School of Geosciences

University of the Witwatersrand

Johannesburg, South Africa

CHARACTERIZATION OF THE PRIMARY KALAHARI AQUIFERS USING HYDROGEOCHEMISTRY AND ISOTOPE TECHNIQUES TO DEVELOP A GROUNDWATER MONITORING NETWORK, KAVANGO EAST AND WEST REGIONS, NAMIBIA

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A Research Report submitted to the School of Geosciences in partial fulfillment of the requirements for the Degree of Master of Science in Hydrogeology

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Johannesburg, 2021

DECLARATION

I Josephine I.N Itengula (Student number: 1928312) hereby declare that:

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Signature: ____________ on the 17 day of Dec 2021 at Windhoek, Namibia.

DEDICATION

Dedicated to my Late beloved Father:

Engelbert Ipinge Itengula

ACKNOWLEDGEMENTS

Firstly, I thank Jehovah for his guidance through all this work.

I would like to thank my sponsors i) The Ministry of Agriculture, Water and Land Reform and ii.) The Federal Institute for Geosciences and Natural Resources, for funding this degree inclusive of the fieldwork and laboratory work that were undertaken in its fulfilment.

I would like to sincerely thank my Supervisor, Prof. Tamiru Abiye for his guidance and support throughout the study and personally when it was necessary. I would also like to thank my supervisors and co-workers at MAWLR for always understanding when I needed time to focus on school.

I thank my parents, Mrs. Linda and Mr. Engelbert Itengula, my siblings Linda and Christian Itengula, Hilaria Ananias, Selma Eliphas, and my fiancé Des Amushila for their continuous support and encouragement. Thanks to Mr. Mike Ndongo for his assistance when needed most. Last but not least, I thank Ms. Anna David my very good friend and fellow student for the companionship, studying, and working together endlessly both in Johannesburg and Namibia.

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PARAMETERS

EC	Electrical Conductivity
Eh	Oxidation Reduction Potential referring to the normal hydrogen electrode
GPS	Global Positioning System
pH	Decimal logarithm of the reciprocal of the hydrogen ion activity
T	Temperature
TDS	Total Dissolved Solids

UNITS

°C	Temperature in degrees celsius
m	Meter
m^3	Cubic meter
mg/l	Milligrams per litre
ml	Millilitre
s	Seconds
%	Percentage
m b g l	Metres below ground level
‰	permill

NOMENCLATURE

AGW-Net:	Africa Groundwater Network
BGR:	Federal Institute for Geosciences and Natural Resources
BH/Bh:	Borehole
BIWAC:	Bittner Water Consult CC
CAN:	Central Areas of Namibia
DAPEES:	Directorate of Agricultural Production, Extension and Engineering Services Agricultural Extension Centres
DWAF:	Department of Water Affairs and Forestry
DWSSC:	Directorate of Water Supply and Sanitation Co-ordination, DWAF
ENWC:	Eastern National Water Carrier
GROWAS II:	National Groundwater Information System at DWAF, Geohydrology Division
IGMTBOA:	Integration of Groundwater Management into Transboundary Basin Organizations in Africa- a Training Manual by AGW-Net, BGR, IWMI, CapNet, ANBO, and IGRAC
IRLUP:	Integrated Regional Land Use Plan
IWRM:	Integrated Water Resource Management Plan
KE	Kavango East Region
KW	Kavango West Region
MASTER STATION:	A monitoring borehole within a strategic major national aquifer
MAWF:	Ministry of Agriculture, Water and Forestry
MAWLR:	Ministry of Agriculture, Water and Land Reform
MEFT:	Ministry of Environment, Forestry and Tourism
MME:	Ministry of Mines and Energy
NAMWATER:	Namibia Water Corporation Pty Ltd
NGDC:	Namibia Groundwater Development Consultants
OKAKOM:	The Permanent Okavango River Basin Commission
TBA:	Transboundary Basin Organization

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1 INTRODUCTION

1.1 General Introduction

The problem of water security in Namibia is growing, not just for the Central Areas of Namibia (CAN) but for the entire country at large. Governmental discussions concerning water require that the development of additional sources of water is fast-tracked, to ensure water security in a changing climate regime.

The former Kavango Region was divided into Kavango East and Kavango West regions in 2013, through the 4th Delimitation Commission under the Integrated Regional Land Use Plan (IRLUP). The capital of the Kavango East and West regions (hereinafter also referred to as the Kavango Region) are the towns of Rundu and Nkurenkuru, respectively. The Region is bordered by the important perennial Okavango River, which supports the livelihood of the inhabitants living nearby. Despite the strategic advantage the Okavango River provides, inhabitants that live further from the resource are in dire need of water and depend on groundwater resources.

More importantly, however, the Okavango River which is shared amongst Namibia, Angola, Botswana, and to a lesser extent Zimbabwe has been earmarked to supply water to the CAN area via the Eastern National Water Carrier (ENWC). According to the Integrated Water Resources Management Plan (IWRM Joint Venture Consultants Namibia, 2010) set out for the Okavango-Omatako Basin, the ENWC would transfer both surface water and groundwater to the central, eastern, and western parts of Namibia. Discussions for such a pipeline from the river are underway, although they will involve major implications for all the countries involved. The project would be the largest water supply infrastructure in Namibia upon implementation.

An assessment of hydrogeological researches done in the regions shows that a few groundwater studies have been conducted thus far, however, a lot more work needs to be done. Studies point towards the existence of groundwater bodies in the Kavango, and these bodies are currently being utilized. On the other hand, these aquifers have not been characterised; there is no information regarding the potential of the resource, recharge rates, aquifer behaviour, isotopic composition, and other important hydraulic parameters. This study has conducted hydrogeochemical and environmental isotope studies to aid in further understanding these aquifers.

1.2 Problem Statement

The Government of Namibia is potentially looking into piping water from the Okavango River to augment supply to the central areas of the country, which is challenging due to the transnational nature of the Okavango River. The Kavango East and West Regions constitute two main aquifers that are currently being utilized but are under-studied. A gap presents itself in that, the underground resources' potential and character is largely unknown, and thus it remains invisible for the above-mentioned purpose. This research proposes to add to existing knowledge through the use of hydrogeochemistry and isotopic studies, to assist with the characterization of the Kalahari Aquifers. A growing understanding of these aquifers will be essential in assisting decision-makers in their efforts to achieve water security for the CAN.

1.3. Aims and Objectives

The overall aim of the study is to characterise the Primary Kalahari Aquifers in the Kavango West (KW) and Kavango East (KE) Regions, through the examination of hydrogeochemistry and isotope signatures. Three study objectives are defined:

- To understand the nature and mechanisms of interactions between groundwater of the Primary Kalahari Aquifers and the Okavango River, through the use of isotope techniques and Hydrogeochemistry.
- To classify groundwater based on chemistry and determine the spatial variation in geochemical patterns and isotopic composition of the Primary Kalahari Aquifers.
- To design and define a mini-groundwater monitoring network for groundwater quality and quantity, to promote a good understanding of the groundwater system, for efficient and sustainable management

2 DESCRIPTION OF STUDY AREA

2.1 Location and Landscape

The Kavango East and Kavango West Regions lie in the north-eastern part of Namibia and form part of the Okavango-Omatako Basin (Figure 2-1). The Basin stretches well beyond the KE and KW to parts of the Otjozondjupa Region. In areal extent, the Okavango-Omatako Basin covers an area of 20 500 km^2, bordering Angola in the north and Botswana to the east (IWRM Joint Venture Consultants Namibia, 2010). The two Kavango Regions cover approximately 48 463 km^2 (Regional Council of Kavango Region, 2006). On a continental scale, the study area forms part of the Transboundary Okavango River Basin.

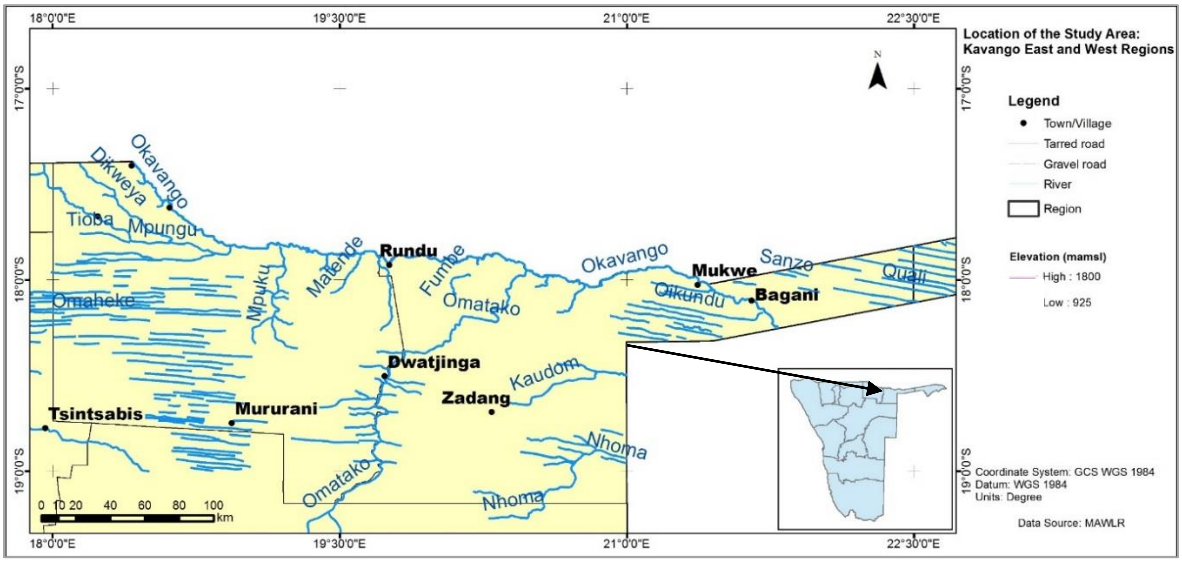


Figure 2-1: Location of Kavango East and West Regions in the northeast of Namibia

A flat landscape covered by thick Kalahari sand is typical for the Kavango Regions. Elevations vary from 1200 m in the central and southern parts of the two regions to 1150 m in the northwest, and the lowest-lying areas of 1000 m occur towards the Angola/Namibia border in Caprivi (Bittner Water Consult CC [BIWAC], 2002). Vegetation in the area comprises trees and shrubs intermixed with grassveld along the dry riverbeds and interdune corridors.

Kalahari woodland comprising broad-leafed deciduous trees grow in the deep sands, whilst the grass and shrubs grow in shallower soils (GEOCARTA Namibia et al., 2015). The predominant soil type is arenosol, which holds little nutrients due to its porous nature. Fluvisols and anthrosols occur along the river; these are utilized for crop cultivation in the floodplains. Calcisols with higher clay and silt proportions lie in interdune valleys and along the omurambas. These are better suited for crop growth.

2.2 Land Use

Agriculture is the main form of land use in the KE and KW, predominantly subsistence agriculture and livestock farming (Figure 2-2). Several agricultural projects have been set up as part of the

Governmental Green Scheme Projects. These include irrigation projects at Ndonga Linena situated approximately 130 km east of Rundu within the Ndiyona Constituency (KW), Shadikongoro in the Mukwe Constituency (KE), Shitemo (KE), Mashare (KE), Musese (KW), and Uvhungu Vhungu Farm (KE) and Sikondo (KW).

