depends on the thickness of the rock or aquifer material that is saturated with water (Christelis & Struckmeier, 2011). Therefore, aquifer thickness can be defined as the measure of the amount of water a rock or consolidated or unconsolidated material can hold and not necessarily the amount of water yielded or produced by an aquifer. The thickness of the aquifer depends on both the consolidated or unconsolidated material found within the aquifer. The geology of a certain area controls the groundwater conditions in that specific area. It is important to note that, the depth of the water table in an aquifer under natural conditions varies and fluctuates over time due to recharge, discharge, and evapotranspiration (Jonker, 2016).

3.2 Recharge Dynamics and quantification

3.2.1 Environmental Isotopes

Environmental isotopes provide information on transport and the interconnectivity of reservoirs and water resources, hence, their increasing use in all parts of the world with different climate conditions. These isotopes involve measuring ratios of elements that make up the water molecule and substance that could give rise to hydrogen and oxygen (Abiye, 2013). This is, however, subject to environmental processes and change. ^{3}H, ^{2}H, ^{18}O form part of the water molecule, therefore, they most accurately simulate the movement of water (Allison et al., 1994). The stable isotopes (^{18}O) and (^{2}H) form the most important atomic constituents of the water molecules, serving as a powerful tracer of hydrological processes in the unsaturated and saturated zone as they provide an integral fingerprint of water origin, flow paths, and transport processes. These stable isotopes have the widest field application in groundwater studies and have become an important tool for hydrogeological studies in arid and semi-arid areas (Geyh, 2000; Külls, 2000; Hamutoko, 2018). Determination of the origin and ages of different water bodies, estimation of the degree of mixing, determination of different recharge sources, locations and proportion of water recharge, identification of streamflow generation mechanism, groundwater flow velocity indication are some of the uses of environmental isotopes. Also, environmental isotopes are the building blocks in the understanding of groundwater dynamics, mixing, and recharge conditions with the use of relative deviation from the Global Meteoric Water Line (GMWL) and the Local Meteoric Water Line (LMWL) (Abiye, 2013).

3.2.2 Recharge Quantification

Groundwater recharge is here defined as an addition of water to an aquifer or a groundwater reservoir or more strictly as the flow of water in a downward direction from the overlying unsaturated zone or surface water body reaching the water table (de Vries & Simmers, 2002; Xu & Beekman, 2003; Scanlon et al., 2006; Abiye, 2016; Gebru & Tesfahunegn, 2019). Hiscock (2005) refers to groundwater recharge as the quantity of renewable water available in an aquifer, for abstraction and the support of the baseflow component of rivers, in the long term.

Groundwater systems are recharged by various sources that are well known. The following are the principal recharge mechanisms from various sources (Külls, 2000; De Vries & Simmers, 2002; Xu & Beekman, 2003; Scanlon et al., 2006, Abiye, 2016).

- Direct/ diffuse recharge: Direct vertical percolation and infiltration of water through the unsaturated zone to the groundwater reservoir at the site of precipitation or application.

- Indirect/ focused recharge: Percolation and infiltration of runoff water to the water table at a different location from where precipitation occurred. The recharge may occur through river bed depressions where runoff flows or in ponds.
- Localized recharge: Percolation and infiltration to the water table of precipitation that accumulated in surface water bodies.

Indirect or localized recharge proves to be more prominent in areas with increasing aridity, this is contributed to the fact that only localized concentration of runoff and subsequent infiltration exceeds the thresholds for deep percolation in more arid environments (Külls, 2000). However, previous studies such as by Mainardy (1999), and Klock (2001), indicate that groundwater in the Kalahari aquifer is being recharged by different sources. Both direct, indirect, and localized recharge occur in the study area. Direct recharge takes place through jointed or karstified hard rocks, from infiltration through sand cover and, along preferred paths in rootlets or structured soils. Indirect recharge in the area arises from ponded water bodies or ephemeral rivers i.e. Omuramba Omatako (Klock, 2001). Localized recharge is assumed to be taking place along the perennial Okavango River.

Recharge into the Kalahari aquifers is believed to be largely from water seeping in a northerly direction with the main recharge area in the elevated area south of the region (Otavi Mountain Land). HMWR (2019) assumed that recharge into the middle Kalahari is direct and diffuse, from the percolation of rainfall during good events and flow from the sub-surface respectively. Direct recharge into the lower Kalahari aquifer unit can arise from elevated outcrops and around the basin rims.

It is observed that present-day recharge is occurring at most locations in the Kalahari aquifers, even though it is very low (Külls, 2000).

Several methods of groundwater recharge are available. However, limitations when applying and the reliability of each of the methods exist. Choosing a method for quantifying recharge will depend on the objective of the recharge study as this determines the space and time required for the study (Scalon et al., 2006; Xu & Beekman, 2003; Abiye, 2016).

Chloride Mass Balance

The Chloride Mass Balance method has been applied during recharge investigations worldwide. The method is based on the assumption of mass between the input of atmospheric (precipitation) chloride and the chloride flux in the subsurface (Bazuhair & Wood, 1996; Xu & Beekman, 2003; Klock, 2001; Dassi, 2010; David, 2013; Abiye, 2016). Chloride is used for recharge estimation because it is considered a conservative tracer and is relatively abundant in precipitation (Subyani & Șen, 2006). The application of the CMB method is relatively simple and is a reliable tool that can be applied in the estimation of recharge even when the expected recharge is less than 1 mm/a (Klock, 2001; Subyani & Șen, 2006). Not all parameters required for the determination of groundwater recharge are included in the method, however, the method does include the main input parameters namely the annual precipitation and the chloride concentration in rainfall and groundwater storage.

The equation applicable to recharge calculation is presented by Xu & Beekman (2003) as:

$$R= \left(\frac{Clp}{Clgw}\right) * MAP$$

Where;

R= Recharge (mm/a)

Cl_p= Chloride in rain (mg/l)

Cl_{gw}= Chloride in groundwater (mg/l)

MAP= Mean annual precipitation (mm).

3.3 Groundwater Potential

The total amount of permanent storage that exists in an aquifer is known as the groundwater potential. This potential depends highly on the aquifer storage and transmission properties, the recharge rates, and how suitable the water is (water quality). There are hydrologic water budget techniques methodologies adopted for the computing of groundwater resources. These are mainly highly specialized water budget equation that requires components of inflow into the aquifer, outflow from the aquifer to be quantified as well as storage changes (Kumar, 2014). For this study, the groundwater resource potential was calculated using a basic water balance approach (DWAF, 2006). One must note, however, that the water balance will provide values of the maximum volume of groundwater estimated to be available on annual basis for abstraction under no abstraction and in normal rainfall conditions. The nature of the rocks underground, the unconsolidated and consolidated material determines whether these rocks, consolidated and unconsolidated material are water-bearing, the water quality that has accumulated, and the amount of groundwater available (Christelis & Struckmeier, 2011).

Several hydrogeological factors need to be considered in the determination of the groundwater potential. These are, for example, the storativity/ specific yield of the aquifer, the thickness of the aquifer, the quality of the groundwater system, the recharge of the aquifer, and the hydrochemistry of the aquifer.

4 MATERIAL AND METHODS

4.1 Sampling Location

One sampling campaign was carried out in March 2020 (Figure 4.1). A total of 86 water samples were collected in the study area: 33 samples were collected from boreholes for stable isotopes analysis and 33 samples were tested for chloride content (Appendix 2). The location of the sampled boreholes and the geographical positions is shown in Figure 4.2 and Table 4.1 respectively. Three (3) samples were collected from the Okavango River and analyzed for stable isotopes. Twelve (12) samples were collected from both boreholes and the Okavango River and analyzed for Tritium. During the field trip, five rain events were sampled and tested for chloride content only at the NamWater laboratories (Appendix 3). The sampled boreholes were selected according to their depth and aquifer lithology. However, not all the selected boreholes were sampled, unavailability of pumps in certain boreholes, the location of the boreholes, and the time of sampling (most boreholes in the study area are equipped with solar pumps, the sampling campaign took place during the rainy season thus unable to sample several boreholes) are some of the constraining factors. A handheld GPS (Global Positioning System) was used to record the position of each sample and collect surface elevations. The water levels of the sampled boreholes recorded were obtained from borehole completion reports supplied by the DWA.

Figure 4.1: Fieldwork undertaken in the study area

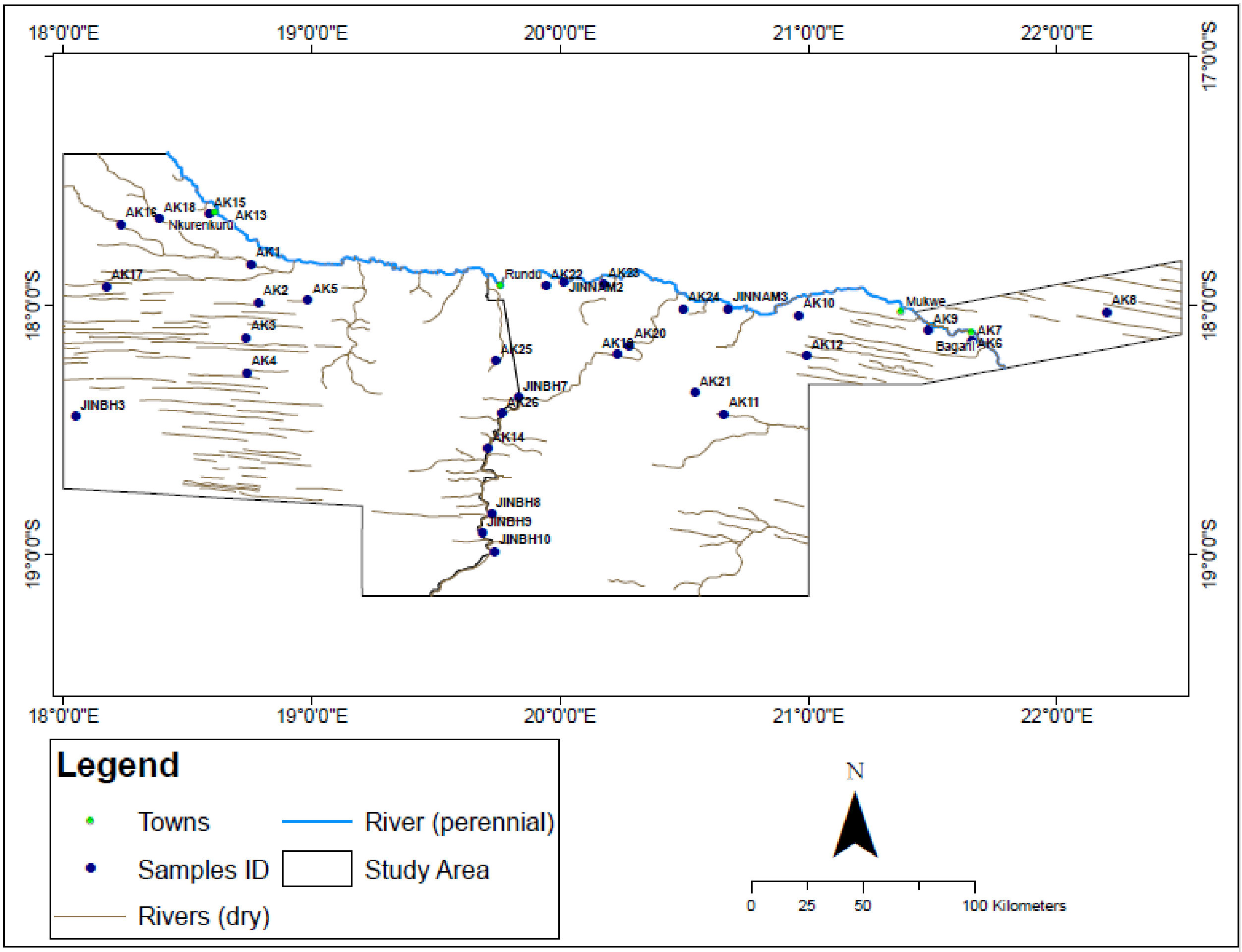

Figure 4.2: Location of the sampled boreholes in the study area

Table 4.1: Boreholes sampled in the study area

Borehole ID	Sample ID	Region	Locality	Latitude	Longitude	Borehole Depth (m)	Depth to Water (m)
WW202839	AK1	KW	Kapangwena	-17.83577	18.75473	55	36.9
WW40571	AK2	KW	Desi	-17.98836	18.78390	120	79.5
WW202840	AK3	KW	Nkambe	-18.12884	18.73435	140	86.4
WW40567	AK4	KW	Tcalikawa	-18.27316	18.73761	180	97.3
WW202842	AK5	KW	Sipwi	-17.98155	18.98177	112	73.7
WW204259	AK6	KE	Tapahutha	-18.14468	21.65592	75	26.3
WW204253	AK7	KE	Rupetho	-18.14468	21.65592	54	22.0
WW34811	AK8	KE	Omega	-18.02855	22.19917	90	45.2
WW204252	AK9	KE	Thikange	-18.10292	21.48038	120	29.6
WW202988	AK10	KE	Mukuvi Teya	-18.03963	20.95791	42	22.9