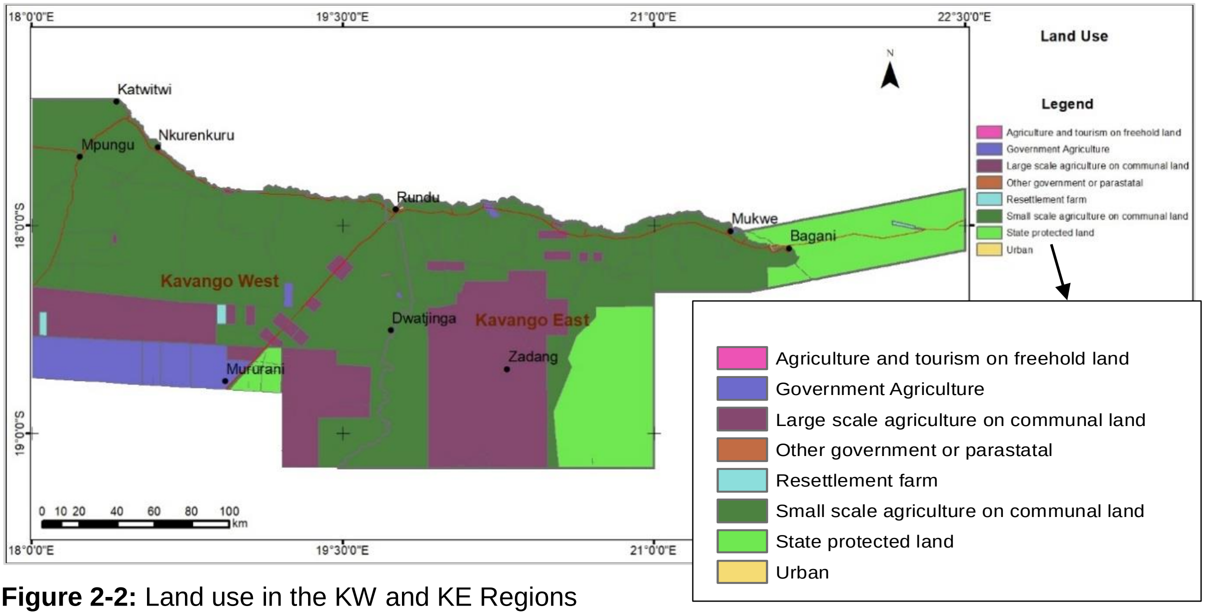


Figure 2-2: Land use in the KW and KE Regions

Irrigated agricultural land covers about 2 197 ha (The Permanent Okavango River Basin Water Commission [OKAKOM], 2010). Livestock farming with cattle and goats at ranches or cattle posts is an important feature for many households in both regions. Large-scale agriculture on commercial farms has surged over the years. Tourism owing to the beautiful sceneries of the Okavango River and wildlife at the Khaudum National bordering Botswana is another important land use feature. Various camps and lodges have been set up to accommodate the ever-increasing numbers of visiting tourists. Other uses of land in the two regions include resettlement farms, protected areas, collection of natural resources for food (mostly fish), construction, and fuel (firewood) and hunting (OKAKOM, 2010; Food and Agriculture Organization of the United Nations [FAO], 2014).

2.3 Climate

The regions' climate is characterised by semi-arid, warm with annual average temperatures of 20 °C, increasing in a southerly direction (Mendelsohn & Obeid, 2004). The two regions lie within the Tropical Summer rainfall zone, where the climate is both affected by the seasonal shift of the ITCZ, as well as by the development of the Angola Low-Pressure System (Reason et al., 2006, as cited in Oldeland et al., 2013).

Rainfall amounts in the study area vary between 450 mm and 600 mm spread out through the two regions. During the 2019/2020 rainfall season, the Kavango East received more rainfall than the Kavango West. Below normal to normal rainfall was recorded in the Kavango West and normal rainfall amounts were recorded in the Kavango East. On average, the two regions receivemore rainfall than that received in most parts of Namibia (GEOCARTA Namibia et al., 2015). Precipitation occurs in summer from October to April, with the highest amounts occurring in January and February (Mendelsohn & Obeid, 2003). The months from May to September are dry. The relative humidity is in the range of 30% in the drier season and about 60 to 70% in the rainy months (BIWAC, 2002). Evaporation rates amount to about 1,950 mm per year which equates to about four times the average rainfall i.e. a net loss. Evaporation is highest in September and October when temperatures are highest (Water Surveys Botswana, 2011).

The annual average rainfall from 50 years (1970-2020) record is calculated as 554 mm/a at the Rundu weather station. The highest amount is recorded in 1978 at 946 mm, and the lowest rainfall figure is recorded in 1992 at 270.8 mm. The years 1970, 1996, 1998, 2005, and 2019 recorded below-average rainfall figures amounting to 319.8 mm, 283 mm, 306.4 mm, 344.1 mm, and 343.1 mm, respectively (Figure 2–3).

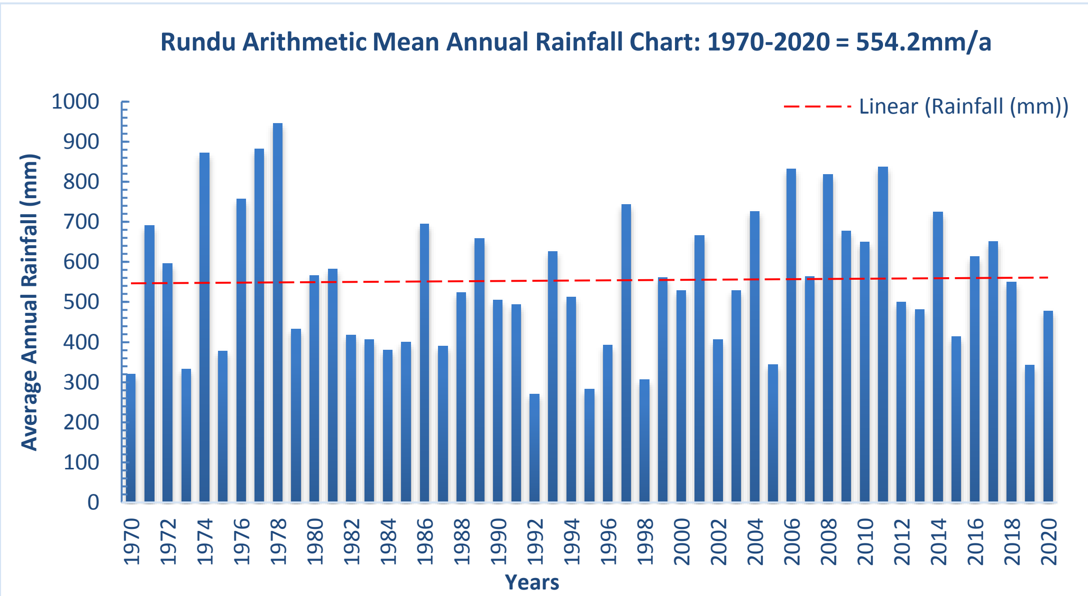


Figure 2-3: Annual average rainfall from 50 years (1970-2020) record at the Rundu Station

Figure 2-3 clearly illustrates the erratic behaviour in rainfall events typical of a semi-arid climate. The overall rainfall trend over the period assessed is fairly constant. Total annual rainfall amounts at 6 stations across the KE and KW from 2014 to 2020 illustrate: Mashare and Rundu stations in the Kavango East recorded the highest rainfall amounts of 767 mm (2017) and 807 mm (2014), respectively during the reported period (Figure 2–4).

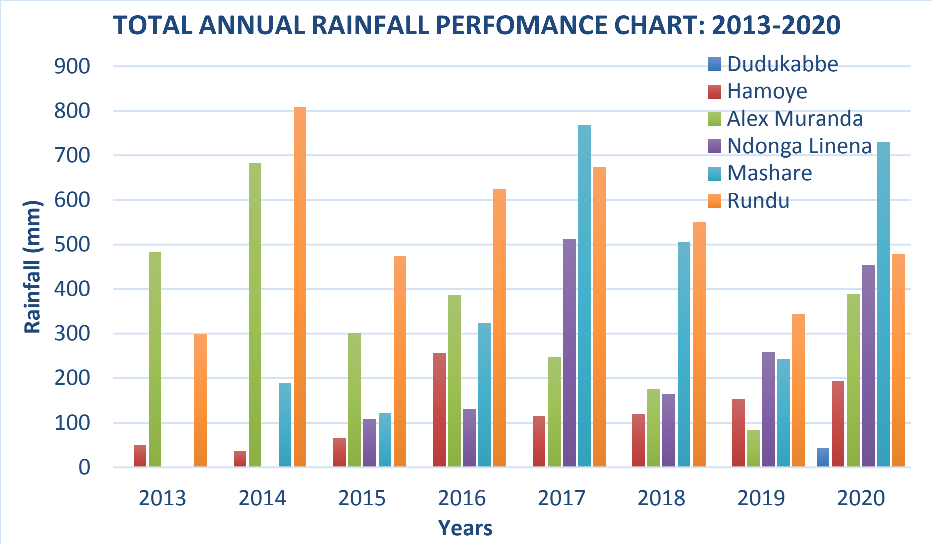


Figure 2-4: Total annual rainfall amounts across the KE and KW from 2013-2020

The lowest rainfall amounts have been recorded at Hamoye Station annually from 2013 to 2020, amounting to as low as 35 mm in 2013 and highest recorded as 256.4 mm in 2016. During the 2019/20 hydrological year, KE and KW Regions received over 400 mm of rain which was spread out throughout the East and the West (Figure 2–5).

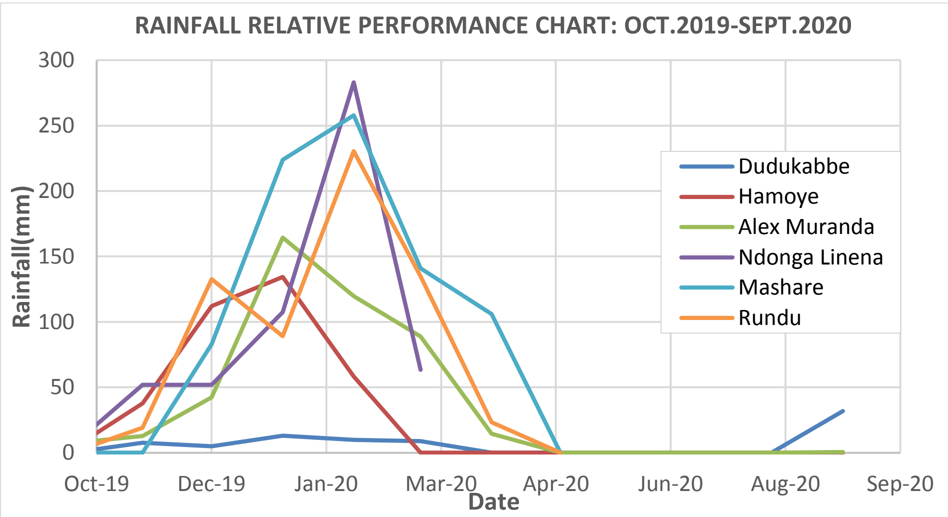


Figure 2-5: Rainfall relative performance during October 2019 - September 2020

Normal to above-normal rainfall is recorded from December through March, followed by a reduction during April. The latter concluded the season with below normal to normal rainfall for KW and normal rain for KE. Average annual temperature figures for Rundu for a period of 20 years are seen in Figure 2–6. Temperature ranges between 20 °C to less than 25 °C during the assessed period. Overall, there has been an increase in temperatures since the year 1990 to 2020 in the range of 1 – 2 °C. The highest average temperatures were recorded in 2015 and 2016 averaging 24.4 °C. Occasional rises in temperatures are observed as peaks in the data in 1992, 1996, 1998, 2005, 2012, 2015, 2016 and 2019. The lowest average temperatures are recorded in 1990 and 2013, averaging 20.4°C.

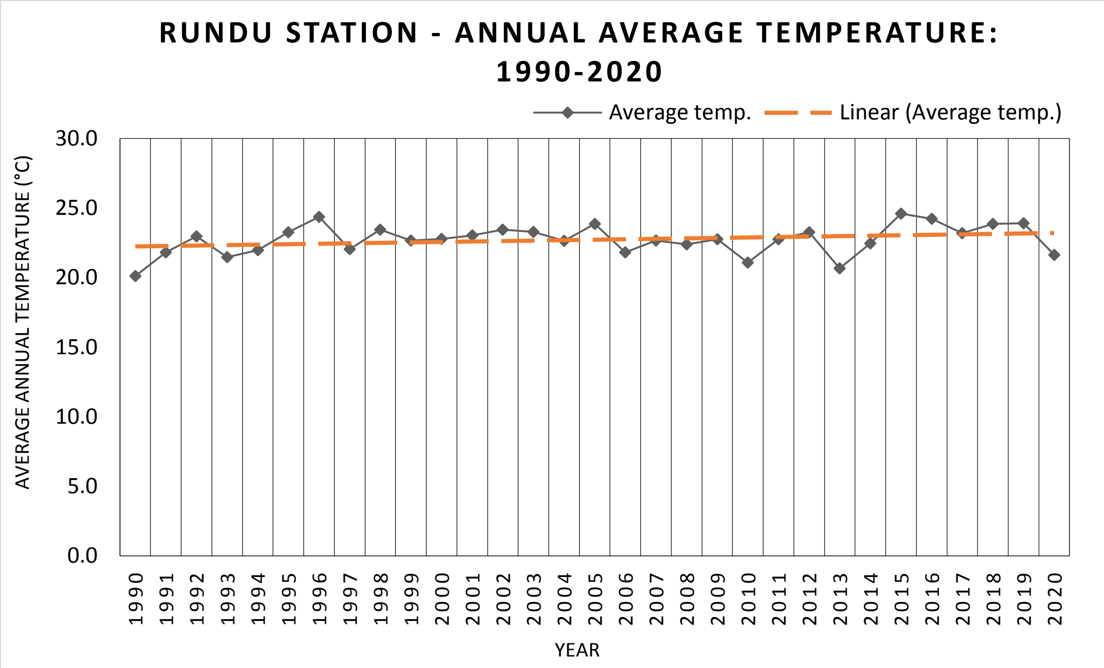


Figure 2-6: Annual average temperature at Rundu station during 1990 - 2020

2.4 Geological & Hydrogeological Setting

2.4.1 Geology and Stratigraphy

A geology map of the KE and KW is presented in Figure 2-7 and the stratigraphy is summarized in Table 2-1. The entire Kavango East and West Regions are positioned in the Kalahari Basin, a vast depression in existence since the Cretaceous which covers most of the central parts of the southern African continent (Burke, 2002). Since its development it has been the main catchment of erosion products, today bearing the most extensive sheet of aeolian sand in the world (Patridge, 1997). Today, the land surface of the KE and KW is characterised by an increasing differentiation of aeolian sands.

The overall stratigraphic sequence as per BIWAC (2002) is described as the bedrock of the Damara Sequence, overlain by the Karoo Sequence sediments, overlain and intruded by volcanic rocks (basalts) of Karoo age, and finally overlain by younger Kalahari Group sediments

The Kalahari Group siliciclastic sediments are semi-consolidated to unconsolidated alluvial and aeolian sediments that have been subdivided into three main units, (1) a basal layer comprising conglomeratic, red clayey sand with carbonate cement overlain by (2) mostly fluvial sand intermixed with minor aeolian deposits, which make up the middle section. (3) The uppermost unit predominantly comprises unconsolidated aeolian sand and fluvial deposited sand (Namibian Groundwater Development Consultants, 1991; BIWAC, 2002; Miller, 2008).

Based on Burke (2002), the older basal sands were deposited on the margins of the Kalahari Basin during Tertiary times, whilst the younger red sands were deposited from the Late Holocene period to today. During the Late Holocene, fluctuating wet and dry conditions led to the formation of calcrete deposits which occur as layers >10 m in borehole intersections, and as concretions within the Kalahari sediments. Increasing arid conditions have been documented during the recent geological past and still lasting today.

Table 2-1: Simplified geology and stratigraphy of the Kavango Region (BIWAC, 2002)

Age	Sequence/Group		Formation	Description
Recent to Late Cretaceous (64 – 0 m.y.)	Kalahari	**Upper**	Kalahari Sand	Thin aeolian sands and loamy, calcareous soil with crusts of ferricrete and calcrete
			Omatako	Ferricrete and ferruginous sandstone
		Middle	Eiseb	Thick layered, light-coloured, sandy silcrete and calcrete, conglomerate bands in the middle unit
		Lower	Tsumkwe	Reworked sandy to clay-rich conglomerate, poorly sorted basal scree with calcareous cement; minor mudstone
Cretaceous (180 - 60 Ma) Cretaceous (180 - 60 Ma)	Karoo		Kalkrand	Plateau Basalt
Early Namibian (900 Ma)	Damara/Nosib		Duruchaus	Fine-grained greyish to brown, feldspathic quartzites with interbedded sandy shales

As a result, the current land surfaces of the KE and KW Regions are characterised by extensive areas of aeolian sand drift and dunes deposited on calcrete erosional surfaces (Simmonds, 2000). These dunes are oriented in the east-west direction and characterise most of western Kavango. Spatially, the Kalahari Sequence decreases in thickness (<50 m) along the border between Namibia and Botswana and increases north-westwards up to >400 m along the basin axis. The Sequence is also thick in the middle section of Omatako-Omuramba River and towards the northwest at Nkurenkuru town (Figure 2-8).

According to Miller (2008), the Karoo Sequence in the Basin constitutes only two units, namely the aeolian Etjo Formation sandstone and the overlying Kalkrand Plateau Basalts of Late Karoo age (equivalent to the Stormberg flood basalts of Botswana). These are also termed the Rundu Basalt Formation. The sandstone and basalt occur extensively in the Kavango Basin, with the basalt mostly overlaying the sandstone except where it is interbedded between the sandstone to the south of the Basin.

Ecca Group sediments are absent or are yet to be proven from drilling sections (Beukes & Masule, 2014; BIWAC, 2002). Underlying the Karoo Sequence are the oldest meta-sediments of the Damara Sequence comprising dolomite, quartzites, shale, and schist. These outcrops in the southern part of the Kaudom National Park within the Nhoma River drainage and at the border between Kavango East and Zambezi Regions near Andara (Namibian Groundwater Development Consultants [NGDC], 1991). Volcanic rock sub-outcrops occur at the Okavango River near Rundu and between Mukwe and Bagani (BIWAC, 2002).

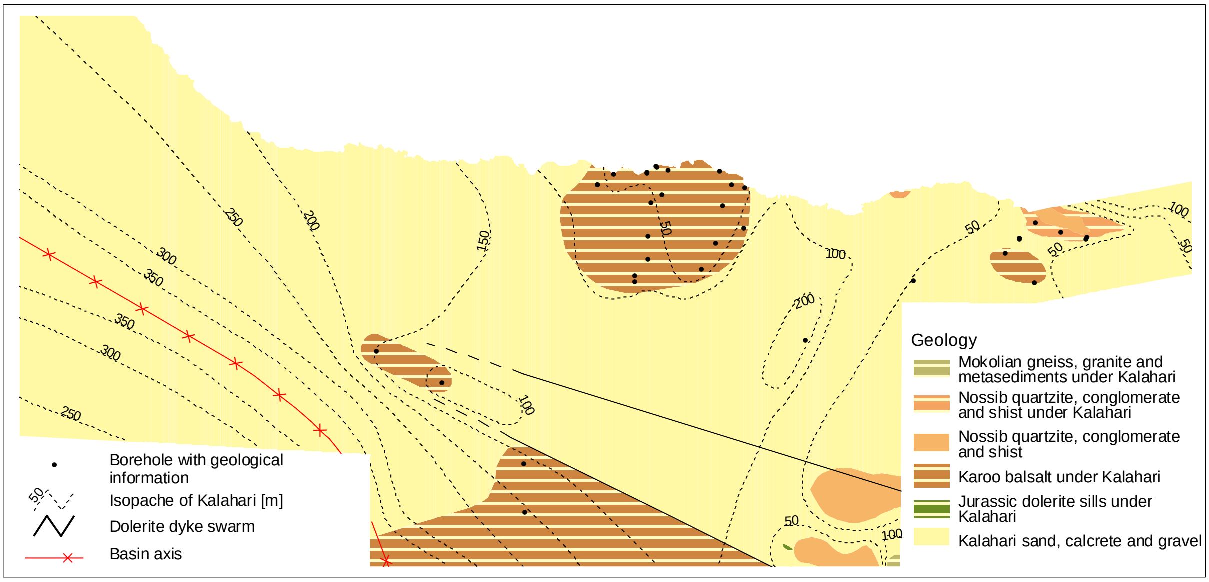


Figure 2-7: Geology of the Kavango East and Kavango West Regions (BIWAC, 2002)

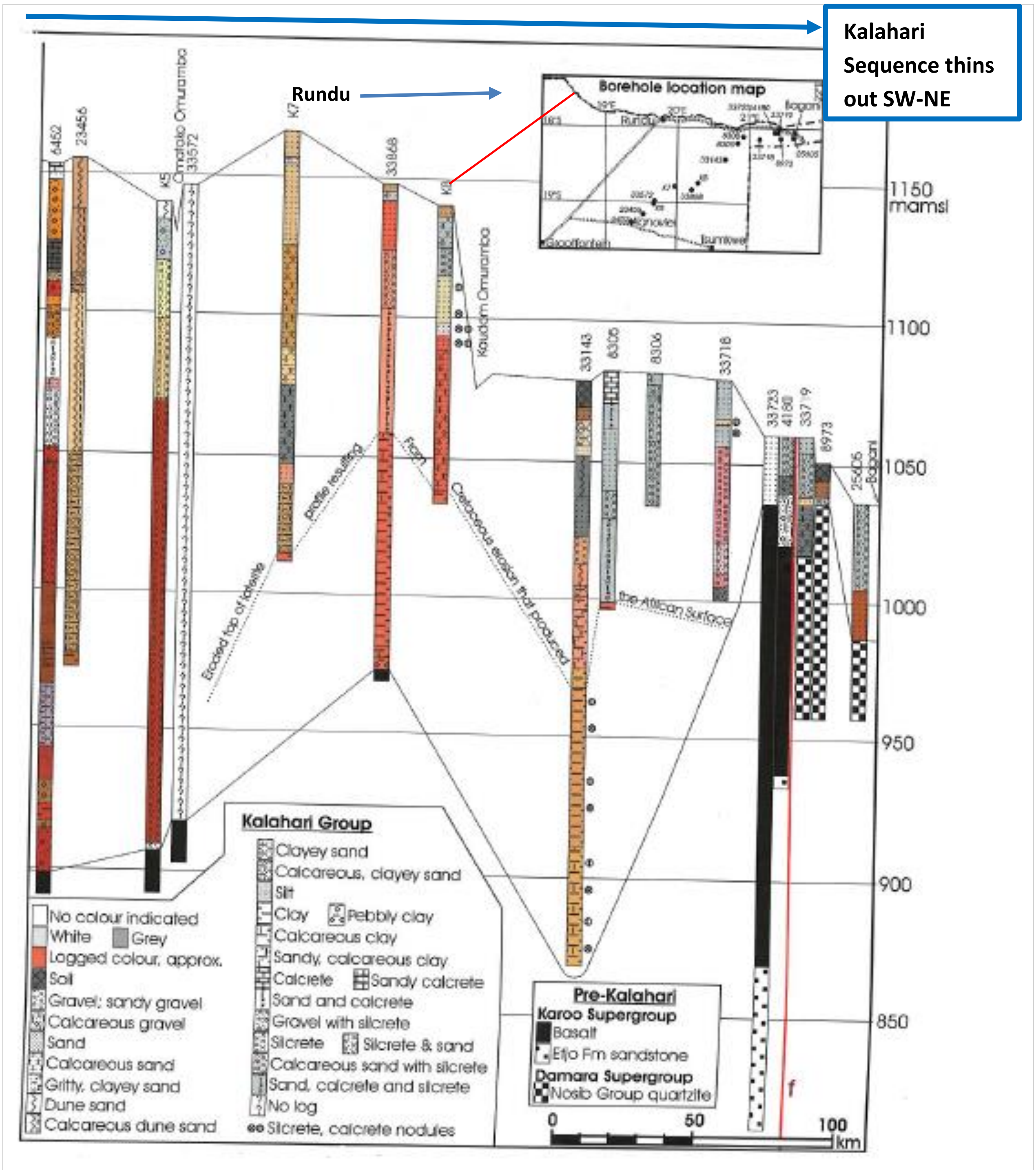


Figure 2-8: Cross-section through the Kalahari Group from Kanovlei (Otjozondjupa Region) to Bagani (KE). Compiled from borehole records from DWA (Miller, 2008)

2.4.2 Structural Geology

The tectonic framework of the area is said to be dominated by the configuration of the pre-Kalahari surface NGDC (1991). A north-northeast trending basement high in the east of the study area forms the eastern limit to the westward deepening Kalahari Basin. In the north, this basement high is defined in areas of the elevated basement beneath the Omatako Omuramba, to the south of Mashare, and east near Andara. Irregular pre-Kalahari topography to the west of the area termed Bushmandland forms the western and south-western boundary of the Basin. The outer limits and the floor of the basin consisted of uplifted fault blocks and associated sub-basins, and generally, the stratigraphy seen locally depends on the distance and nature of the rocks comprising basement highs (NGDC, 1991).

The breakup of Gondwana into separate continental masses of Africa, South America, Madagascar, India, Australia, and Antarctica continued in the Late Jurassic and Cretaceous (Miller, 2008). Each tectonic development left regional structural trends (NE-SW; NW-SE) in the fabric of the underlying basement and produced tectonic belts (Miller, 2008). Rifting in the Okavango Graben is proposed to have occurred by east-west extension, which implies a component of strike-slip in the NW-SE directions. This east-west extension reactivated the north-easterly basement fabric, to form oblique-slip faults, and eventually produced a divergent strike-slip system (McCarthy et al., 1993b, as cited in Milzow et al., 2009).