Borehole ID	Sample ID	Region	Locality	Latitude	Longitude	Borehole Depth (m)	Depth to Water (m)
WW204132	AK12	KE	Livayi	-18.20588	20.99039	71	21.8
WW28594	AK13	KW	Kahenge	-17.67612	18.67242	40	5.3
WW202832	AK14	KE	Naingopo	-18.57639	19.70692	120	18.1
WW201974	AK15	KW	Nkurenkuru TC	-17.63215	18.58639	80	41.0
WW10021	AK16	KW	Mpungu	-17.67431	18.23087	98	63.5
WW202837	AK17	KW	Cause West	-17.92551	18.17229	150	65.8
WW202835	AK18	KW	Sawato	-17.65355	18.38408	110	52.3
WW40572	AK19	KE	Vikota	-18.19972	20.22908	45	33.0
WW204140	AK20	KE	ShinungaToring	-18.16090	20.27760	106	11.0
WW204138	AK21	KE	Tcausha	-18.35120	20.54189	90	20.9
WW204256	AK22	KE	Ngone	-17.92076	19.94223	72	14.0
WW204257	AK23	KE	Mururoteya	-17.91382	20.17214	57	35.3
WW204134	AK24	KE	Shamapiri	-18.01488	20.49401	68	41.6
WW204255	AK25	KW	Hamweyi Manyondo	-18.22229	19.73993	75	12.8
WW204254	AK26	KW	Gcigco	-18.43498	19.76516	75	10.3
WW25540	JINNAM2	KE	Sambui	-17.90710	20.01390	60	11.4
WW31944	JINNAM3	KE	Nyangana	-18.01510	20.67540	62	12.0
WW41274	JINBH3	KW	Bravo	-18.44797	18.04867	125	85.8
WW7912	JINBH7	KE	Ncaute	-18.37084	19.83067	57.6	6.1
WW33868	JINBH8	KE	Klein Karakuwisa	-18.84035	19.72279	172.6	12.7
WW39967	JINBH10	KE	Zadang	-18.99097	19.73580	117	13.9
WW35534	JINBH9	KE	Satoka	-18.91755	19.68625	145	100.9

4.2 Sampling Procedures

4.2.1 Field Procedures

The samples were collected from boreholes that supply domestic and drinking water to the habitants of the two Kavango regions, therefore, no purging of boreholes was required. The sample bottles were pre-washed at least 2-3 with borehole or river water before a sample was collected. Two samples were collected per borehole, 1 for stable isotope analysis and the other sample for chemical analysis (chloride content). Several boreholes out of the total sampled boreholes were sampled for tritium analysis. A sample was collected upstream, middle stream, and downstream of the Okavango River for both stable isotopes and tritium analysis. A 500 ml polypropylene bottle filled to the brim was used to collect the sample for chloride content analysis. For stable isotopes a 50 ml glass bottle was used, the glass bottle was carefully sealed to prevent evaporation. Tritium samples were collected using a 500 ml glass bottle. All samples were stored in a cooler box at 4 °C until they were analysed at the laboratory. Rainfall samples were collected from different rain stations across the study area and were analyzed for chloride and stable isotopes.

Physical parameters namely temperature, pH and electric conductivity were measured onsite using a Hach field-portable instrument (HQ 14d conductivity meter, HQ 11d pH meter, HQ 40d multi-meter). The physical and chemical parameters measured in the field for the 40 samples collected in the study area are presented in appendix 1.

4.2.2 Laboratory Procedures

Chemical Analysis

The chloride content in the groundwater samples was measured at the Namibia Water Corporation (Ltd) (NamWater) Laboratory in Windhoek using the Induced Coupled Optical Emission Spectrometer (ICP-OES). The pH was analyzed using the electrometric method No.4500.The Chloride content in the rainfall samples collected in the study area was also measured at the NamWater Laboratory.

Environmental Isotopes

Stable Isotopes of ^{18}O and ^{2}H were analyzed using the off-axis integrated cavity output spectroscope (OA-ICOS, Los Gatos DLT-100) at the University of Namibia (UNAM). The analytical results are given as delta-values, expressed as per mil (‰) deviation relative to the international standard in this case the Vienna Standard Mean Ocean Water (VSMOW, which is normalized to V-SMOW/SLAP scale) as presented commonly in the delta-notation:

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{\text{sample}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{standard}}} - 1 \right) \times 1000\ ‰$$

Tritium analysis was conducted at iThemba Laboratories in Gauteng, South Africa. The samples were first distilled and subsequently enriched with electrolysis. These electrolysis cells comprise concentric metal tubes and these two metal tubes are insulated from one another. The 500 ml of a water sample that contains sodium hydroxide was distilled and then introduced into the cell. A direct current of 10-20 ampere was passed through the cell, this cell was cooled because of the heat that is generated during the processing of the sample. The electrolyte volume was reduced to 20 ml after a couple of days. In essence, the tritium is enriched to a factor of about 20 from the volume reduction of 25 times. Spikes were run in one cell to check the enrichment attained. The enriched samples were distilled from the highly concentrated electrolyte, thereafter 11 ml of the Ultima Gold was mixed with 10 ml of the distilled water sample. The sample was placed in a vial in an analyzer. After the placement, the sample was then counted 2 to 3 cycles of 4 hours. The tritium's detection limits are 0.2 TU for enriched samples (Butler et al., 2020).

4.3 Calculations and data analysis

4.3.1 Storativity/ Specific yield

Measuring storativity/ specific yield directly has proven to not be easy. Therefore, storativity/specific yield for the Kalahari was obtained from the analysis of pumping test data. Pumping test data is available for certain boreholes in the study area. The Cooper-Jakob Straight Line Pumping Test Analysis (Pongmanda & Suprapti, 2020) was used to determine the storativity/specific yield.

4.3.2 Aquifer Thickness

Various approaches can be used in the estimation of the thickness of the aquifers. For one to determine aquifer thickness one needs to figure out whether the base of the aquifer is well defined or not, therefore, the study reviewed previous lithological logs, water strike levels, and borehole completion reports.

It is important to note that the main aquifers in the region are located in the Kalahari Group. From the recent drillings conducted in the study area, it is observed that the middle Kalahari aquifer is unconfined while the lower intergranular aquifer is semi-confined. A clay-rich layer separates the two aquifers, that is assumed to be slightly permeable, and therefore, the two aquifers are not entirely separate. DWA contains a great number of borehole completion reports from drillings in the study area with sufficient lithological description to distinguish between the low, middle, and upper Kalahari Group. Klock (2001) developed a distribution map of the Kalahari aquifer thicknesses covering part of the study area, however, this thickness was not subdivided into formations. A similar map was created by Biwac (2002) for the study area, with no subdivision of the Kalahari into Lower, Middle, and Upper Formation as well. For this study, over 100 borehole completion reports were thoroughly reviewed. From this information, the Kalahari was subdivided into the Lower, Middle, and Upper Formations. The thickness for each 50 m depth interval was obtained from calculating the elevation difference between that particular interval, which is taken as the base and the water table.

4.3.3 Recharge quantification

Groundwater recharge quantification is becoming increasingly prevalent in semi-arid areas as it is an important aspect of groundwater management. However, groundwater recharge remains one of the most challenging parameters to quantify with regards to groundwater study, the determination is not straightforward. Several factors influence recharge, these factors such as topography, human-induced activities, climate, land-use type, and soil characteristics are associated with spatial and temporal variability of a high degree and levels of high uncertainty (Dassi, 2010; Jonker, 2016; Abiye, 2016; Gebru & Tesfahungen, 2019). Even though several studies have been carried out in semi-arid areas over several decades, estimating recharge accurately is still very challenging. Scarce data, income, and poor technology still contribute to how accurate recharge is estimated in developing countries such as Namibia.

Numerous methods are available for quantifying groundwater recharge, with limitations on each of the method with regards to the reliability and applicability. When selecting a method for groundwater quantification the objective of the study should be known prior (Xu & Beekman, 2003). Given the objectives of this study and the available data, the Chloride Mass Balance method is used.

The equation applicable to recharge calculation is presented by (Xu & Beekman, 2003) in Jonker (2016) and David (2013) as:

R= $\left(\frac{Clp}{Clgw}\right) * MAP$

Where;

R= Recharge (mm/a)

Clp= Chloride in rain (mg/l)

Clgw= Chloride in groundwater (mg/l)

MAP= Mean annual precipitation (mm)

The chloride mass balance method is applied to the saturated zone. Water samples were collected from selected boreholes in the study area (Table 4.1). The hydro-chemical (chloride content) analysis for the Kavango West and East regions is available from the field trip undertaken in March 2020, from boreholes drilled in the two regions in 2020 under the Nawasa 2019/2020 Drought Relief Program and from data that was accessed from the Growas II database within the Department of Water Affairs (DWA), mainly the chloride content obtained during the drilling of the sampled boreholes.

The chemistry of the rain is only limited to the content of chloride, these are the only other parameter required in the determination of groundwater recharge using the Chloride Mass Balance approach. The chloride content in rainfall data is, however, close to non-existent in Namibia. Rainfall samples were collected during the field trip from several rainfall stations in the study area and analyzed for chloride at the laboratory. Chloride in rainfall data was furthermore obtained from Klock (2001).

4.3.4 Groundwater Storage Calculations

The storage of the Kalahari Group aquifers in the study area was determined by multiplying the saturated aquifer thickness (ΔH) of the unit and the surface area (A) by the porosity/ specific yield (S) (Mac Donald et al., 2012). Therefore:

Groundwater storage V=$\sum A\ S\ \Delta H$.

4.3.5 Groundwater Resource Potential Calculations

The groundwater potential was only determined after determining the recharge rates and groundwater storage of the aquifers. Results from the above analysis were used in the calculation of groundwater potential. It is worth noting that the values obtained represent maximum volumes (m^3) of groundwater estimated, which is potentially available for abstraction annually under conditions of no abstraction and normal rainfall.

A basic water-balance approach was used for the potential calculations (DWAF, 2006).

Resource potential = $R_e + \left({S_v}/{D_i}\right) - B_f$

Where, R_e= Mean Annual Potential Recharge (m/a)

S_v= Mean Volume of Water stored in Aquifer (m^3)

D_i= Drought Index- Output of Harvest Potential (Baron et al., 1998)

B_f= Mean Annual contribution to River Baseflow- Okavango River

According to Baron et al. (1998), the rainfall reliability factor can be used to calculate the drought index, this is equal to the Median/ 20^{th} Percentile of the annual rainfall, where the expected length of drought is reflected by the inverse. An average of 1.25 was obtained for the drought index and was, hence, used for the study (Appendix 3).

The baseflow contribution data is provided by the Department of Water Affairs, Hydrology Division. One station located in Rundu with reliable data from 1945 to 2020 was used to determine the annual average baseflow contribution from the aquifer into the perennial Okavango River (Appendix 4). An average of 177.11 Mm^3/a was obtained and was, therefore, used in this study.

4.3.6 Groundwater Availability and Exploitation Estimates

Transmissivity and borehole yield is commonly used when determining possibilities of groundwater abstraction. The magnitude of transmissivity data affords a notion of how a hydrogeological body can easily transmit water. Transmissivity data can, therefore, be used as a decisive factor when considering groundwater abstraction possibilities (Holland, 2012). However, transmissivity data are scarce in the study area, as such yields for the Kalahari aquifers, determined from several pumping tests analyzed for the study area were used. Borehole yields do not only indicate the capacity of boreholes to deliver water, they are also able to indicate the rate at which these boreholes provide water. In essence, the yields depend on both the pump capacity and aquifer potential. Boreholes must therefore be drilled in a way that matches the transmissivity and nature of the aquifer, and be spaced suitably to allow capturing all the groundwater available in an aquifer. A range of possible values was determined for the identified middle and lower Kalahari aquifer based on lithology.

5 RESULTS AND DISCUSSIONS

5.1 Hydraulic Parameters of the Kalahari aquifers

5.1.1 Storativity/Specific Yield

The storativity/specific yield of the Kalahari aquifers in the study area is essential for the calculation of the storage of groundwater and the resource potential. Therefore, these aquifers were assigned average storativity/specific yield which is presented in Table 5.1. The storativity/specific yield for the Kalahari aquifers was obtained from the analysis of pumping test data of forty (40) boreholes from the study area.

Table 5.1: Storativity/Specific yield values assigned to the Kalahari Aquifers (Data source, DWA)

Group/Formation	Average storativity/Specific yield
Middle Kalahari/Eiseb Formation	0.07
Lower Kalahari/Tsumkwe Formation	0.003

Not surprisingly, the lower Kalahari aquifers have recorded low storativity/ specific yield compared to the middle Kalahari aquifers based on the pumping test data. The value obtained is relatively higher for the middle Kalahari aquifer and slightly lower for the low Kalahari when comparing it to the storativity/specific yield value assumed for the sediments of the Kalahari Group, which is presented in DWA (1997) as 0.005.

5.1.2 Groundwater level and aquifer saturated thickness

Various approaches can be employed into estimating the thickness of the aquifer taking into account whether or not the base of a particular aquifer is well defined. The water level used in the calculation of the saturated aquifer thickness represents the rest water levels obtained during the drilling of the boreholes.

Using the borehole completion reports for the regions and in addition to literature, the saturated thickness of the Kalahari Group sediments for each 50 m interval is calculated. The calculated saturated aquifer thickness is presented in Table (5.2). Through a drilling campaign that was carried out by DWA in (1997), it was determined that the saturated thickness of the middle Kalahari is less than 100 m. With a decrease in the saturated thicknesses, most borehole yields were noted to decline.

An average of 52.42 m is calculated for the middle Kalahari aquifer (Tsumkwe Formation) for the Kavango West and East regions and 77.69 for the lower Kalahari aquifer (Eiseb Formation). It is worth noting that the thickness averages obtained were dominated by the deeper and thicker deposits.

Table 5.2 Saturated thickness of the Kalahari aquifers in 50 m interval

Group/Formation	**Depth Interval (m)**	**Average Water Level (mbgl)**	**Base Aquifer (mbgl)**	**Saturated Thickness (m)**
Middle Kalahari/Eiseb Formation	0-50	22.89	50	27.11
	51-100	26.55	100	73.45
	101-150	68.47	150	81.53
	150-200	92.62	200	107.38
Lower Kalahari/ Tsumkwe Formation	0-50	16.92	50	33.08
	51-100	20.33	100	79.67
	101-150	48.95	150	101.05
	150-200	66.40	200	133.60

5.2 Environmental Isotope analysis

The environmental isotopes (^{18}O, ^{2}H, Tritium), is composed of elements isotopic ratio that makes up the water molecules, these elements are subject to environmental processes and change (Abiye, 2013). The variation of isotope components does not only assist in the determination of the age and origin of different water bodies (Levin & Verhagen, 2013). They can also assist in the following (Gat et al., 2000):

- Provide an estimate for the degree to which mixing is taking place,
- Determining the proportion and location of water recharge and,
- Indicate the groundwater flow’s velocity.

5.2.1 Stable Isotopes

Even though stable isotopes do not provide the residence time of the sampled groundwater, they do provide a tool that differentiates between modern recharge, past recharge or, recharge from other sources (Kendall, 1998). The $\delta^{18}O$ and $\delta^{2}H$ data for different sampling points within the study area including boreholes, rainfall and the Okavango River are presented in Table 5.3. The water samples are plotted on the $\delta^{18}O$ versus $\delta^{2}H$ graph (Figure 5.1). For the interpretation of results, a Local Meteoric Water Line for the Cuvelai Etosha Basin (CEB) has been included. The CEB has a similar physiographic and climatic setting to the study area. The CEB LMWL which was developed from rainfall data collected between 2013 to 2015 and historical data has a slope of 7.2 and intercepts at +4.4 ($\delta^{2}H= 7.2* \delta^{18}O + 4.4‰$) (Hamutoko, 2018).

The Global Meteoric Water Line (GMWL) ($\delta^{2}H= 7.91* \delta^{18}O + 8.72‰$) (Terzer et al., 2013) was also plotted and used as a reference for the interpretation of the results. Even though useful, it must be noted that the GMWL is associated with data that is too broad and does not necessarily provide insight into conditions that are unique to the study area. Most groundwater samples are displaced from the LMWL, but plot parallel to the LMWL with a few outliers. A few samples were plotted on the LMWL with two or three samples plotting above the LMWL. The relative proportions of $\delta^{2}H$ and $\delta^{18}O$ that is contained in water when measured are referred to as the d-excess, this measure can be portrayed visually as a deviation index from the GMWL D=10 in the $\delta^{18}O/\delta^{2}H$ space (Abiye et al., 2013). Deuterium-excess ($d\text{-}excess=\delta\,^{2}H-8\delta^{18}O$) is calculated for the samples collected within the study area and is summarized in Table 5.3. A range of variation of 4.32‰ – 13.70‰ was obtained, showing an influence of regional moisture circulation in the study area.

Table 5.3: Results of the Environmental isotopic samples collected

Sample ID	**Sample location**	**Latitude**	**Longitude**	**$\delta^{18}O$ (‰)**	**s.d.**	**$\delta^{2}H$ (‰)**	**s.d.**	**d-excess (‰)**
AKS1	Kapangwena	-17.83577	18.75473	-9.46	0.09	-64.52	0.54	11.15
AKS2	Desi	-17.98836	18.7839	-9.49	0.12	-67.93	0.29	7.97
AKS3	Nkambe	-18.12884	18.73435	-9.33	0.18	-65.79	1.18	8.86
AKS4	Tcalikawa	-18.27316	18.73761	-9.45	0.14	-66.36	0.98	9.24
AKS5	Sipwi	-17.98155	18.98177	-8.72	0.09	-62.45	0.50	7.29
AKS6	Tapahutha	-18.14468	21.65592	-9.44	0.16	-61.80	1.07	13.70
AKS7	Rupetho	-18.14468	21.65592	-8.58	0.16	-60.29	0.95	8.38

Sample ID	Sample location	Latitude	Longitude	$\delta^{18}O$ (‰)	s.d.	$\delta^{2}H$ (‰)	s.d.	d-excess (‰)
AKS8	Omega	-18.02855	22.19917	-8.67	0.12	-60.09	1.33	9.25
AKS9	Thikange	-18.10292	21.48038	-9.53	0.16	-64.44	1.19	11.81
AKS10	Mukuviteya	-18.03963	20.95791	-9.23	0.12	-61.66	1.00	12.21
AKS11	Tcwiba	-18.43813	20.65737	-9.09	0.14	-64.71	0.76	8.04
AKS12	Livayi	-18.20588	20.99039	-7.80	0.14	-54.51	0.83	7.89
AKS13	Kahenge	-17.67612	18.67242	-9.10	0.12	-62.95	0.32	9.84
AKS14	Naingopo	-18.57639	19.70692	-8.70	0.14	-61.04	0.82	8.56
AKS15	Nkurenkuru town	-17.63215	18.58639	-6.81	0.16	-43.89	0.77	10.61
AKS16	Mpungu	-17.67431	18.23087	-9.11	0.12	-66.02	0.23	6.90
AKS17	Cause West	-17.92551	18.17229	-9.64	0.19	-67.37	0.90	9.76
AKS18	Sawato	-17.65355	18.38408	-9.65	0.18	-67.60	0.93	9.63
AKS19	Vikota	-18.19972	20.22908	-8.43	0.15	-62.55	0.85	4.88
AKS20	ShinungaToring	-18.16090	20.2776	-9.60	0.10	-66.58	0.85	10.19
AKS21	Tcausha	-18.35120	20.54189	-9.46	0.13	-63.86	1.75	11.80
AKS22	Ngone	-17.92076	19.94223	-9.63	0.14	-65.14	0.61	11.89
AKS23	Mururoteya	-17.91382	20.17214	-9.31	0.41	-63.89	2.03	10.57
AKS24	Shamapiri	-18.01488	20.49401	-9.30	0.06	-65.40	0.37	9.03
AKS25	Hamweyi Manyondo	-18.22229	19.73993	-9.68	0.08	-67.01	0.40	10.43
AKS26	Gcigco	-18.43498	19.76516	-9.85	0.07	-68.62	0.36	10.15
JINNAM2	Sambui	-17.90710	20.0139	-9.19	0.15	-66.69	1.29	6.80
JINNAM3	Nyangana	-18.01510	20.6754	-9.19	0.10	-64.98	0.30	8.54
JINBH3	Bravo	-18.44800	18.04867	-8.96	0.39	-67.32	1.43	4.32
JINBH7	Ncaute	-18.37080	19.83067	-9.33	0.14	-66.97	0.99	7.68
JINBH8	Klein Karakuwisa	-18.84040	19.72279	-8.98	0.12	-64.87	0.61	7.00
JINBH10	Zadang	-18.99100	19.7358	-8.85	0.08	-64.13	0.65	6.70
JINBH9	Satoka	-18.91755	19.68625	-9.34	0.07	-66.87	0.33	7.82
AKS30	Okavango River - Nkurenkuru site	-17.62143	18.61515	-9.13	0.10	-62.82	0.36	10.20
AKS29	Okavango River- Rundu site	-17.87269	19.80273	-6.78	0.08	-44.53	0.42	9.73
AKS32	Okavango River- Popa falls site	-18.12230	21.5829	-7.42	0.18	-48.23	1.09	11.13
AKS31	Mpungu Rainfall	-17.66451	18.23269	-6.06	0.14	-32.56	1.11	15.89
JINR1	Ndonga Linena rainfall	-17.95299	20.47504	-4.51	0.12	-26.68	1.02	9.44
JINR2	Mashare rainfall	-17.89747	20.21395	-4.61	0.16	-27.60	0.64	9.27
JINR3	Rundu rainfall	-19.76871	17.9127	-3.41	0.09	-22.53	0.70	4.77
JINR4	Rundu Guesthouse rainfall	-19.74833	17.91967	-13.39	0.07	-94.16	1.38	12.95

A close scattering of the groundwater samples is observed with a few samples branching out. The isotopic composition of the groundwater samples ranges between $\delta^{18}O$ -6.81 ‰ ~ $\delta^{18}O$ -9.85 ‰ indicating relatively water that was recharged in a warmer region. Some groundwater samples plotted directly on the LMWL indicating direct infiltration of rainwater. Several samples from the study area plotted below the LMWL indicating infiltration after evaporation, even though most of these samples were plotted parallel to the LMWL with a limited evaporation enrichment. The groundwater samples are more depleted in both $\delta^{18}O$ and $\delta^{2}H$ than the Okavango River and rainfall. One river sample collected upstream of the Okavango River was plotted with some groundwater samples. A mixing trend between the river water and most of the groundwater is portrayed in the study area. It must be noted that most groundwater samples from boreholes along the river have isotopic values similar to the river samples, showing the possibility of seepage from/into the Okavango River. Whereas samples from boreholes located further from the Okavango River plotted away from the samples collected from the river.

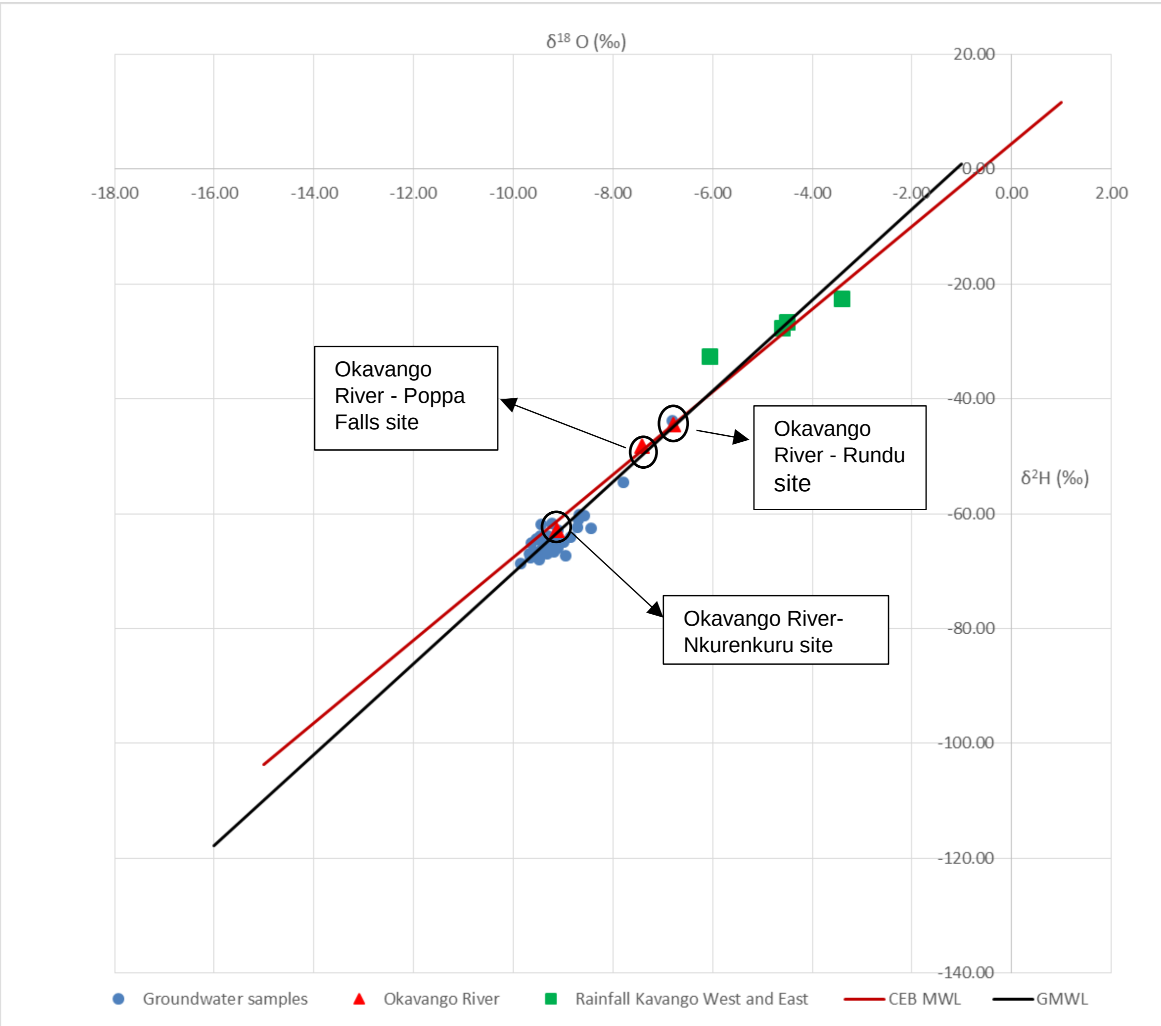

Figure 5.1: Plot of the stable isotope data on a δ18 O versus δ2H graph, relative to both the Global and Local Meteoric Water Lines