Antithetic faults are said to form in such systems, such as the northeast striking faults of Gomare, Thamalakane, and Kunyere which extend (except for the Thamalakane Fault) from Botswana to Namibia. These faults have since controlled deposition in the larger Okavango Graben. Klock (2001) terms the NW-SE structure as the Kalahari basin axis initiated during the uplift of the African Atlantic continental margin, while the NE-SW structures are extensional. The latter was developed after Karoo deposition before the uplift of the continental margin along the Damara pre- weakened structures, and they are also recently reactivated. High-resolution aeromagnetic data (Figure 2.9) obtained from Miller (2008) indicate a narrow, northwest-trending, fault-bounded, basalt-filled graben extending southeastwards into a broad fan of basalt, itself fault and dyke bounded in its upper reaches, with northeast-trending faults terminating parts of the fan in the southeast.

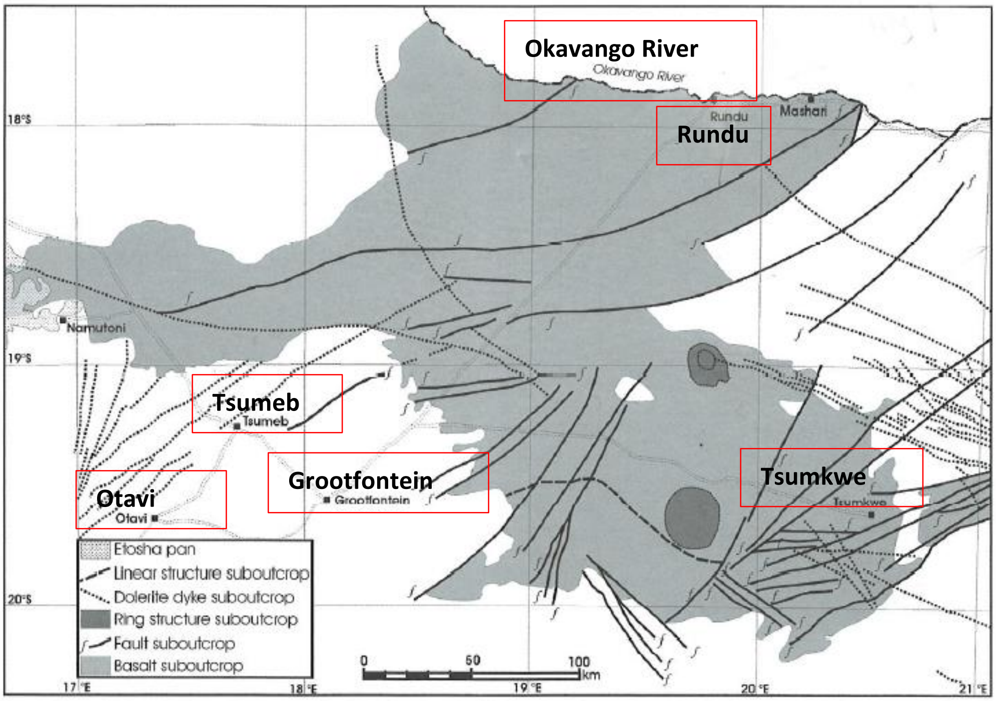


Figure 2-9: Interpretation of aeromagnetic data - Karoo basalts, ring structures, dykes, ring swarms, and major faults in the KW and KE, Otjozondjupa, and Oshikoto Regions (Miller, 2008)

The basalt is extensive over the basin and precedes several large and small-scale faults with broad NE trends, the N-S and NE dyke swam west of the Tsumeb and Otavi towns.

2.4.3 Hydrology

The regions are bordered to the north by the perennial Okavango River and lie within the regional Okavango River Basin or Cubango Okavango River Basin (CORB). The Okavango River catchment in Namibia covers an area of about 41 500 km^2 (OKAKOM, 2010). The River flows in a north-easterly direction from the Angolan Highlands, through eastern Namibia into Botswana, where it forms the prominent Okavango Delta. The river has two main tributaries (Figure 2-10) i.e. Cubango and Cuito Rivers in Angola, which receive most of the runoff in the upper parts of the Basin. Other remnants and inactive tributaries are present in the CORB, with the latter in Namibia referred to as 'omiramba', which generally drain eastwards. The main "Omuramba" is the Omuramba-Omatako which has active headwaters, however, it does not contribute to runoff in the Okavango River. Other omirambas have little to no flow, such that the little runoff that occurs forms isolated ponded areas, while flows from the Okavango River flow into the Omuramba-Omatako for a short distance at the confluence (Water Surveys Botswana, 2011).

The ephemeral Omuramba-Omatako originates at the main watershed between west and east-flowing rivers north of the town of Okahandja northeasterly into the Kavango Regions. The confluence with the Okavango River is at Ndonga, some 60 km east of Rundu (IWRM Joint Venture Consultants Namibia, 2010). The catchment of the Omuramba-Omatako includes the Grootfontein Karst Aquifer, one of the most productive aquifers utilized for irrigation and commercial farming in Namibia. Other rivers include the Omiramba Nhoma and Kaudom which drain through the Kaudom Game Park into Botswana and eventually into the Okavango Delta (IWRM Joint Venture Consultants Namibia, 2010). According to Mendelsohn and El Obeid (2003), the average total runoff of the Okavango River as it leaves Namibia is about 9800 Mm^3.

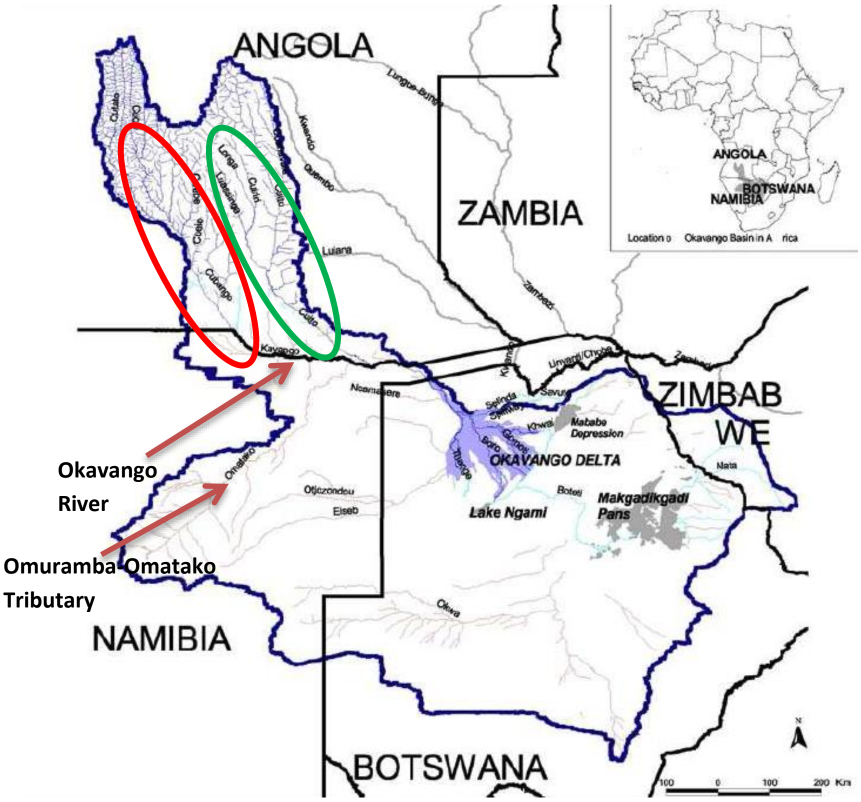


Figure 2-10: The Okavango River Basin (blue) and minor tributaries. The former are Cuito (green) and Cubango (red) tributaries, and the latter Omatako-Omuramba, respectively (Kgathi et al., 2006).

The flat landscape of the two regions and the high permeability of the sandy soils produce little surface drainage in the area, and rarely, water collects and flows in the dry omiramba/river beds. In other areas, water collects in pans in shallow depressions.

2.4.4 Hydrogeology

Two prominent aquifer types occur in the study area, namely (1) primary porosity aquifers comprising sand and sandstone of the Kalahari Group sediments with intercalated calcrete beds and (2) secondary permeability aquifers constituting weathered and fractured pre-Kalahari bedrock i.e. Damaran meta-sediments and the basalts of the Karoo Supergroup (NGDC, 1991). Table 2-2 shows the major aquifers and aquitard units in the study area (BIWAC, 2002), whilst Figure 2-11 presents the hydrogeological map.

The Kalahari Group aquifers are subdivided into sub-aquifers, namely; an Upper aquifer (a local perched aquifer), and Middle aquifer (main regional aquifer), and a Lower aquifer. The Kalahari Group aquifers are porous, argillaceous, and arenitic semi-consolidated to unconsolidated sediments, occurring throughout the study area, although at varying thicknesses (BIWAC, 2002).

Table 2-2: Simplified hydrogeology of the KE and KW after BIWAC (2002)

Age	Sequence/Group		Formation	Aquifer	Aquitard
Recent to Late Cretaceous (64 – 0 m.y.)	Kalahari	**Upper**	Kalahari Sand	Thin aeolian sands, ferruginous sandstone (Local perched Aquifer)	Calcareous soil with crusts of ferricrete and calcrete
			Omatako		
		Middle	Eiseb	Thick layered, light-coloured, sandy silcrete and calcrete, conglomerate (Main Regional Aquifer)	Minor clay horizons
		Lower	Tsumkwe	Reworked sandy conglomerate (often has higher salinity)	Clay rich conglomerate, minor mudstone **(Aquitard)**
Cretaceous (180 - 60 Ma)	Karoo		Kalkrand	Plateau Basalt	**Aquitard**
Early Namibian (900 Ma)	Damara/Nosib		Duruchaus?	Fine-grained greyish to brown, feldspathic quartzites (fractured) (Fractured Aquifer)	Shale, solid quartzite **(Aquitard)**

The aquifers include sand and sandstone horizons and the aquitards are calcrete, clay, and silcrete layers. The Kalahari Group sediments constitute the most important aquifers being utilized for bulk water supply, in particular paleo-channels of the Okavango River (NAMWATER Boreholes) and rural settlements.

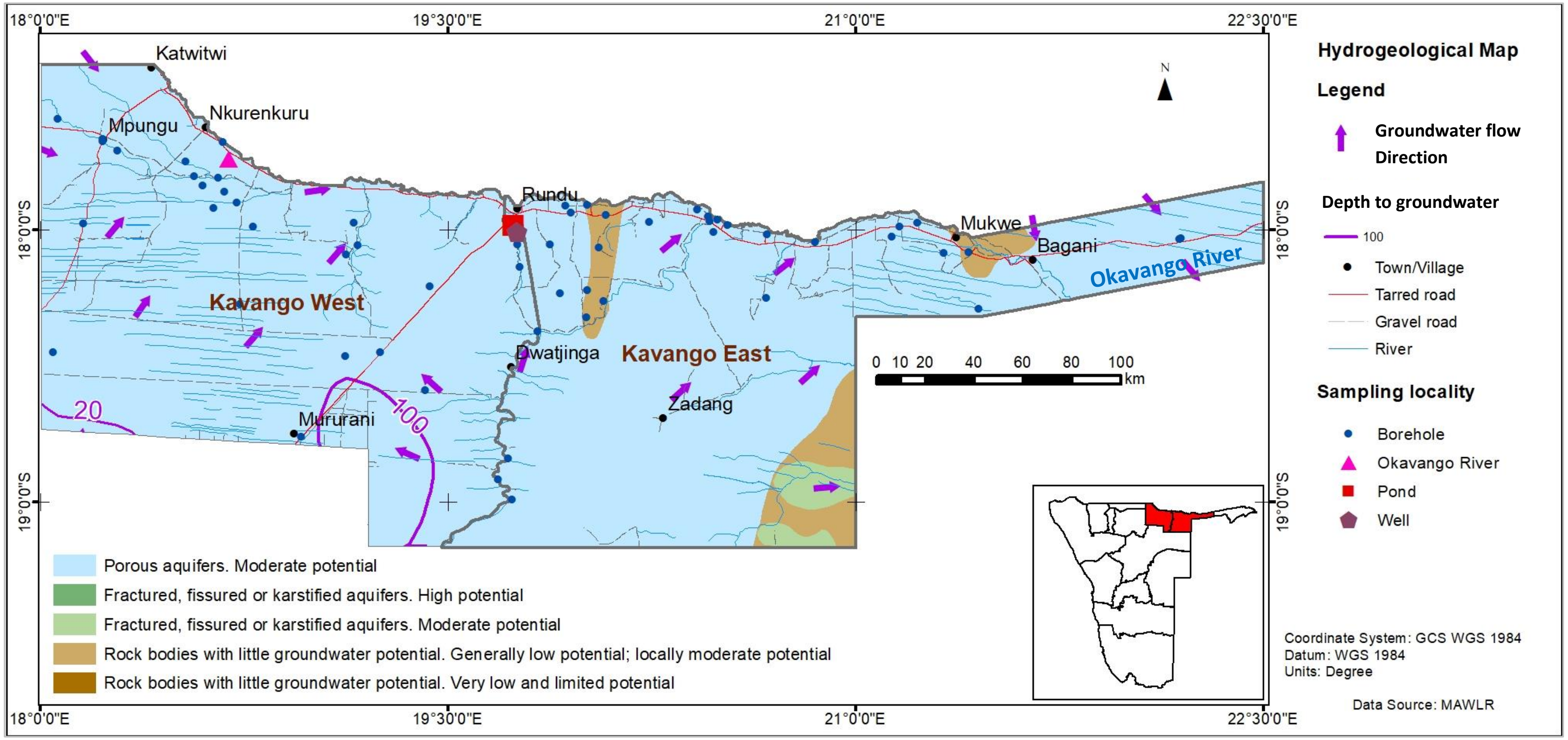


Figure 2-11: Hydrogeological map for the KE and KW Regions, illustrating sampled boreholes localities and groundwater flow directions. Depth to groundwater is given in meters below ground level (m b g l), (MAWLR, 2021).

The Kalahari Group sediments thin out towards the north-eastern and south-eastern parts of the two regions, ranging from zero to about 400m along the basin axis (southwest). In the east, pre-Kalahari inliers are present, such that groundwater is supplied from the secondary aquifers (NGDC, 1991).

Groundwater-table and flow directions

Three main groundwater flow systems and one sub-system were identified in the Kavango East and West Regions based on BIWAC (2002). These flow systems (Figure 2-12) are in two main directions i.e. I. northwards towards the Okavango River and II. westwards towards the Omuramba Omatako River and the basin axis. The first (I) flow system with a hydraulic gradient of 0.0003 occurs in the southwest of the Kavango West Region and is directed towards the north i.e. Okavango River, with recharge emanating from the calcareous Otavi Mountainland north of Grootfontein town. Additionally, a small proportion of the groundwater was recharged in the calcareous Kalahari cover between Abenab and the regional border of the KW.

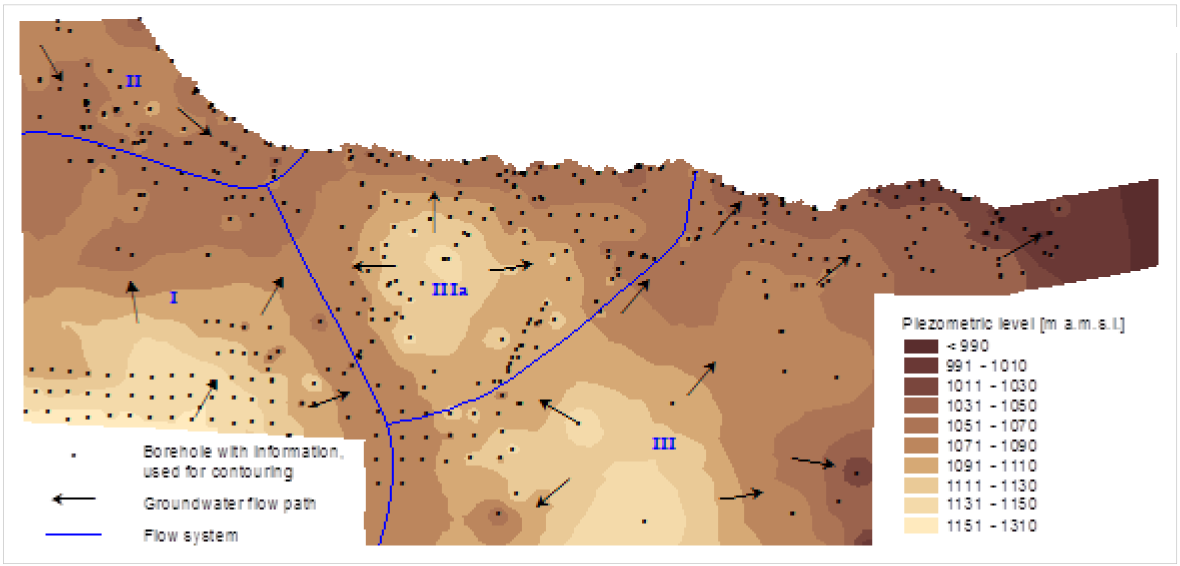


Figure 2-12: Identified groundwater flow systems in the KE and KW Regions (BIWAC, 2002)

The second flow system (II) is said to control the groundwater flow in the north-western corner of the Kavango West Region between the Angolan border, the Omuramba Mpungu tributary, and the Okavango River near Nkurenkuru. Here, the flow is directed from north to south with the recharge area situated in Angola, most probably in the upper catchment of the Okavango River. The flow is again directed towards the Omuramba Mpungu and eventually towards the Okavango River. The flow gradient is rather flat. The third (III) system dominates the larger part of the two regions east of the basin axis, with flows in all directions towards the Eiseb, Omatako, and Okavango Basins. The recharge area is located to the north of Tsumkwe (Figure 2-9). Lastly, a locally developed sub-system occurs in the elevated area southwest of Rundu, within the Kalahari Sequence. It is a localized shallow Kalahari aquifer with radial flow from a central recharge zone (Water Surveys Botswana, 2011). Water table depths vary greatly in the KW and KE, where shallow depths of 10-40 m b g l (Figure 2-13) occur in the eastern parts of the study area, and depths ranging from 50-130 m b g l are seen in the west along the Kalahari basin axis (BIWAC, 2002).

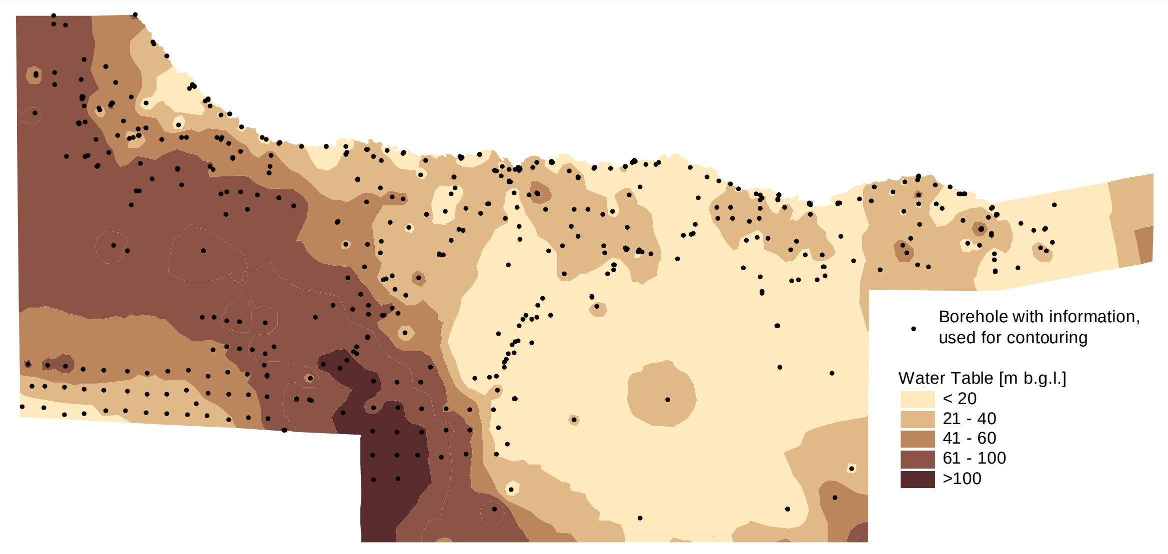


Figure 2-13: Piezometric level map in the KE and KW (BIWAC, 2002)

The water quality in the KE and KW Regions determined from the sampling of boreholes indicates good quality water for both human consumption and livestock watering. Localized, poor quality water occurs as patches of groundwater with high TDS values (>2600-10 000 mg/l) (NGDC, 1991). Along the banks of the Okavango River, there is poor quality water with high contents of iron and manganese above the allowable drinking limits for human consumption (OKAKOM, 2010). An assessment of borehole drilling and pump testing reports in the GROWAS II database indicates that borehole yields in the two regions range from 1 m^3/h to 70 m^3/h, with most boreholes yielding between 5 m^3/h and 10 m^3/h. Based on the report by Water Surveys Botswana (2011), high-yielding boreholes are recorded adjacent to the Okavango River and within the 'shallow' Kalahari aquifer southwest of Rundu. Borehole pumps (positive displacement and submersible) are powered by diesel engines, electric motors, solar or by wind, or boreholes are equipped with hand pumps. Rural water supplies are at present unmetered and as such abstraction volumes are unknown.

2.5 Limitations of the study

This study focuses mainly on the Kalahari Group aquifers collectively referred to as the Primary Kalahari Aquifers. This study aimed to focus on the main regional (sub) aquifer, however, after studying the borehole designs from the Rural Water Supply boreholes in the area, it was clear that they penetrated the entire Kalahari succession and not just a singular sub-aquifer. A groundwater sample taken from these boreholes would constitute a mixed sample, thus it would be incorrect to assume that a sample is representative of only the main regional (sub) aquifer. In some rare cases, boreholes intersect a singular sub-aquifer, however, due to unclear logging, and lack of borehole design; it is not always possible to validate this scenario. Boreholes are drilled in the Kalahari aquifers for the simple purpose of water supply, regardless of the changing hydrogeology. The secondary aquifers are generally avoided for water supply purposes.

3 LITERATURE REVIEW

3.1 Hydrogeochemistry

3.1.1 Factors controlling Groundwater Chemistry

Groundwater comprises organic and inorganic substances in solution or suspended or colloidal form. These substances are classified into major (> 5 mg/l), minor (<5 mg/l), trace (<0.1 mg/l) and dissolved gasses (Freeze & Cherry, 1979). They may be of natural or anthropogenic origin. The origin provides information on groundwater movement, as well as processes that affect the composition of groundwater such as adsorption, desorption, and dispersion (Geyh et al., 2000).

The assessment of the chemistry of groundwater and its influence on groundwater quality is an important aspect of hydrogeological investigations. The geochemistry of groundwater depends on many factors, such as general geology, the degree of chemical weathering of various rock types, and the quality of the recharge water, and inputs from sources other than rock-water interactions (Mostafa et al., 2017). An understanding of these processes and even recharge mechanisms would often lead to further understanding of both groundwater quantity and quality (Chang & Wang, 2010).

Groundwater is continuously moving in the subsurface where it interacts with the geology and thus evolves in chemical makeup. The initial signature of groundwater is acquired during precipitation, followed by recharge, movement through the aquifer, and finally discharge (Gomo, 2017). The chemistry of rain as reported by Freeze and Cherry (1979) is acidic, very dilute, and oxidizing. The time of day, temperature, source of clouds, latitude, and longitude play a significant role in the composition of rainfall.

Hydrogeochemical processes differ in the various types of aquifers owing to differences in aquifer properties such as permeability and transmissivity which affect flow rates and patterns. As an example, a fractured rock aquifer compared to an alluvial aquifer will generally have high flow rates due to the presence of faults, which reduces the time for rock-water interactions. Notwithstanding the above, differential uptake by biological processes in the soil zone, seawater intrusion in coastal areas and atmospheric dry deposition in recharge areas also influence groundwater chemistry (Hiscock, 2005).

Water quality analysis can be conducted for three main purposes, namely, i) source rock deduction, ii) determining chemical trends iii) determining aerial trends, and iv) examining for mixing and mass balance calculations (Chapter 4: Water Quality Interpretation, n.d.). This is achieved through the use of graphical methods as well as varying calculations based on identified methodologies. This study describes the hydrochemical facies and identifies dominant hydrogeochemical processes through analysis of major ions and trace elements in groundwater of the Primary Kalahari Aquifers.