The surface water samples collected from the three selected sites on the Okavango River show a narrow range of stable isotope values of $\delta^{18}O$ -6.78 ‰~ $\delta^{18}O$ -9.18 ‰ which is relatively similar to groundwater. The surface water stable isotope signature displays the Okavango River being more depleted upstream, while more enriched downstream, It can be assumed that the Cuito River that flows from the Angolan highlands into the Okavango River downstream has a different isotopic signature to that of the Okavango River. Two river samples were plotted directly on the LMWL and one was plotted slightly below the LMWL. The rainfall samples collected in the study area are more enriched in $\delta^{18}O$ and $\delta^{2}H$ compared to the groundwater and the surface water samples. The isotopic signature of the surface water can be interpreted as water mixed with groundwater, water that has gone through some evaporation and rainfall that is from a different location and not from the study area. It is possible to suggest that this rainfall is from the catchment area in Angola. The limited amount of isotopic data in the study area does not allow a clear distinction between the type of effects (continental, altitude, seasonal) attributing to the isotopic composition in groundwater.

5.2.2 Tritium

The tritium values obtained from the laboratory for the collected groundwater and surface water samples (Table 5.4) ranged between 0.0 TU to 0.9 TU for groundwater and 1.5 TU to 1.8 TU for surface water, respectively. The presence of tritium in most of the sampled boreholes indicates modern recharge in the study area. There is a clear indication of base flow within the Okavango River. Most tritium values of groundwater samples are relatively low (0.2 to 0.7 TU) with one sample (AKT10) measuring zero tritium content. Two groundwater samples (AKT2 and AKT7) have tritium of 0.8 TU and 0.9 TU respectively.

Table 5.4: Tritium results of the samples collected

Sample ID	Sample location	Latitude	Longitude	Tritium (TU)	
AKT1	Nyangana	-18.0151	20.6754	0.2	±0.2
AKT2	Sambiu	-17.9071	20.0139	0.8	±0.2
AKT3	Satoka	-18.9176	19.6863	0.4	±0.2
AKT4	Okavango river (Andara site)	-18.0630	21.4480	1.8	±0.3
AKT5	Okavango river (Poppa Falls)	-18.1222	21.5807	1.8	±0.3
AKT6	Nkambe	-18.1288	18.7344	0.2	±0.2
AKT7	Omega	-18.0286	22.1992	0.9	±0.2
AKT8	Okavango river (Rundu site)	-17.8727	19.8027	1.5	±0.3
AKT9	Nkurenkuru	-17.6322	18.5864	0.7	±0.2
AKT10	Kahenge	-17.6761	18.6724	0.0	±0.2
AKT11	Okavango river (Nkurenkuru site)	-17.6214	18.6152	1.8	±0.3
AKT12	Shamapiri	-18.0149	20.4940	0.5	±0.2

The Tritium vs $\delta^{18}O$ plot (Figure 5.2) shows groundwater samples recharged from a similar source over a different period except for sample AKT9 which represents water recharged from a different source. Groundwater shows distinctively less tritium content than the river, it can, therefore, be assumed that a considerable fraction of the water that recharged the aquifers has low tritium concentrations.

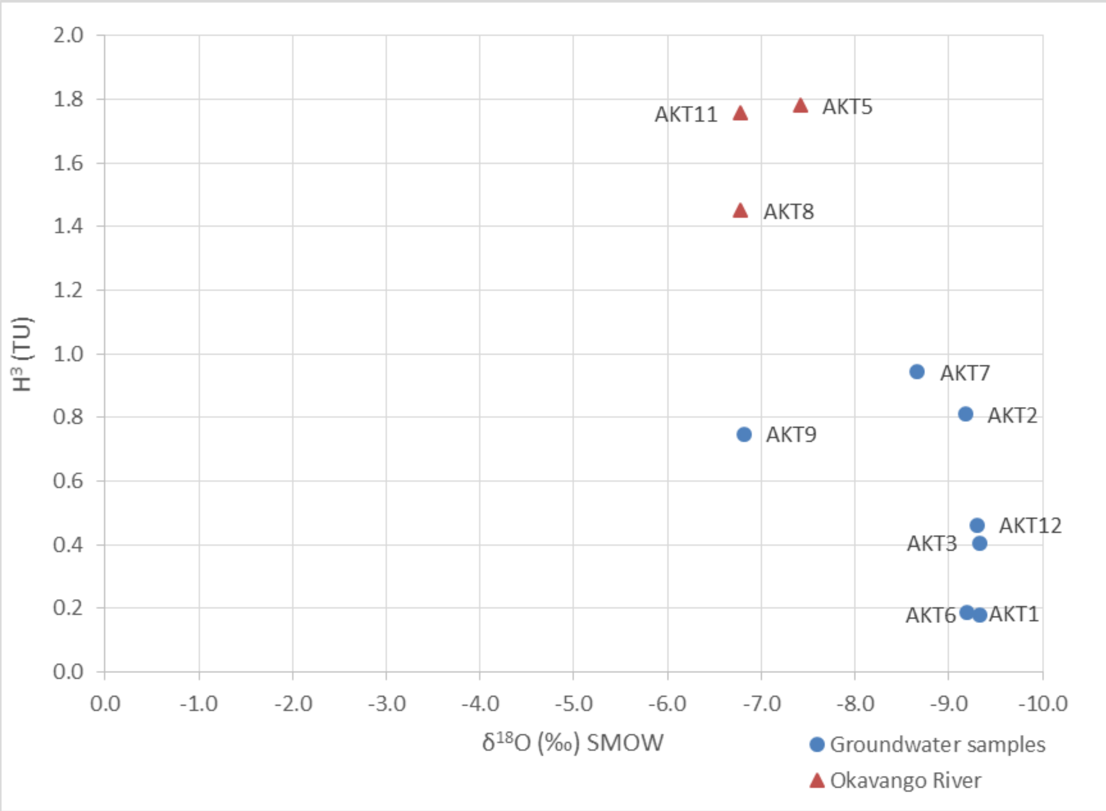

Figure 5.2: Plot of tritium vs δ18O of the collected samples in the study area

The initial tritium content in rainfall is estimated at 2.73 TU (Lindenmaier & Christelis, 2012). Namibia lacks data on tritium in rainfall. It is worth noting that Windhoek has only recorded tritium in rainfall until the year 2000. Considering this fact, data for Windhoek was, therefore, not used. An average value was obtained from the analysis done in the Cuvelai Etosha Basin (CEB) in 2008 and the amount obtained was assumed for the rainfall in the study area. An attempt was made to calculate the mean residence time of the groundwater and the river water (Table 5.5). The residence time of the Okavango River upstream (Nkurenkuru site) is similar to that of the Okavango River downstream with a residence time of 7.5 years. Middle stream of the river (Rundu), the water is relatively older, 10.7 years. This may be attributed to baseflow that is from different aquifers i.e the baseflow into the river at Rundu could be water which is stored in the aquifer at a longer time whereas the baseflow into the river at both Nkurenkuru and Andara could be water stored in the aquifer at a shorter time. Samples from the lower Kalahari aquifer have a longer residence time compared to the samples from the middle Kalahari aquifers. One sample (AKT6) from a borehole tapping in the middle Kalahari aquifer did, however, record a high residence time compared to other samples in the same aquifer.

Table 5.5: Residence time of the samples collected

Sample ID	Locality	Tritium (T. U)		Residence time (Years)
AKT1	Nyangana	0.2	±0.2	46.9
AKT2	Sambiu	0.8	±0.2	22.0
AKT3	Satoka	0.4	±0.2	34.4
AKT6	Nkambe	0.2	±0.2	46.9
AKT7	Omega	0.9	±0.2	19.9
AKT9	Nkurenkuru	0.7	±0.2	24.4
AKT10	Kahenge	0	±0.2	-
AKT12	Shamapiri	0.5	±0.2	30.4
AKT4	Okavango river (Andara site)	1.8	±0.3	7.5
AKT5	Okavango river (Poppa Falls)	1.8	±0.3	7.5
AKT8	Okavango river (Rundu site)	1.5	±0.3	10.7
AKT11	Okavango river (Nkurenkuru site)	1.8	±0.3	7.5

5.2.3 Origin

Two fundamental groups are revealed from the plot of the $\delta^{18}O$ vs $\delta^{2}H$ for the samples collected in the study area, namely the data points that are plotted on/along the local meteoric water line and the data points that fell below the LMWL. Some samples plot along the local meteoric water line representing groundwater that is similar to present meteoric water, this alternatively confirms how valid it is to use the CEB-LMWL and not the GMWL. The samples collected from the Okavango River were also plotted on the LMWL. From the $\delta^{18}O$ vs $\delta^{2}H$ plot, it is also noted that three rainfall samples plotted above the LMWL.

5.2.4 Recharge

Recharge is one of the factors required in the estimation of the groundwater potential in the study area. Tritium is present in most of the groundwater samples analyzed for radionuclides, substantiating that modern recharge is taking place in the study area. Sample AKT10 did, however, record negligible tritium, indicating that modern recharge is possibly absent in a few localities within the study area.

The stable isotopes data collected for the study area indicate that there are signs of direct rainfall recharge as some groundwater samples fall on the LMWL when plotted on the $\delta^{18}O$ versus $\delta^{2}H$ graph. Signs of seepage from the Okavango River is also observed. The chloride mass balance (section 5.4) indicates that there is recharge occurring at some places in the study area, this is confirmed by the tritium data.

From the analysis of stable isotopes, the chloride contents recorded in the study area and as stated in previous studies, several sources of groundwater recharge are evident. Such as recharge along preferred flow paths, direct recharge through the jointed or karstified hard rocks, and direct diffuse infiltration through the sand covers. Indirect recharge from the ephemeral rivers(Omuramba Omatako), and the perennial Okavango River is also observed within the study area.

Episodic recharge events are assumed for the study area when looking at both recent recharge and major recharge inputs. This assumption is concluded from observations made from the sampled boreholes in the study area. Boreholes sampled within the same lithological units, same aquifer system recorded different values of tritium. Some recorded no tritium and others recorded low tritium content with some samples showing some degree of mixing. Added to this, uniform recharge of groundwater is also observed in the Kalahari aquifers. This is observed from the parallel displacement of most groundwater samples to the local meteoric water line. It is observed that most of the samples were plotted below the local meteoric line, however, parallel to the LMWL indicating water that was recharged under conditions of direct infiltration.

5.2.5 Surface water and aquifer connectivity

Extensive interaction between the surface water and groundwater is observed from the samples collected in the study area. Sample AKS13 from a borehole located in Kahenge has a stable isotope signature similar to that of the Okavango River (upstream) and plots directly next to the surface water sample collected from Nkurenkuru. However, the tritium value (AKT10) was 0.0 TU, in essence, indicates no modern recharge. This borehole can be considered to be tapping from the lower Kalahari aquifer that is losing water to the river. AKS15 sample from a borehole located in Nkurenkuru town upstream of the Okavango River plotted with the surface water samples, however, when considering the tritium content of 0.7 TU was obtained. This sample taps from the middle Kalahari aquifer. It is observed that the Okavango River is gaining water from the aquifer at this locality. From the collected water samples in the study area, it is assumed that the Okavango River is both a gaining and loosing river.

According to the hydrochemical analysis done by Itengula (2021) for the Kavango West and East region, the groundwater in the Kalahari aquifers can be easily linked to five water types namely Ca-Mg-HCO_3, Na-HCO_3, Na-Cl, Na-Cl-SO_4, Na-Ca-HCO_3, with a certain degree of mixing between this water types. Four of these water (Ca-Mg-HCO_3, Na-HCO_3, Na-Cl-SO_4, and Na-Ca-HCO_3) types are more common, and Na-CO_3 is a predominant water type.

Most of the samples collected from both the middle Kalahari and lower Kalahari aquifers plotted in the same cluster and thus indicating mixing between the two aquifers. Both the middle Kalahari and the lower Kalahari aquifer show a variable $\delta^{18}O$ and $\delta^{2}H$ with no visible trend, some plotting on the CEBLMWL and others below the CEBLMWL.

5.3 Recharge Quantification

When considering groundwater management, recharge quantification becomes relatively important especially in semi-arid regions such as the study area with generally low rainfall averages and high rates of evapotranspiration. It is essential to estimate groundwater recharge rates to ensure the long-term sustainability of this resource. Therefore, groundwater recharge was estimated across the study area using the Chloride Mass Balance method. The following equation presented by Xu & Beekman, 2003, was used in the calculation:

$$R = \left(\frac{Clp}{Clgw}\right) * MAP$$

Where;

R= Recharge (mm/a)

Clp= Chloride in precipitation (mg/l)

Clgw= Chloride in groundwater (mg/a)

MAP= Mean annual precipitation (mm/a)

5.3.1 Mean Annual Precipitation (MAP)

Precipitation data were obtained from the Namibian Meteorological Services. Two stations were considered in this study.The Rundu station is located in the Kavango East, while the Nkurenkuru station is located in the Kavango West. These stations illustrated the variability of the annual precipitation. For the Rundu station, the data from 1940 to 2019 were reliable with the mean annual precipitation of 567.4 mm/a. The Nkurenkuru station contain the rainfall data from 1924 to 2011. By excluding the years 1974, 1966, 1983-1985, 1998-2008 due to missing data, the mean annual precipitation of 577.1 mm/a was recorded. Annual precipitation for the hydrological years, taken from October 1 of a given year to September 30 was used. An average of 570 mm/a is thought to be representative for the entire study area and is, therefore, used for recharge calculation.

5.3.2 The Concentration of Chloride in rainfall and groundwater

Time-related data of chloride in rainfall is valuable in the calculation of recharge using the CMB method, this data is, however, not available for the study area. Namibia lacks data for chloride concentration in rainwater, which is more difficult to obtain in a highly understudied area like the study area. The chloride concentration in rainwater used for this study is estimated from the five rainfall samples collected during the field trip and data acquired from Klock (2001). An average chloride in rainwater of 0.8 mg/l was estimated.

Data for chloride concentration in groundwater was obtained from the sampled boreholes in the study area, additional chloride concentration was obtained from sampled boreholes from a parallel study done by Itengula (2021), sampling from 2019/2020 NAWASA Drought Relief Drilling project, and data from Growas II database hosted at the DWA. Such data, the distribution of chloride is presented in Figure 5.3 using kriging points.

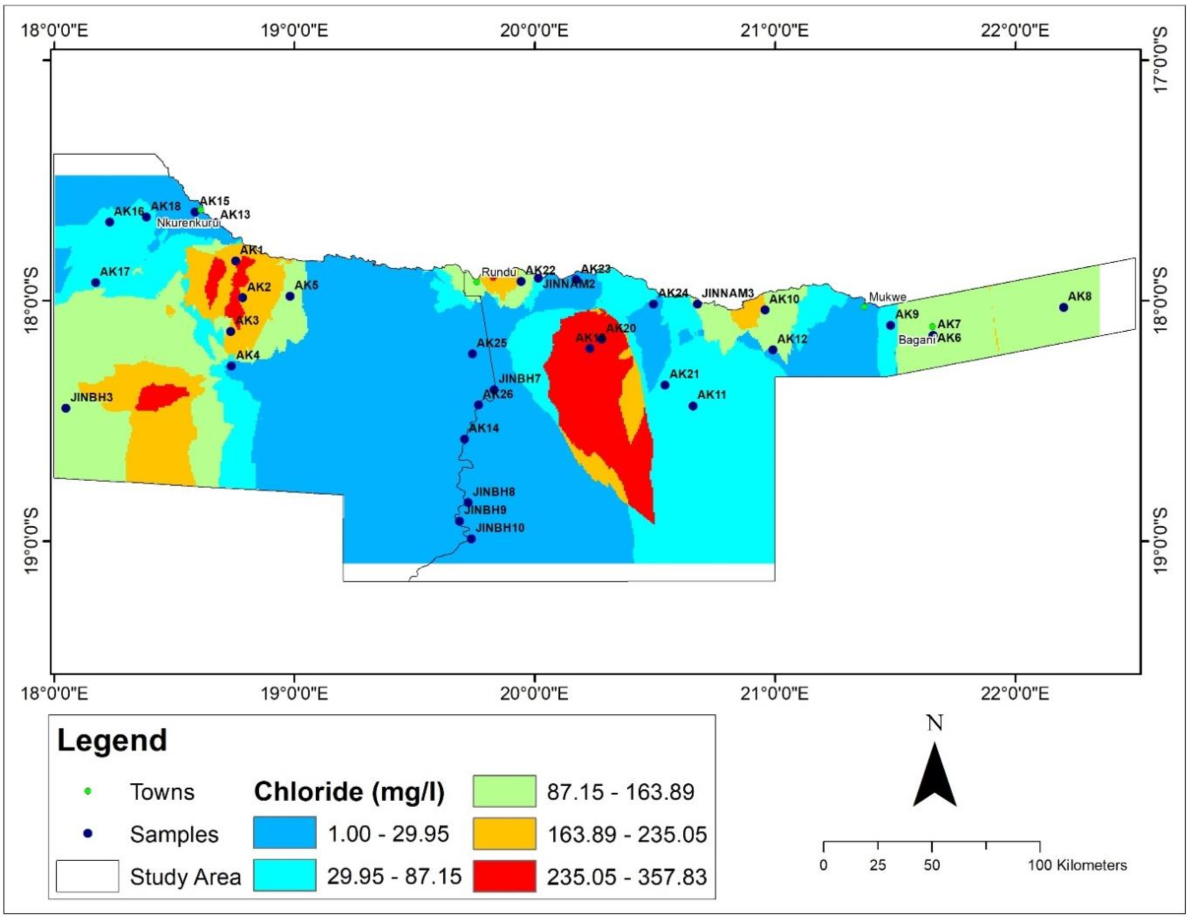

Figure 5.3: The spatial distribution of chloride concentration in the study area

5.3.3 Chloride Mass Balance Calculation

Mean annual recharge values were calculated for several sites across the study area, the recharge values obtained were interpolated utilizing the kriging method to create a recharge map (Figure 5.4). The recharge values obtained range from 0.32 mm locally to more than 456 mm with an average of 6.03 mm/a of recharge calculated for the study area. Recharge varies at different sites within the study area. Recharge calculated for the sampled sites is summarised in Table 5.6.

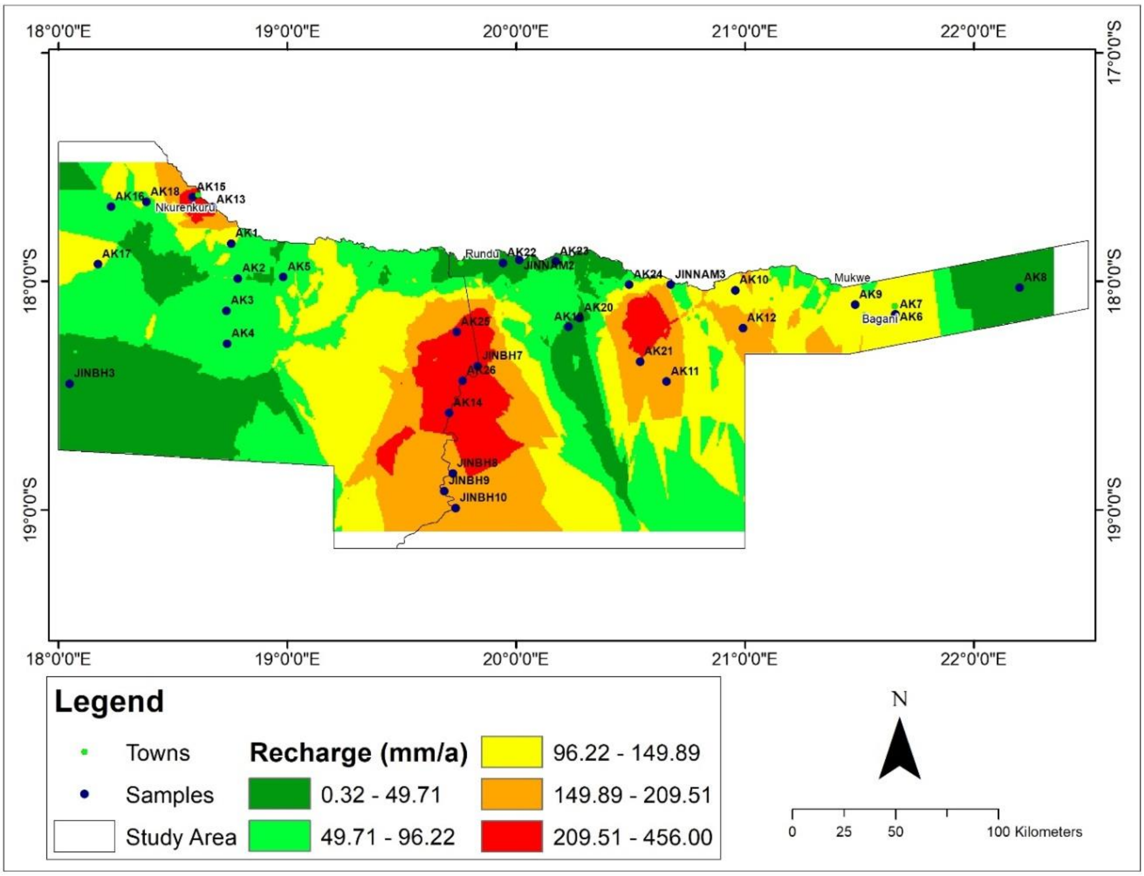

Figure 5.4: The interpolated recharge values in the study area

Sampled sites with a chloride concentration of 1 mg/l are observed in the study area recording relatively high rates of recharge amount, these sites are particularly close to the perennial Okavango River and along the dormant Omuramba Omatako (ephemeral river system found in the study area). Klock (2001) indicated that most parts of the research area recorded recharge values of above 50 mm/a even though mostly covered by the Kalahari.

This corresponds very well with most recharge values calculated for the study area. Also, Klock (2001) observed that areas with rainfall amounts of above 550 mm/a locally recorded recharge rates above 60 mm/a.

Table 5.6 : Recharge values for the sampled borehole

Sequence/ Group	Sample ID	Locality	Chloride in Groundwater (mg/l)	Chloride in Rainwater (mg/l)	Recharge (mm/a)
Middle Kalahari	AK1	Kapangwena	1	0.8	456.00
	AK2	Desi	7	0.8	65.14
	AK3	Nkambe	1	0.8	456.00
	AK4	Tcalikawa	24	0.8	19.00
	AK5	Sipwi	85	0.8	5.36
	AK8	Omega	150	0.5	1.90
	AK10	Mukuvi Teya	1	0.5	285.00
	AK11	Tcwiba	25	0.6	13.68
	AK12	Livayi	14	0.5	20.36
	AK14	Naingopo	1	0.7	399.00
	AK15	Nkurenkuru TC	1	0.9	513.00
	AK16	Mpungu	13	0.9	39.46
	AK17	Cause West	7	0.9	73.29
	AK23	Mururoteya	9	0.6	38.00
	AK25	Hamweyi Manyondo	1	0.7	399.00
	AK26	Gcigco	1	0.7	399.00
	JINBH3	Bravo	65	0.9	7.89
	JINBH7	Ncaute	1	0.7	399.00
	JINBH9	Satoka	1	0.7	399.00
	JINNAM2	Sambui	125	0.7	3.19
Lower Kalahari	AK9	Thikange	1	0.5	285.00
	AK13	Kahenge	1	0.8	456.00
	AK18	Sawato	10	0.9	51.30
	AK20	ShinungaToring	220	0.6	1.55
	AK21	Tcausha	8	0.6	42.75
	AK22	Ngone	15	0.7	26.60
	JINNAM3	Nyangana	1	0.6	342.00
	JINBH8	Klein Karakuwisa	15	0.7	26.60
	JINBH10	Zadang	17	0.7	23.47

An attempt was made to quantitatively estimate recharge for different Kalahari Groups (Table 5.7). An average recharge of 17.08 mm/a and 14.25 mm/a was obtained for the middle Kalahari Groupand the lower Kalahari Group aquifers respectively.