Moreover, the usability of groundwater for human consumption, livestock watering, and possibly agricultural works will be assessed based on the limits defined in the Water Act (1956). The Act stipulates that the concentration of and limits for aesthetic, physical, and inorganic determinants define the group into which water is classified i.e.

- GROUP A: water with an excellent quality
- GROUP B: water with acceptable quality
- GROUP C: water with low health risk
- GROUP D: water with high health risk, or water unsuitable for human consumption

Ideally, water should be of GROUP A and GROUP B; although in reality, many determinants may fall out of these ranges. If water is classified as GROUP C, attention should be given to the problem, although it is not critical yet. If water is classified as GROUP D, urgent and immediate attention should be given to the problem. The overall group given would depend on the determinant that complies least with the Guidelines for Drinking Water Quality.

3.1.2 Sequence of Hydrochemical Evolution of Groundwater

To identify hydrochemical processes and interpret groundwater chemistry, Chebotarev (1955, as cited in Hiscock, 2005) indicates that it is essential to adopt his concept of hydrochemical facies/water types.

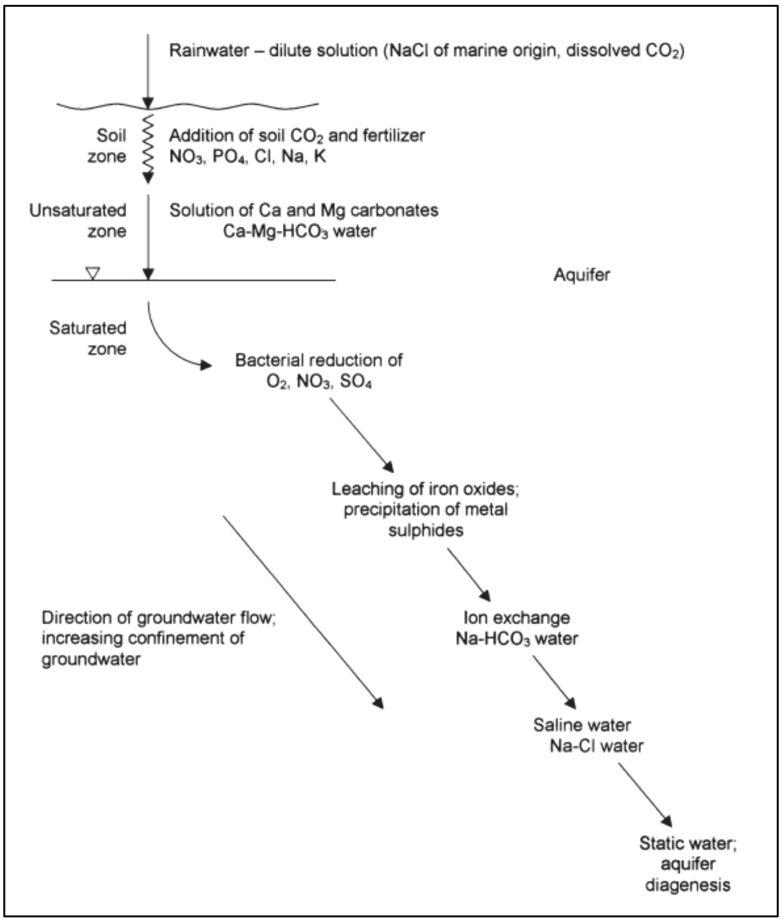


Figure 3-1: Schematic diagram of the evolution of groundwater along a flow path, showing important hydrochemical processes changing groundwater chemistry (Hiscock, 2005)

A hydrochemical facies is defined as a distinct zone of groundwater that is described as having cation and anion concentrations within definite limits (Hiscock, 2005). In Figure 3-1 one can visualize the processes that occur as groundwater flows along a flow path from the recharge area to a confined section.

3.1.3 Methods for Groundwater Quality Analyses

The Piper (1944) is effective in determining the sources of dissolved constituents in waters, geochemical evolution of groundwater and surface waters, and related geochemical problems. It gives details on the similarities and differences in the composition of waters by classifying different chemical water types, as well as basic conclusions on mixing, precipitation/solution, and ion exchange reactions. In a nutshell, the position of analyses on a Piper diagram (Figure 3-2) can be used to make a tentative conclusion on the origin of groundwater in connection with the bicarbonate to silica ratio. Four basic conclusions are drawn from analyses plotted on the Piper plot including water types, precipitation or solution processes, mixing, and ion exchange processes (Chapter 4: Water Quality Interpretation, n.d).

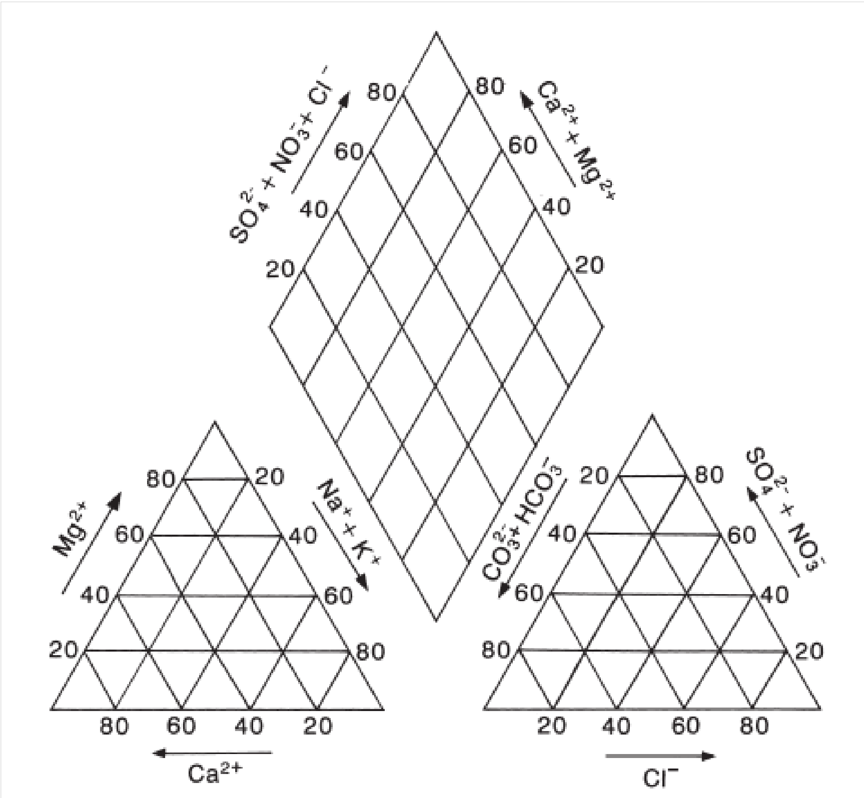


Figure 3-2: Piper plot for the classification of water types (Hiscock, 2005)

In terms of water types, Ca-HCO_3 hydrochemical facies are typical of recently recharged groundwater depending on the geochemical composition of the aquifers as well as groundwater circulation. Rainwater mixes with carbon dioxide to form a weak carbonic acid which reacts with carbonate rocks found in abundance in the near-surface environment. This reaction (eq. 1) gives rise to a Ca-HCO_3 facie type of water (Hiscock, 2005; Gomo, 2017).

$$H_2CO_{3(aq)} + CaCO_{3(s)} \leftrightarrow Ca^{2+}{}_{(aq)} + 2HCO_3^-{}_{(aq)} \qquad \textbf{eq.1}$$

Na-HCO_3 facies are typical of deep groundwater influenced by ion exchange processes (Hiscock, 2005). Ca-HCO_3 type groundwater may undergo cation exchange processes, where the Ca^{2+} is exchanged with Na^+ from the rocks/sediments making up the aquifer, to form Na-HCO_3 type water.

Other graphical presentations including Stiff diagrams, Kite diagrams, Vector diagrams, Histograms, Box Whisker Plots, Durov diagrams, Bar charts, Pie Charts and Variograms are described and used in several publications (Kulls, 2000; Klock, 2001; Hiscock, 2005; Lohe & Hoeben, 2014). Other methods include the Gibbs Plot, which highlights the processes that control groundwater chemistry (Gibbs, 1970). Three major mechanisms that control 'surface water' chemistry are recognized: atmospheric precipitation, rock–water interactions, and evaporation–crystallization. The major cations characterizing the end members of the world's surface waters are identified as calcium for freshwater and sodium for highly saline water bodies. In the Gibbs Plot (Figure 5-33), the weight ratio of the cations Na/(Na+K+Ca) (Gibbs ratio I) is plotted on the x-axis and TDS on the y-axis. A similar plot is created with the anions Cl/(Cl+HCO_3) (Gibbs ratio II) on the x-axis and TDS on the y-axis. The Gibbs Plot has since been used in groundwater hydrogeochemistry to determine the processes controlling the composition/addition of dissolved salts to groundwater.

Marandi and Shand (2018) assessed the correctness of applying the Gibbs Plot to 'groundwater' studies and remarked that it is not incorrect to do so. Plotting ion ratios and salinity of groundwater can lead to a better understanding of key hydrochemical processes. Furthermore, according to Alley et al. (1998; as cited in Marandi & Shand, 2018), two-thirds of streamflow around the world is groundwater that has been discharged into streams. Marandi and Shand further state that the incorrect use of the Gibbs Plot occurs when groundwater studies analyse process-based models that have been developed for surface waters and link these to the Gibbs Plot to assess groundwater processes. In conducting these kinds of analyses, the interpretation of data is slowed down. Additionally, the use of the Gibbs Plot in isolation oversimplifies and leaves out many other important processes that affect the chemistry of groundwater.

Geochemical models are good tools used to calculate chemical reactions in groundwater such as dissolution, precipitation of solids, and sorption of ions by clay minerals and ion exchange processes. It is good practice to determine the saturation index (SI) of minerals in groundwater. The SI of a selected mineral is a measure of that mineral with respect to the surrounding system (Al-Ruwaih, 2018). According to the same source, the formula for SI is written as:

$$\mathrm{SI} = \log \frac{K_{iap}}{K_{sp}} \qquad \textbf{eq. 2}$$

Where K_{iap} refers to the ion activity product of the dissociated chemical species in solution, while K_{sp} is the solubility product of the mineral.SI<0 shows that groundwater is under-saturated with the mineral and SI>0 groundwater is oversaturated with the mineral. In the latter case, groundwater can no longer dissolve more of the mineral. In using this method, P_{CO2} in the groundwater samples and SI for minerals such as anhydrite, gypsum, calcite, halite, and silica are calculated to draw conclusions. Many other methods such as bivariate plots, calculating Kelly's Ratio (KR), Chloro-Alkaline Indices (CAI) are very useful in hydrogeochemical studies. The ratio of Ca^{2+}/Mg^{2+} has been used to determine the sources of calcium and magnesium ions in groundwater. The Na^{+}/Cl^{-} ratio is used to identify salinity in groundwater (Srinivasamoorthy et al., 2013).

To understand the reactions and processes that control groundwater chemistry, it is important to first understand the geology of the area and then the relationship between the water chemistry and the aquifer lithology (Al-Ruwaih, 2018). The schematic diagram (Figure 3-3) below highlights possible reactions in a groundwater system.

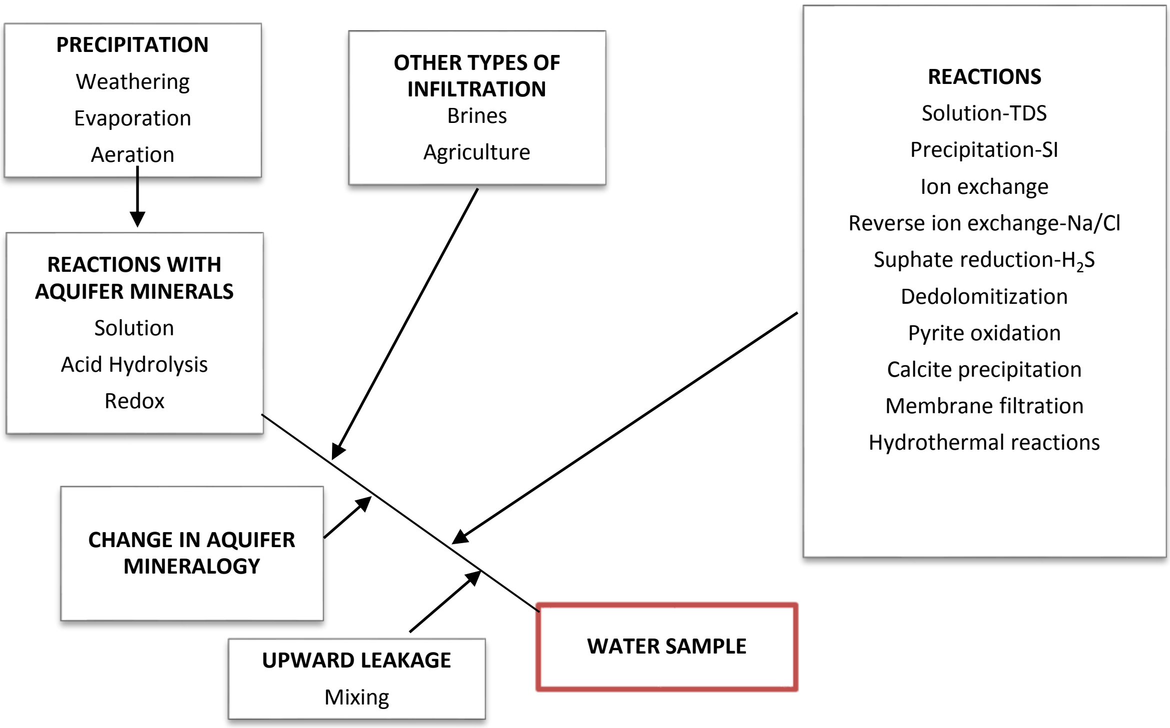


Figure 3-3: Schematic of the possible reactions in groundwater (Chapter 4: Water Quality Interpretation, n.d).

3.1.4 Previous Hydrogeochemical Investigations conducted in the area

Several hydrochemical surveys have been carried out in the Kavango East and West Regions, inclusive of the nationwide CSIR Survey Project aimed at producing a water quality map for DWA. The survey was the first comprehensive hydrochemical study carried out, soon followed by the study by the NGDC (1991), which combined hydrochemical data from the CSIR Survey, recent data from the Department of Water Affairs database, and some 375 samples (Table 3-1) carried out during field investigations in Kavango and Bushmanland.

Table 3-1: Table of results from the 375 samples collected as part of the groundwater investigations in the former Kavango Region and Bushmanland. Reproduced from NGDC (1991).

No of Samples	Criteria	Cumulative %
15	TDS>2000 mg/l	4
21	TDS>1500 mg/l	6
53	TDS>1000 mg/l	15
359	TDS>30 mg/l	100
		% in each class
189	Class A	53
126	Class B	35
19	Class C	5
25	Class D	7

The investigation by NGDC (1991) had started the initial identification of hydrochemical trends in groundwater in what was then the Kavango Region. By use of a Piper Plot, three water types were identified i.e. Ca-Mg-HCO_3 type, which is indicative of recently recharged water; dynamic underflow Na-HCO_3 character waters, and stagnant waters of the type $Na_2SO_4 \rightarrow NaCl$. Samples that were collected from shallow dug wells ranged in character from HCO_3 type to SO_4 without any increases in TDS levels. These samples represent recently recharged groundwater; and due to the low TDS levels, the residence time is short. The sulphate was concluded to be sourced from anthropogenic sources. Most samples from boreholes displayed the character of co-ordinated waters of the basin underflow regime, with high HCO_3 indicative of recent steady recharge of the aquifers.

NaCl and SO_4^{2-} rich water was identified in the areas of Twitima, Dumushe, and Kandjara. At Dumushe, sampling revealed that the quality of water changed with increased pumping from fresh water to NaCl type water to Na_2SO_4 composition. This showed that the freshwater aquifer is perched on top of saline waters. As BIWAC (2002) indicated, the perched aquifer is not continuous throughout the study and occurs only at some localities. 90% of the analyses made in the CSIR Survey as reported by NGDC (1991) comprised an appreciable amount of Na^+, which is a result of ion exchange of Ca^{2+} and Mg^{2+} in groundwater substituting for Na^+ and K^+ in the aquifer.

According to the same report, good quality water predominates the KE and KW, where TDS levels for very few samples reached 1000 mg/l. Isolated groundwater from specific boreholes had TDS values >2000 mg/l, however, this was limited to groundwater in a radius of 5 km of the sampled site. 2% of the samples were recorded to be substandard due to high fluoride content above the permissible limit. Thus, poor-quality groundwater is localized throughout the regions.

The study ‘Hydrogeology of the Kavango Region’ by BIWAC (2002) is the most recent study on hydrogeology and hydrogeochemistry conducted in the KE and KW. Lund (2002) also carried out a study titled ‘Regional Rural Water Supply Development Plan for the Kavango Region’. Studies thereafter have focussed on localized areas/villages, using these reports as a primary source of information. Overall, these studies have concluded that the water quality in the two Kavango Regions is suitable for human consumption (BIWAC, 2002; OKAKOM, 2010; Water Surveys Botswana, 2011; DWRM, 2018;). The water quality parameters investigated include Total Dissolved Solids (TDS) (Figure

3-4), sulphate (Figure 3-5) and nitrate (Figure 3-6), and fluoride distributions over the two Kavango regions (BIWAC, 2002; Water Surveys Botswana, 2011).

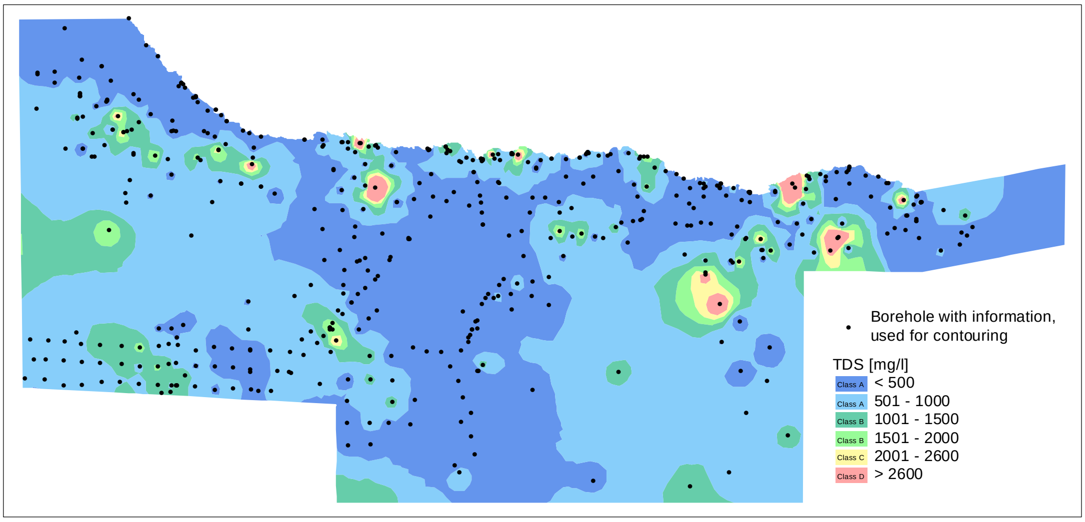


Figure 3-4: Spatial distribution of TDS over the larger Kavango Region (BIWAC, 2002)

High groundwater salinity is largely localized, with TDS values up to 2600 mg/l occurring along the Okavango River, Omuramba Mpungu, and northwest/east of the Kaudom National Park (BIWAC, 2002). Salinity is said to be related to deep-seated groundwater in bedrock that rises along faults and mixes with the fresh waters of the upper Kalahari aquifers.

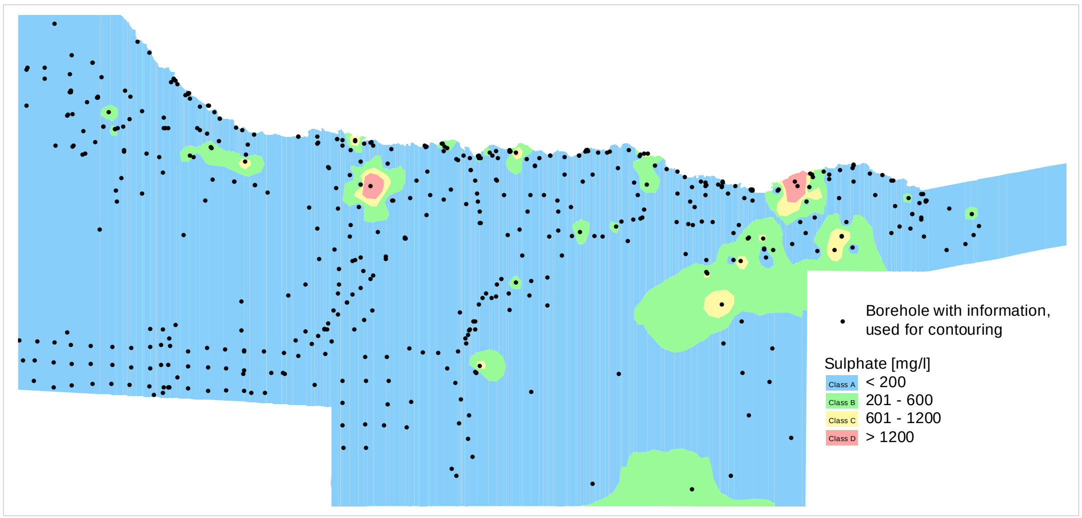


Figure 3-5: Spatial distribution of sulphates over the larger Kavango Region (BIWAC, 2002)

High nitrate and sulphate concentrations occur in areas with high salinity; nitrate concentrations are not recognized to be from animal waste or irrigation production. The study does not, however, identify the likely source in these areas, except for the area in proximity to the Mangetti Block where intensive livestock farming occurs and could be a potential source of elevated nitrate in the area.

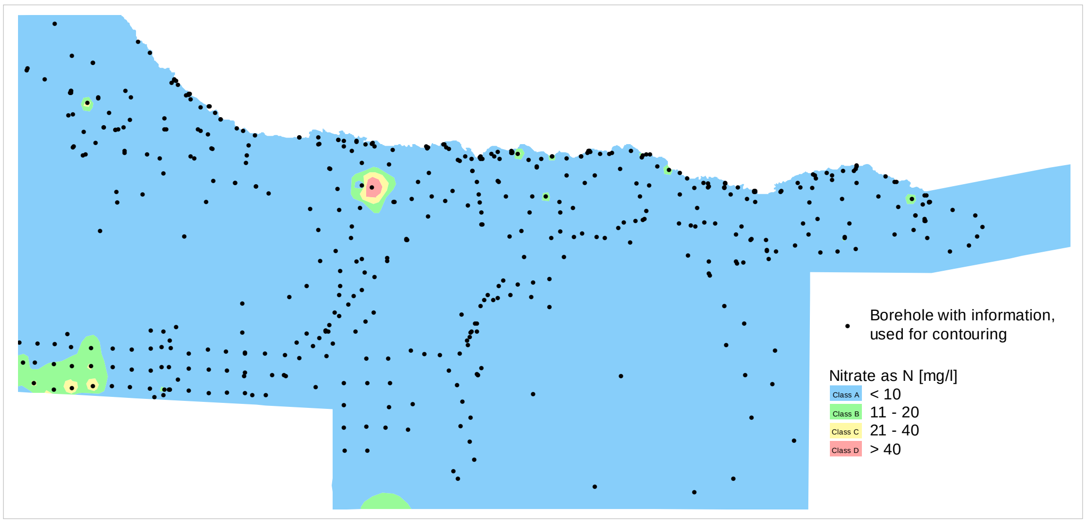


Figure 3-6: Spatial distribution of nitrates over the larger Kavango Region (BIWAC, 2002)

TDS values from the River range from a minimum of 31 mg/l in both regions and a maximum of 55 mg/l in the Kavango East Region (Table 3-2). Nitrate values in the Okavango River, along its length through the two Regions are all below 0.5 mg/l.