Table 5.7: Recharge within the Kalahari Group aquifers

Group/Sequence	MAP (mm/a)	Total Area (km^2)	Average Groundwater Chloride (mg/l)	Average Rainfall Chloride (mg/l)	Recharge (mm/a)	Recharge (Mm^3/a	Recharge %
Middle Kalahari	570	45920.5	26.7	0.8	17.08	784.32	2.99
Lower Kalahari	570	45920.5	32	0.8	14.25	654.37	2.50

Indirect recharge from surface water to groundwater system in the study area is assumed to occur when the river gradient change by rapids, reducing the gradient through the damming of water upstream. Steps are created through successive rapids causing the dammed water in the rapids above the regional groundwater in the area, accounting for water losses from the river to the groundwater system contributing to recharge (DWA, 1997).

Recent recharge is also visible in the study area, most of which is taking place in the Omuramba Omatako area and several boreholes close to the river (Figure 5.4). This is confirmed by Itengula (2021), through water type plot, where most of the samples at Omuramba Omatako are Ca-Mg-CO_3 water type which indicates recent recharge. Klock (2001) has also assumed that indirect recharge in the area arises from ponded water bodies or ephemeral rivers i.e. Omuramba Omatako, this is observed in the study area.

5.4 Groundwater Storage

The Kalahari Group sediments are assumed to cover most of the study area (Figure 2.4), constituting the most important aquifers in the region where a vast majority of boreholes drilled for rural and bulk water supply intersect these aquifers (Biwac, 2002). As such, the groundwater potential is only calculated for the Kalahari aquifers in the study area. Within the study area, both the middle Kalahari aquifer and the lower Kalahari aquifer presented great storage volumes with the middle Kalahari aquifer having a greater storage volume. The volumes of the groundwater held in the storage of the Kalahari aquifers are calculated (Table 5.8). A larger specific yield for the middle Kalahari aquifer has contributed to the larger volumes. It is of importance to note that the groundwater storage volumes calculated for the Kalahari aquifers in the study area represent average values that may increase or decrease depending on several factors. In addition, not all the groundwater stored in these aquifers is available for abstraction, when considering effective porosity, the volume of water pumped out of an aquifer is frequently less.

The storage of groundwater also reflects the morphology and the spatial distribution of the structural features present. The distribution of this feature varies even though not considered in the Kalahari aquifers, this in essence makes the calculation of the groundwater storage difficult.

The confidence in the calculated groundwater storage results is a function of several components. Site-specific data were not always available due to the area being large and highly understudied. Some vital information was scarce for the study area leading to some data being generalized. Therefore, the degree of confidence in the calculated volumes as a representative of the Kalahari Group aquifers in the study area is moderate.

Table 5.8: The storage volume held in the Kalahari aquifers

Group/ Sequence	Lithology	Total Area (Km^2)	Saturated Thickness (m)	Storativity /Specific Storage	The volume of groundwater stored in the aquifer		
					Total (Mm^3)	Unit (m^3/km^2)	%Total Volume
Middle Kalahari	Sandstone, Sand & Clay	45 920.5	52.42	0.07	168 500.68	3669 399.94	94.03
Lower Kalahari	Marl and Clay; Sandstones, Conglomerate & Gravel	45 920.5	77.69	0.003	10 702.69	233 069.97	5.97
Total					179 203.37	3902 469.91	100

5.5 Groundwater Potential

The potential of groundwater for the Kalahari aquifers is determined after attempting to understand various control on groundwater in the two regions. With this, the resource potential is quantified and summarized in Table 5.9. The total groundwater resource potential estimated for the Kalahari aquifers in the study area is 144 447.16 x 10^6 m^3/a. Both the lower and the middle Kalahari aquifers have shown great potential in the study area, however, the middle Kalahari aquifer has the greatest potential accounting for 94 % of the total resource potential.

The total potential calculated for the Kalahari aquifers in the study area represents each aquifer's potential capacity without abstraction. A considerable volume of water is available for abstraction from each of these aquifers when considering a full utilization of the aquifers.

The exploitability of the resource not only provides the size indication of the resource but also indicates how this resource can be exploited in a manner that is sustainable without mining. This knowledge is deemed useful for the water managers, helping in the regulation.

Table 5.9: Groundwater resource potential of the Kalahari Aquifers

Group/ Sequence	**Lithology**	**Total Area (Km^2)**	**Groundwater Storage (Mm^3)**	**Drought Index (Years)**	**Recharge (Mm^3/a)**	**Baseflow (Mm^3/a)**	**Groundwater Resource Potential (Mm^3/a)**	**Annual Groundwater Resource Potential (m^3/km^2)**
Middle Kalahari	Sandstone, Sand & Clay	45920.5	168 500.68	1.25	784.32	177.11	135 407.75	2948 742.93
Lower Kalahari	Marl and Clay Sandstones, Conglomerate & Gravel	45920.5	10 702.69	1.25	654.37	177.11	9039.41	196 849.11
Total							144 447.16	3145 592.04

5.6 Groundwater Availability and Exploitation

Given the scope of the project, the transmissivity and the borehole yield for the middle and the lower Kalahari aquifers could not be directly measured and was therefore determined from several pumping test analyses throughout the study area. Even so, the lack of data availability in the study area has resulted in only a limited number of pumping test data being analyzed. The transmissivity and the borehole yields that can reasonably be expected within the Kalahari aquifers in the study area are summarized in Table 5.10. The borehole yields are used in the determination of the likely availability of groundwater accessible per borehole per km^2 in the middle and lower Kalahari aquifers (Table 5.11).

Table 5.10: Transmissivity and borehole yield obtained for the study area

Group/ Sequence	Lithology	Transmissivity (m^2/d)	Borehole Yield (m^3/h)	Average Borehole Yield (m^3/a)
Middle Kalahari	Sandstone, Sand & Clay	1-870	0.5-15	74738.37
Lower Kalahari	Marl and Clay	8-900	3-50	133595.79
	Sandstones, Conglomerate & Gravel			

Transmissivity values ranging between 1 to 870 m^2/day for the middle Kalahari and 8 to 900 m^2/day for the lower Kalahari are estimated for the study area. These transmissivity values are highly variable and according to Kashaigili (2010), this is attributed to the heterogeneity in the aquifer system. Aquifer thickness and hydraulic conductivities control transmissivity, hence, the high transmissivity of the Kalahari aquifers is associated mostly with the sediment types. These sediments can range from clay size particles to sand to boulders and a decrease in the later results in poor transmissivities. Similarly, the borehole yields in the Kalahari aquifers depend on the size of the particles, however, the borehole yields can as well generally depend on the drilling method and borehole design. It was observed that the yields of boreholes drilled in recent years in the Kalahari aquifers have improved when compared to boreholes drilled earlier. Biwac (2002) noted that the majority of the boreholes drilled in the Kalahari yield between 5 m^3/h to 10 m^3/h, this is reflected in the yields obtained where the middle Kalahari yield is averaged at 8.53 m^3/h, while the yields in the lower Kalahari aquifers are at an average of 10.77 m^3/h. It is of importance to note that moderate to good groundwater potential zones are expected in the Kalahari sediments close to the Okavango River channels. These areas along the river are expected to comprise high-yielding boreholes. Low yields in the study area can be expected in areas where high clay content is comprised in the Kalahari sediments and areas with deep water tables.

Even though not the highest yielding aquifers, the Kalahari aquifers have proven essential to the livelihood of the inhabitants in the regions, the groundwater has proven sufficient to the needs of the inhabitants. The yields obtained can be regarded as suitable to satisfy the general rural water supply-demand in the study area. When considering the aridity of the study area where recharge is generally low and deep water tables in certain areas, the flow of the groundwater is relatively steady. The Kalahari sediments can be regarded to contain storage that is sufficient in providing a natural buffer against climate variability and can therefore sustain abstraction even through periods of drought and inter-annual recharge variations.

Table 5.11: The likely availability of accessible groundwater per borehole per km^2 in the Kalahari aquifers

Group/ Sequence	**Lithology**	**Total Area (Km^2)**	**Recharge (Mm^3/a)**	**Groundwater Resource Potential (Mm^3/a)**	**Groundwater Availability**			
					Average Borehole Yield (m^3/a)	**Annual Borehole Yield (m^3/km^2)**	**% of Recharge**	**% of Resource Potential**
Middle Kalahari	Sandstone, Sand & Clay	45 920.5	784.32	135 407.75	74 738.37	1.627	0.009	0.00005
Lower Kalahari	Marl and Clay	45 920.5	654.37	9 039.41	133 595.79	2.909	0.02	0.001
	Sandstones, Conglomerate & Gravel							

The Kalahari Group aquifers exhibit relatively good potential, these aquifers are mainly hosted in the sandstones which are very efficient aquifers usually with high porosity and permeability. A similar study done by Jonker (2016) in the Eastern Kalahari Region of South Africa on the potential of the aquifers in that region indicated that the Kalahari sediments had the greatest potential compared to the fractured aquifers in the area. The high clay content comprised in the sediments at certain areas as well as the calcrete within the Kalahari sediments has somewhat decreased the permeability of these sediments subsequently decreasing the yields. However, the Kalahari aquifers remain a vital source of water in semi-arid regions such as the study area with relatively high storage capabilities. It is worth noting that the storage and resource potential calculations carried out in this study only cater to thicker and deeper deposits within the Kalahari sediments (the middle and lower Kalahari aquifers) since the upper Kalahari aquifer is rarely utilized in the study area and not widely spread. If all the aquifers were to be taken into consideration, the estimated storage and resource potential would have been more than what is currently being utilized. The significant storage space in the Kalahari aquifers can permit the storage of groundwater recharge for numerous decades, thus providing a dynamic buffer against variable climates.

The Kalahari aquifers have shown some recharge in some parts of the study area. The chloride mass balance and the environmental isotope data have indicated the presence of active recharge with higher recharge close to the Okavango River and the Omuramba Omatako area. When considering a regional scale, recharge from the Okavango River becomes of limited importance. Indirect and local diffuse recharge is assumed to be a dominant recharge mechanism in the area even though poor quantitative estimates characterize this type of recharge. Also, the geological nature of the Kalahari Group sediments, which are at times associated with clay-dominated sands can at times attribute to poorly estimated recharge. The clay-dominated sand has the capability of absorbing rainwater in large volumes and poorly transmits this water through the zones of unsaturation.

The quality of the groundwater in these aquifers can be considered of reasonable quality with minimal outliers that presented poor quality water. Most of the groundwater is considered to be suitable for both human consumption and livestock consumption. An extensive study on the quality of the Kalahari aquifers was carried out by Itengula (2021) parallel to this study.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Droughts in Namibia have been of great concern during the last few years (2015-2018), and has caused devastating effects on local communities and agriculture with most of the communities experiencing water shortages. Even with a perennial water source, the Kavango regions are of no exception. Most communities especially those further from the Okavango River experienced water shortages resulting in inhabitants having to travel long distances to obtain water for domestic purposes. As such, drilling boreholes under drought relief programs has become a common practice. Increasing the dependency of the inhabitants in the study area on groundwater. There is insufficient knowledge of the hydrogeological processes within these aquifers, in essence increasing groundwater exploitation of the aquifers.

Results of the stable isotope show a close scattering of the samples indicating the main group of groundwater recharged under similar weather conditions and similar moisture sources except for sample AKS12 collected at Livayi and sample AKS15 collected from Nkurenkuru that showed recharge under different moisture sources and deferring weather conditions. Episodic recharge is also observed from the $\delta^{18}O$ and tritium where groundwater from similar sources is recharged over different years within the study area. Tritium content in certain boreholes and the hydrochemical studies done for the study area have indicated modern recharge occurring in the Kalahari aquifers.The analysis of stable isotopes and tritium were also employed in determining the connectivity between the Okavango River and the Kalahari aquifers, outlining where the Okavango River is gaining water from the aquifers in the region and areas where it is losing water to the aquifers.

The spatial distribution of chloride in the Kalahari aquifers indicates that recharge is occurring in most of the Kalahari aquifers at varying recharge rates. Areas with high chloride content are linked to low rates of recharge while areas with low chloride content are linked to high rates of recharge. Several samples in the study area recorded chloride content of 1 mg/l indicating modern and high recharge rates. High rates of recharge are assumed to occur along the boundaries of the Kavango West and East Region within the Omuramba Omatako area. Recharge rates of high magnitude are also observed close to the Okavango River in Nkurenkuru and the north-eastern side of the Kavango East Region.

Results of the Resource Potential calculations show the middle Kalahari aquifer recording the greatest potential accounting for 94 % of the total potential. The middle Kalahari aquifer is unconfined while the lower Kalahari is semi-confined in the study area and therefore recording lower potential due to its degree confinement. A total of 144 447,16 x 10^6 m^3/a is estimated for the Kalahari aquifers demonstrating a great resource potential, with significant storage space. These aquifers can therefore be regarded as high potential aquifers. According to Itengula (2021), these aquifers generally have good water quality with only minor areas that showed deteriorating water quality i.e. the Mpungu area in the Kavango West Region. If utilized sustainably, the Kalahari aquifers can sustain abstraction through periods of drought.It should be noted that there are numerous factors at play when determining the behaviour of the Kalahari aquifers. Even though some generalizations have to be made, one must note that there is a wide range of interdependent factors within the same aquifers and they will, therefore, not exhibit similar characteristics. As such, detailed knowledge of groundwater conditions is required when considering strategies on how to use water for a particular aquifer. Also, the groundwater storage and resource potential estimated within the project area indicate the distribution and availability of the groundwater resources within the Kalahari aquifers on a regional scale. Therefore, detailed studies are still required to develop, quantify and exploit single groundwater abstraction schemes.

6.2 Recommendations

Lack of data in the project area has resulted in the study being more general, the volumes of groundwater estimated give an indication of the distribution and availability of groundwater in the Kalahari aquifers at a regional scale. When developing and exploiting groundwater abstraction schemes in the regions it would be recommended that detailed studies be carried out. Information on aquifer thickness of both fractured and primary aquifers could in the future assist in the determination of the groundwater available for the entire regions therefore it is recommended that the delineation of the aquifers be considered in the future. The exact aquifer parameters can be obtained from a multiwell pumping test analysis, it is therefore recommended that monitoring and observation wells be drilled in the study area.

It is recommended that more tritium analysis together with stable isotopes be conducted in the study area to identify the level at which the aquifers in the region are interacting with the Okavango River. Water sampling for isotope analysis should be included in the future groundwater quality sampling schedule.

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8 APPENDICES

Appendix 1- Measured physical parameters of the collected samples

Sample ID	Borehole ID	Locality	Latitude	Longitude	Cond. (mS/cm)	Temp˚C	pH
AK1	WW202839	Kapangwena	-17.83577	18.75473	48.5	27.4	7.56
AK2	WW40571	Desi	-17.98836	18.7839	84.1	27.9	7.19
AK3	WW202840	Nkambe	-18.12884	18.73435	78.4	27.3	7.13
AK4	WW40567	Tcalikawa	-18.27316	18.73761	60.2	29.2	7.30
AK5	WW202842	Sipwi	-17.98155	18.98177	133.3	27	7.68
AK6	WW204259	Tapahutha	-18.14468	21.65592	31.4	28.7	7.32
AK7	WW204253	Rupetho	-18.14468	21.65592	48.8	27.6	7.27
AK8	WW34811	Omega	-18.02855	22.19917	197.2	27.6	7.35
AK9	WW204252	Thikange	-18.10292	21.48038	38.6	27.5	7.92
AK10	WW202988	Mukuvi Teya	-18.03963	20.95791	42.5	27.6	7.14
AK11	WW40407	Tcwiba	-18.43813	20.65737	65.5	27	7.18
AK12	WW204132	Livayi	-18.20588	20.99039	109.5	25.7	7.37
AK13	WW28594	Kahenge	-17.67612	18.67242	33.1	26.6	8.29
AK14	WW202832	Naingopo	-18.57639	19.70692	40.7	26.8	7.70
AK15	WW201974	Nkurenkuru TC	-17.63215	18.58639	48.7	29.7	8.03
AK16	WW10021	Mpungu	-17.67431	18.23087	62.3	26.8	8.27
AK17	WW202837	Cause West	-17.92551	18.17229	138.2	27.5	7.91
AK18	WW202835	Sawato	-17.65355	18.38408	38.3	27	7.77
AK19	WW40572	Vikota	-18.19972	20.22908	72.7	26.4	6.90
AK20	WW204140	ShinungaToring	-18.1609	20.2776	21.1	27.8	7.36
AK21	WW204138	Tcausha	-18.3512	20.54189	52.3	27.1	7.55
AK22	WW204256	Ngone	-17.92076	19.94223	73.3	23.7	8.50
AK23	WW204257	Mururoteya	-17.91382	20.17214	67.2	26.6	7.45
AK24	WW204134	Shamapiri	-18.01488	20.49401	88.4	27	7.90
AK25	WW204255	Hamweyi Manyondo	-18.22229	19.73993	38.4	26.3	7.32
AK26	WW204254	Gcigco	-18.43498	19.76516	38.0	27.1	7.50
JINNAM2	WW25540	Sambui	-17.9071	20.0139	21.5	-	8.90
JINNAM3	WW31944	Nyangana	-18.0151	20.6754	52.3	-	7.40
JINBH3	WW41274	Bravo	-18.448	18.04867	122.8	-	7.40
JINBH7	WW7912	Ncaute	-18.3708	19.83067	42.4	-	7.80
JINBH8	WW33868	Klein Karakuwisa	-18.8404	19.72279	72.1	-	8.10
JINBH10	WW39967	Zadang	-18.991	19.7358	65.5	-	7.50
JINBH9	WW35534	Satoka	-18.91755	19.68625	44.5	-	

Appendix 2 Choride amounts in groundwater and physical parameters

Sample ID	Locality	Latitude	Longitude	pH	Conductivity (mS/m)	TDS (mg/l)	Cl- mg/l
AK1	Kapangwena	-17.83577	18.75473	8.2	49.5	332	1
AK2	Desi	-17.98836	18.7839	7.8	87.3	585	7
AK3	Nkambe	-18.12884	18.73435	7.7	80.5	539	1
AK4	Tcalikawa	-18.27316	18.73761	8.3	60.6	406	24
AK5	Sipwi	-17.98155	18.98177	8.1	136.8	917	85
AK6	Tapahutha	-18.14468	21.65592	7.7	32.5	218	1
AK7	Rupetho	-18.14468	21.65592	7.7	50.6	339	1
AK8	Omega	-18.02855	22.19917	8	202	1353	150
AK9	Thikange	-18.10292	21.48038	7.7	39.6	265	1
AK10	Mukuvi Teya	-18.03963	20.95791	7.8	43.8	293	1
AK11	Tcwiba	-18.43813	20.65737	7.9	67.5	452	25
AK12	Livayi	-18.20588	20.99039	7.8	107.9	723	14
AK13	Kahenge	-17.67612	18.67242	7.9	34.2	229	1
AK14	Naingopo	-18.57639	19.70692	8.2	41.5	278	1
AK15	Nkurenkuru TC	-17.63215	18.58639	8	47.9	321	1
AK16	Mpungu	-17.67431	18.23087	8.1	65	436	13
AK17	Cause West	-17.92551	18.17229	8.4	139.2	933	7
AK18	Sawato	-17.65355	18.38408	7.9	39	261	10
AK19	Vikota	-18.19972	20.22908	7.2	748	5012	2360
AK20	Shinunga Toring	-18.1609	20.2776	8	217	1454	220
AK21	Tcausha	-18.3512	20.54189	8	53.5	358	8
AK22	Ngone	-17.92076	19.94223	8.4	76.2	511	15
AK23	Mururoteya	-17.91382	20.17214	7.7	68.2	457	9
AK24	Shamapiri	-18.01488	20.49401	7.8	90	603	5
AK25	Hamweyi Manyondo	-18.22229	19.73993	7.3	39.2	263	1
AK26	Gcigco	-18.43498	19.76516	7.9	38.7	259	1
JINNAM 2	Sambui	-17.9071	20.0139	8.9	215	1441	125
JINNAM 3	Nyangana	-18.0151	20.6754	7.4	52.3	350	1
JINBH3	Bravo	-18.448	18.04867	7.4	122.8	823	65
JINBH7	Ncaute	-18.3708	19.83067	7.8	42.4	284	1
JINBH8	Klein Karakuwisa	-18.8404	19.72279	8.1	72.1	483	15
JINBH10	Zadang	-18.991	19.7358	7.5	65.5	439	17
JINBH9	Satoka	-18.91755	19.68625	7.7	44.5	298	1

Appendix 3 Rainfall chloride collected in the study area (2020)

Locality	Chloride amount in rainfall (mg/l)
Rundu	1
Kahenge	1
Mashare Agriculture	1
Mpungu	1
Andara	1
Rundu Met Services	1

Appendix 4- Drought Index Calculation

Year	October	November	December	January	February	March	April	May	September	Total
1940-1941	19.6	28.4	220.7	204.0	74.4	1.0	27.4	0.0	0.0	575.6
1941-1942	29.2	7.9	108.7	78.0	86.6	0.0	0.0	0.0	0.0	310.4
1942-1943	29.5	16.0	150.9	140.0	63.0	167.6	152.7	2.5	0.0	722.1
1943-1944	2.5	39.4	100.3	170.7	316.5	106.4	0.0	0.0	0.0	735.8
1944-1945	6.6	51.3	96.0	87.6	210.6	132.3	0.0	0.0	0.0	584.5
1945-1946	2.0	177.0	153.9	75.7	170.9	59.4	13.5	0.0	0.0	652.5
1946-1947	5.3	148.3	0.0	99.6	132.8	110.2	8.6	0.0	0.0	504.9
1947-1948	23.6	52.1	94.2	179.3	327.7	159.5	24.4	0.0	0.0	860.8
1948-1949	5.3	42.4	9.1	93.7	29.2	133.4	19.1	0.0	0.0	332.2
1949-1950	0.0	40.9	39.9	163.1	135.1	93.2	34.0	1.3	0.0	507.5
1950-1951	0.0	26.2	126.2	86.3	65.8	54.4	147.3	11.9	0.0	518.1
1951-1952	80.9	33.4	177.1	125.8	287.8	7.6	0.0	0.0	0.0	712.6
1952-1953	48.5	39.7	88.6	171.4	207.1	56.5	65.7	6.5	2.0	686.0
1953-1954	20.5	65.2	44.2	159.6	170.5	96.8	35.0	0.0	0.0	591.8
1954-1955	6.3	22.2	264.0	188.0	52.8	179.4	34.8	0.0	0.0	747.5
1955-1956	20.9	70.3	133.1	142.9	205.4	127.7	23.1	0.0	24.5	747.9
1956-1957	1.2	55.5	11.0	82.0	237.8	83.0	3.0	0.0	0.8	474.3
1957-1958	29.5	79.5	106.0	297.1	101.1	34.0	4.5	0.0	20.5	672.2
1958-1959	47.5	18.5	143.9	85.9	156.0	191.0	18.0	1.8	0.0	662.6
1959-1960	11.8	40.2	62.0	50.5	244.8	37.7	72.2	13.0	0.0	532.2
1960-1961	0.0	76.4	28.0	126.1	89.1	165.3	51.9	18.0	0.0	554.8
1961-1962	4.0	92.4	88.9	115.0	233.3	12.6	11.5	0.0	0.0	557.7
1962-1963	8.0	70.0	56.0	126.5	76.0	55.7	74.0	0.0	0.0	466.2
1963-1964	42.0	74.1	108.5	47.1	7.5	76.0	3.0	0.0	0.0	358.2
1964-1965	16.2	11.7	67.0	89.0	105.3	13.0	15.4	0.0	0.0	317.6
1965-1966	6.0	103.1	21.0	208.5	133.5	128.0	28.5	0.5	4.1	633.2

1966-1967	1.2	7.3	104.7	198.2	133.9	84.0	179.5	0.0	0.0	708.8
1967-1968	2.2	191.0	41.0	234.2	35.5	232.5	24.5	0.0	0.0	760.9
1968-1969	6.6	54.2	7.1	133.2	271.5	110.6	0.0	0.0	3.0	586.2
1969-1970	21.5	95.2	44.8	58.8	74.0	0.0	0.0	0.0	0.0	294.3
1970-1971	3.0	35.2	148.8	389.2	136.0	57.5	42.5	1.5	0.0	813.7
1971-1972	0.5	9.6	53.0	148.0	36.5	267.0	35.5	0.0	0.0	550.1
1972-1973	41.0	0.0	68.5	42.0	58.5	73.1	20.5	0.0	0.0	303.6
1973-1974	0.0	61.0	78.3	343.5	225.4	12.4	69.1	0.3	11.7	801.7
1974-1975	48.7	83.1	78.1	69.8	117.7	72.3	23.4	19.4	3.0	515.5
1975-1976	11.6	24.4	36.5	246.5	225.2	98.2	28.0	0.0	4.7	675.1
1976-1977	12.2	70.5	71.5	163.5	220.5	100.8	44.2	17.2	7.3	707.7
1977-1978	24.4	37.4	266.8	206.9	387.4	114.0	76.6	0.0	0.0	1113.5
1978-1979	56.2	57.8	47.3	121.3	135.1	45.5	13.2	7.5	0.0	483.9
1979-1980	15.9	58.1	34.3	89.0	147.9	167.4	15.9	0.0	8.7	537.2
1980-1981	11.5	67.9	57.8	141.0	175.7	68.1	15.1	0.0	4.1	541.2
1981-1982	26.6	60.5	87.8	74.2	90.7	60.3	21.4	0.0	2.9	424.4
1982-1983	7.0	74.2	87.3	175.9	46.9	38.8	2.9	0.0	0.0	433.0
1983-1984	5.5	51.1	132.2	64.8	80.3	75.5	12.8	7.0	0.0	429.2
1984-1985	25.8	32.1	82.4	123.1	145.4	91.2	2.6	2.4	0.0	505.0
1985-1986	34.7	0.0	0.0	120.6	142.1	118.9	16.7	0.0	24.0	457.0
1986-1987	106.2	109.9	56.4	59.5	130.5	101.2	5.6	0.0	0.0	569.3
1987-1988	3.1	19.8	70.3	208.0	52.5	24.4	39.9	0.0	0.0	418.0
1988-1989	14.1	82.4	101.3	294.9	228.0	74.6	21.0	0.0	0.0	816.3
1989-1990	5.5	20.4	14.2	146.0	77.2	136.8	30.5	0.0	0.0	430.6
1990-1991	4.8	65.0	44.5	195.7	71.9	55.5	0.0	0.0	4.3	441.7
1991-1992	44.8	36.9	84.7	67.7	44.1	66.3	4.5	0.0	0.0	349.0
1992-1993	1.8	34.6	51.8	69.2	258.4	49.4	25.2	0.0	0.0	490.4
1993-1994	68.8	37.2	118.2	296.7	101.5	31.9	7.4	0.0	0.0	661.7
1994-1995	2.9	47.8	24.3	41.8	132.2	49.8	9.0	0.3	1.4	309.5

1995-1996	8.6	16.0	23.9	126.1	95.4	14.2	1.0	0.0	1.3	286.5
1996-1997	3.5	52.3	98.8	323.6	178.7	131.5	1.8	0.0	22.5	812.7
1997-1998	43.4	19.1	22.5	100.1	21.0	31.4	4.3	0.0	1.7	243.5
1998-1999	3.5	40.2	104.2	186.1	48.3	101.9	0.0	1.0	0.4	485.6
1999-2000	16.0	46.4	160.9	252.0	114.4	59.7	20.6	0.0	0.0	670.0
2000-2001	5.8	12.7	63.9	27.7	279.3	88.4	74.8	0.6	0.3	553.5
2001-2002	15.8	145.5	34.6	142.5	80.0	93.2	10.8	0.0	0.0	522.4
2002-2003	10.7	29.7	39.0	253.0	118.3	14.6	7.3	8.2	1.3	482.1
2003-2004	6.3	64.0	49.6	131.1	88.9	369.8	16.3	0.0	0.0	726.0
2004-2005	11.8	45.9	63.0	93.5	57.8	86.2	7.3	0.0	0.0	365.5
2005-2006	0.0	57.5	41.8	243.3	254.5	124.3	2.4	0.5	0.0	724.3
2006-2007	23.0	75.8	108.5	106.1	140.2	118.6	3.5	0.0	0.0	575.7
2007-2008	20.1	47.0	128.7	358.0	178.3	83.1	0.0	10.7	0.0	825.9
2008-2009	10.1	111.1	67.6	258.5	134.6	99.1	6.1	4.8	1.3	693.2
2009-2010	15.4	82.6	74.9	121.8	57.4	142.7	155.5	0.1	0.0	650.4
2010-2011	0.0	54.4	108.1	293.8	74.3	162.1	54.9	13.3	0.0	760.9
2011-2012	14.8	73.6	150.8	155.2	94.7	51.5	0.0	0.0	2.0	542.6
2012-2013	15.6	75.9	104.4	146.7	62.5	44.9	7.1	3.8	0.0	460.9
2013-2014	6.2	52.2	158.7	160.1	157.3	142.0	53.1	0.0	2.0	731.6
2014-2015	27.2	100.3	83.3	111.0	59.4	65.5	8.3	0.0	1.5	456.5
2015-2016	5.1	33.7	136.8	214.4	54.3	155.6	12.2	0.0	0.0	612.1
2016-2017	3.6	50.2	123.2	156.6	201.3	135.8	23.9	0.0	0.0	694.6
2017-2018	3.7	1.3	127.9	52.6	118.8	170.2	36.7	0.0	0.0	511.2
2018-2019	16.6	4.3	136.5	43.6	63.6	24.9	0.0	0.0	0.0	289.5
Average	17.2	54.4	86.1	151.6	134.6	92.0	27.4	2.0	2.0	567.4

Median	553.5
20th Percentile	432.0
Drought index	1.3

Year	October	November	December	January	February	March	April	May	September	Total
1925-1926	0.0	23.8	54.9	66.6	73.0	95.6	93.2	25.8	0.0	432.9
1926-1927	7.7	119.1	68.0	134.0	30.0	83.3	0.0	0.0	0.0	442.1
1927-1928	29.7	120.8	36.4	94.0	82.9	199.5	13.8	5.3	8.3	590.7
1928-1929	2.8	44.5	23.7	76.9	60.4	60.9	0.0	0.0	0.0	269.2
1929-1930	0.0	60.7	93.6	57.0	58.9	41.0	84.6	0.0	0.0	395.8
1930-1931	0.0	17.2	66.7	59.0	88.5	175.4	86.1	0.0	0.0	492.9
1931-1932	25.1	69.5	37.3	14.4	76.0	88.7	19.0	0.0	0.0	330.0
1932-1933	0.0	28.1	153.9	106.0	37.7	25.1	0.0	0.0	0.0	350.8
1933-1934	0.0	32.9	103.2	269.3	200.7	128.5	33.8	0.0	0.0	768.4
1935-1936	0.0	23.4	65.1	89.0	92.7	250.6	5.6	5.8	0.0	532.2
1936-1937	20.3	7.3	47.2	122.3	148.4	58.3	109.5	0.0	0.0	513.3
1937-1938	11.9	32.8	135.0	133.0	126.7	15.8	18.1	34.8	0.0	508.1
1938-1939	35.0	75.1	78.7	63.8	69.4	222.9	7.5	0.0	0.0	552.4
1939-1940	45.7	0.0	0.0	176.0	278.9	55.9	59.7	0.0	17.5	633.7
1940-1941	35.1	30.5	61.7	97.5	27.9	27.2	0.0	0.0	0.0	279.9
1942-1943	44.7	40.9	144.3	163.8	79.5	18.3	0.0	0.0	0.0	491.5
1943-1944	2.0	70.9	81.8	249.7	194.1	125.0	0.0	0.0	0.0	723.4
1944-1945	0.0	63.0	121.9	114.3	131.6	162.6	0.0	0.0	0.0	593.3
1945-1946	0.0	110.5	187.2	40.4	33.3	55.6	33.5	0.0	0.0	460.5
1946-1947	29.2	27.7	67.3	104.4	203.5	107.4	0.0	0.0	0.0	539.5
1947-1948	24.9	29.0	184.9	64.3	196.6	24.9	50.0	2.0	0.0	576.6
1948-1949	26.2	127.0	18.5	65.8	44.2	127.8	2.0	0.0	0.0	411.5
1949-1950	0.0	21.1	52.6	140.2	172.7	108.7	36.6	0.0	0.0	531.9
1950-1951	1.5	52.3	269.0	149.7	106.8	123.0	119.0	32.2	0.6	854.1
1951-1952	84.0	48.2	113.7	71.4	126.5	1.0	0.0	0.0	0.0	444.8

1952-1953	11.8	88.2	114.5	200.2	177.0	38.6	102.7	5.3	0.0	738.3
1953-1954	22.5	46.3	119.6	127.8	112.2	213.1	89.5	0.0	4.6	735.6
1954-1955	7.7	37.8	149.1	214.4	3.3	112.6	48.6	0.0	0.0	573.5
1955-1956	33.5	15.0	68.8	188.7	230.4	106.7	110.4	0.0	14.2	767.7
1956-1957	2.5	34.6	47.6	91.6	253.9	141.8	0.0	1.7	0.3	574.0
1957-1958	37.4	112.7	169.0	326.6	72.0	106.7	5.1	0.1	8.2	837.8
1959-1960	11.1	50.2	73.0	67.6	177.0	5.3	81.4	9.6	0.0	475.2
1960-1961	3.7	105.3	62.9	80.9	74.7	65.8	73.0	12.6	0.0	478.9
1961-1962	18.0	89.5	79.1	141.7	65.6	32.4	18.5	0.0	0.0	444.8
1962-1963	3.5	75.4	112.2	113.5	160.6	217.5	43.3	0.0	10.5	736.5
1963-1964	7.9	311.4	72.3	109.5	47.6	80.1	10.7	17.5	0.0	657.0
1964-1965	22.9	40.7	102.9	79.2	85.0	75.0	68.5	0.0	1.0	475.2
1967-1968	37.0	118.6	77.1	266.6	106.5	152.5	44.0	0.0	0.0	802.3
1968-1969	8.5	0.0	87.5	166.9	235.5	108.0	0.0	0.0	6.9	613.3
1969-1970	24.8	113.3	54.8	105.1	136.5	74.7	0.0	0.0	0.0	509.2
1970-1971	3.0	69.1	137.8	220.4	199.4	56.3	15.0	0.8	4.5	706.3
1971-1972	15.5	41.5	92.7	154.2	56.1	277.4	19.2	0.5	0.0	657.1
1972-1973	13.2	14.9	56.1	60.5	95.5	138.8	17.5	0.0	0.0	396.5
1973-1974	50.0	60.5	125.0	430.7	139.5	57.0	196.0	0.0	1.5	1060.2
1974-1975	12.5	44.2	91.8	136.5	167.3	201.5	34.8	1.5	0.0	690.1
1975-1976	13.2	21.7	53.1	352.2	169.2	138.2	15.5	0.0	0.0	763.1
1976-1977	33.0	30.7	81.9	71.2	197.5	83.7	113.0	8.5	0.0	619.5
1977-1978	0.0	35.3	190.1	160.0	196.8	149.2	31.0	0.0	1.2	763.6
1978-1979	23.4	53.7	164.2	181.6	195.6	19.1	1.5	0.3	3.2	642.6
1979-1980	19.2	108.0	44.7	72.0	103.1	150.3	36.5	0.0	1.1	534.9
1980-1981	0.0	24.0	102.4	158.6	206.2	98.8	17.2	0.0	0.0	607.2
1981-1982	0.0	71.1	76.5	63.4	196.7	71.2	23.3	0.0	0.9	503.1
1982-1983	0.0	52.9	164.7	152.8	44.8	0.0	35.6	10.0	0.0	460.8
1986-1987	67.3	57.1	26.0	54.5	194.4	80.5	0.0	0.0	1.0	480.8

1987-1988	3.6	37.0	161.7	130.9	169.3	60.8	58.9	0.0	0.0	622.2
1988-1989	9.5	43.7	173.1	242.2	186.6	20.5	99.7	0.0	0.0	775.3
1989-1990	0.0	0.0	27.1	190.3	14.7	185.6	21.6	0.0	0.0	439.3
1990-1991	12.8	65.7	118.4	210.6	130.6	102.2	0.0	0.0	6.7	647.0
1991-1992	16.5	21.1	97.8	97.3	67.4	68.9	0.0	0.0	13.4	382.4
1992-1993	14.2	37.1	143.0	117.7	92.7	71.0	2.1	0.0	0.3	478.1
1993-1994	59.3	43.7	78.0	452.6	172.9	45.7	1.7	0.0	0.0	853.9
1994-1995	0.0	37.9	25.1	17.8	90.4	141.9	21.9	0.0	0.0	335.0
1995-1996	0.0	50.4	45.0	146.3	87.0	1.5	0.0	0.0	0.0	330.2
1996-1997	0.0	76.0	83.0	171.5	212.8	158.2	0.0	0.0	9.2	710.7
2006-2007	0.0	34.5	149.4	89.3	76.2	90.5	8.5	4.0	0.0	452.4
2007-2008	4.0	49.0	90.0	178.5	21.0	2.0	0.0	0.0	0.0	344.5
2009-2010	19.0	37.0	165.5	156.7	93.0	137.0	58.0	0.0	0.0	666.2
2010-2011	0.0	51.0	43.0	197.5	117.5	152.4	108.0	3.5	0.0	672.9
Average	15.9	55.6	95.1	142.2	123.1	98.1	35.4	2.7	1.7	569.6
								Median		552.4
								20^{th} Percentile		443.7
								Drought Index		1.2

Appendix 5- Baseflow