Table 3-2: Water Quality results from samples taken from the Okavango River (Directorate of Water Resources Management [DWRM], 2018)

Kavango East Region	pH	Conductivity (mS/m)	TDS (mg/L)	Nitrate (mg/L)	Turbidity (NTU)	Total Phosphate (mg/L)	Chlorophyll a (µg/l)
Hakusembe river lodge	7.15	40.1	54	<0.5	3.8	0.05	<0.10
Kaisosi Oxidation ponds	7.25	41.7	55	<0.5	3.48	0.03	<0.10
Kaisosi river lodge	7.21	41.3	55	<0.5	3.86	0.04	<0.10
Nkwazi river lodge	7.23	41.7	53	<0.5	3.81	0.03	<0.10
NdongaLinena	7.31	42.2	31	<0.5	3.71	0.03	1
Nyangana Hospital	7.26	43.9	33	<0.5	3.74	0.04	<0.10
Andara Hospital	7.25	42.5	32	<0.5	3.11	0.04	<0.10
Frans Dimbare Youth Center	7.27	42.3	30	<0.5	3.19	0.04	<0.10
Popa falls	7.43	42.5	48	<0.5	3.32	0.04	<0.10
KIFI	7.32	42.4	31	<0.5	3.21	0.04	<0.10
Kavango West Region	**pH**	**Conductivity (mS/m)**	**TDS (mg/L)**	**Nitrate (mg/L)**	**Turbidity (NTU)**	**Total Phosphate (mg/L)**	**Chlorophyll a (µg/l)**
Katwitwi border post	7.34	38.6	49	<0.5	3.35	0.04	<0.10
Nkurenkuru Town	7.45	39.1	51	<0.5	3.74	0.04	<0.10
Bunya	7.24	40.2	31	<0.5	4.12	0.14	<0.10
Rupara	7.34	40.3	31	<0.5	3.9	0.05	0.6
Irrigation Guideline	6 to 9		1000-2000	10 to 20	1 to 5	0.077-0.6	
Aquatic Ecosystem Guideline	**not vary by >15%**		**not vary by >15%**	**<0.5**	**<25**	**Not >15% background data**	**0.01-0.12**

3.2 Groundwater Isotopes

The field of Isotope Hydrology forms an integral part of Hydrogeological research and applications within the Geosciences sphere (Clark & Fritz, 1997). Isotopes provide valuable information on the transport and interconnectivity of water resources and reservoirs, and thus playing a role in the effective management of resources (Abiye, 2013). Isotope tracers are capable of integrating small-scale variability to give an effective indication of catchment scale processes and may be used to do so without the need for extrapolation and additional assumptions as does point measurement data i.e. water levels or chemistry data (Kendall & McDonnell, 1998).

Isotopes are defined as atoms of the same element that have different numbers of neutrons and thus different atomic mass (Mook, 2001). Two types of tracers are distinguished as historical and environmental tracers. Environmental tracers exist naturally and they are classified principally into stable and unstable/radioactive isotopes. The most investigated isotopes include the common stable isotopes, oxygen-18 (^{18}O), deuterium (^{2}H), and carbon-13 (^{13}C), as well as the radioactive isotopes of hydrogen, tritium (^{3}H), and carbon-14 (^{14}C). Geyh et al. (2000) identified historical tracers commonly used in hydrological studies as the bomb tracers ^{3}H, ^{14}C, ^{36}Cl, and ^{137}Cs.

Stable isotope ratios are expressed in δ units according to equations 3 and 4:

$$\delta\ (‰) = \frac{Rsample - Rstandard}{Rstandard} \times 1000$$ **eq. 3**

Where R sample and R standard are isotopic abundances of the sample and standard, respectively (Freeze & Cherry, 1979; Gat et al., 2000; Hiscock, 2005).

$$R = \frac{abundance\ of\ rare\ isotope}{abundance\ of\ abundant\ isotope};\ \text{where } R_H = {}^{2}H/{}^{1}H$$ **eq.4**

R in eq. 4 is the isotope under consideration (Gat et al., 2000). The standard used for stables isotopes of $\delta^{18}O$ and $\delta^{2}H$ is Vienna Standard Mean Ocean Water (V-SMOW). The lighter isotope of an element is usually more abundant than the heavier isotope.

Water in various parts of the hydrologic cycle has varying vapour pressures and freezing points, which result in differences in isotopic concentrations of 18O and 2H in the water. When the isotopic content of water changes as a result of evaporation, diffusion, condensation, melting, freezing, chemical reactions, or biological processes it is termed isotopic fractionation (Freeze & Cherry, 1979; Gat et al., 2000; Geyh et al., 2000). Simply put, fractionation refers to the partitioning of stable isotopes amongst different co-existing phases as a function of mass and temperature (Clark & Fritz, 1997; Marah, 2017).

Water vapour in air masses is typically not in equilibrium with ocean water. When evaporation occurs, the lighter isotope evaporates first and so the vapour is more depleted in the heavy isotopes (^{18}O, ^{2}H) compared to ocean water by about 12-15‰ ^{18}O and 80-120‰ in ^{2}H (Freeze & Cherry, 1979). During condensation, the condensate is more enriched in the heavy isotopes relative to vapour. Evaporation is largely affected by humidity in the atmosphere, and therefore the higher the humidity, the less change in $\delta^{18}O$ and δD (Marah, 2017).

The isotopic composition of rainfall is related to its formation conditions, particularly the temperature of formation, the origin of air masses, and the degree and mechanism of rain out (International Atomic Energy Agency [IAEA], 2005). According to Freeze and Cherry (1979), the isotopic composition of water vapour in continental areas varies between 0 to -25‰ ^{18}O and 0 to -150‰ ^{2}H. Deviations from these ranges may occur during individual rainfall events due to differences in temperatures during condensation or as a result of progressive isotopic depletion as an air mass moves.

The isotopic composition of the groundwater sampled will, therefore, differ from the composition of precipitation for many reasons including but not limited to: seasonal recharge, evaporation of surface waters, interception and transpiration, a non-representative sampling, and time intervals (Marah, 2017). At high temperatures in the subsurface i.e. 50 to 100 °C, chemical reactions between groundwater and the aquifer material may change isotope concentrations in groundwater (Freeze & Cherry, 1979). At normal temperatures in shallow aquifers, isotope concentrations likely do not change much as chemical reactions are limited. In these systems, the isotope composition of groundwater correlates to that of precipitation that fell and recharged the aquifer, likely to be affected/not by evaporation before penetration.

3.2.1 Uses of isotopes in groundwater studies

Isotope tracers are essential tools for better understanding of groundwater origin, for detecting surface water and groundwater interactions, precipitation, and climate studies, surface water studies, mixing process and recharge rates in aquifers, as well as for providing timescales of groundwater flow in groundwater systems, on large spatial and temporal scales. Stable water isotopes of ^{2}H and ^{18}O are useful and are used as tracers in solutes and waters in catchments because of their conservative behaviour and large variability in isotope ratios $^{2}H/^{1}H$and $^{18}O/^{16}O$ (Gat et al., 2000). The field of Isotope Hydrology is a beneficial tool to give proof or disproof other hydrogeochemical measurements (Kendall & McDonnell, 1998). A summary of practical uses of isotopes in groundwater flow systems (Marah, 2017) include:

- Isotopes are used as tracers of groundwater source and recharge processes and mechanisms, and to provide information on aquifer evolution
- To determine the origin of specific solutes dissolved in groundwater
- To identify pollution sources and their fate in the groundwater environment
- To assess aquifer vulnerability to pollution as a Decision Support System (DSS)
- To provide estimates of aquifer residence times (determination of non-renewable groundwater resources)
- To study flow and interconnections between aquifers; deduce mixing processes
- Groundwater flow understanding at the local and regional scale

- To assess the source and process of groundwater salinization as well as induced effects of over-abstraction
- To validate and calibrate pollutant transport models
- Utilized in catchment/aquifer management, river basin management, coastal zone management; geothermal, artificial recharge, wetlands, urban hydrology, and many more.
- Historically elevated tritium levels from nuclear bomb tests are used to understand young groundwater systems

3.2.2 Previous Work Done

This study presents one of the first few studies using isotope hydrology techniques specifically for the KE and KW. There are numerous works done in the adjacent Zambezi Region; notably, the study by Bäumle et al. (2019) on the hydrogeology and hydrogeochemistry of the deep-seated and semi-fossil Lower Kalahari Aquifer in the Zambezi Region. Other studies in the Zambezi include BEDMAR (1999) and Margane et al. (2005) for further reading.

3.3 Groundwater Monitoring

3.3.1 Groundwater Monitoring: Rationale and Design

Groundwater monitoring is defined as "the scientifically-designed, continuous measurement and observation of the groundwater situation; including evaluation and reporting procedures" (International Groundwater Resources Assessment Centre, 2008). To monitor a resource, clear objectives should be set to answer particular management questions. These monitoring objectives are required to guide planning, allocation of resources, implementation, and the use of that information for management. If these objectives are not defined or remain unclear or are based on insufficient knowledge of the groundwater system; groundwater monitoring becomes a mere data collection exercise. The lack of groundwater monitoring on the other hand results in undetected degradation of groundwater resources due to over-abstraction or contamination of the resource. A decline in groundwater levels and depletion of the resource; reduced access to drinking water supply and water for irrigation schemes; reduced spring base flows and/or flows to wetlands; deterioration of groundwater quality leading to increased costs in water treatment and land subsidence are some negative impacts experienced (IGRAC, 2008).

3.3.2 Design of a Groundwater Monitoring Network: A General Reference Monitoring Network

Based on IGRAC (2008), two types of groundwater networks are recognized in terms of size i.e. regional/sub-national networks and local networks. Regional networks are larger and are designed for the monitoring of regional groundwater systems. These are opted for during the early stages of groundwater assessment, where information on the resource is limited, and monitoring is aimed at assessing the potential of the aquifer(s) for development. Local networks on the other hand deal with monitoring of local well-fields or point sources of pollution.

A *'general reference monitoring network'* is a regional network that is aimed at supplying data for the characterisation of the regional groundwater systems, as well as the monitoring of trends in time and impacts of abstraction on the resource (IGRAC, 2008). The objectives of such a network may not necessarily be met at the same time due to a lack of funds or capacity. Once these matters are resolved, a general network can be upgraded into a more comprehensive primary network. One such limitation to this network is that it looks at the larger scheme of things, and does not necessarily give details on local contamination or effects on groundwater levels of individual well-fields.

In designing the 'general reference monitoring network', the initial step is to conduct groundwater assessment (Figure 3–7). Groundwater assessment refers to the evaluation of the physical, chemical, and biological status of groundwater in relation to natural conditions and human interference (IGRAC, 2008). The steps involved in 1) groundwater monitoring and assessment are depicted in the diagrams below:

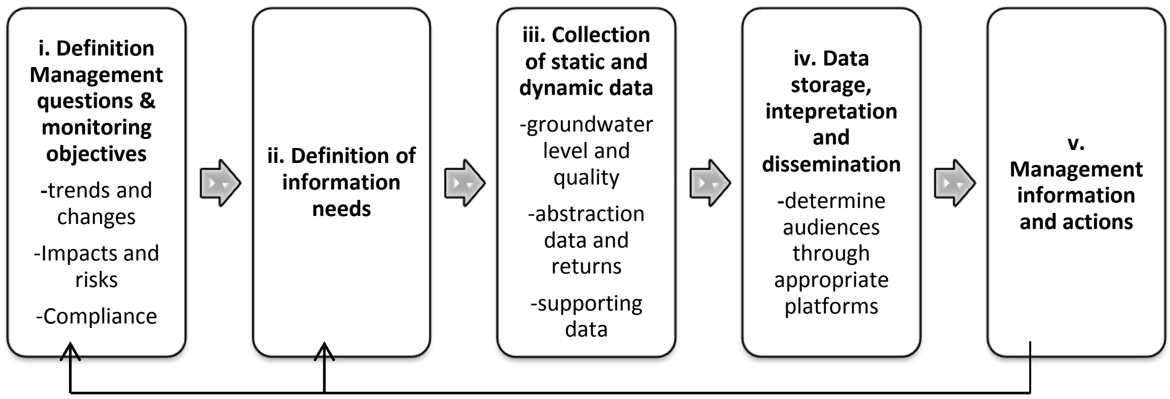


Figure 3-7: Monitoring cycle (adopted from the Integration of Groundwater Management in Transboundary Basin Organizations in Africa (IGMTBOA), (AGW-Net, 2015).

There are generally four basic objectives for establishing a monitoring system based on IGMTBOA (AGW-Net, 2015).

- **Resource monitoring:** to understand the groundwater system and how it functions through investigating recharge, discharge, surface-water groundwater interactions; changes in quality and levels in the long term
- **Compliance monitoring:** to determine how effective management is in preventing over-abstraction of resources: involves measuring groundwater use, well yields, quality parameters, requesting groundwater abstraction returns, issuing drilling and abstraction licenses
- **Protection monitoring:** for potential impacts on groundwater bodies/infrastructure such as well fields/springs from land subsidence, archaeological sites from rising water levels, wetlands, and strategic water reserves from pollution hazards.

- **Pollution containment monitoring:** gives early warning information on the effects of potential pollution hazards from solid waste landfills, mines, industrial sites, intensive agricultural land use

In designing a groundwater monitoring network, the following steps are considered (Figure 3–8):

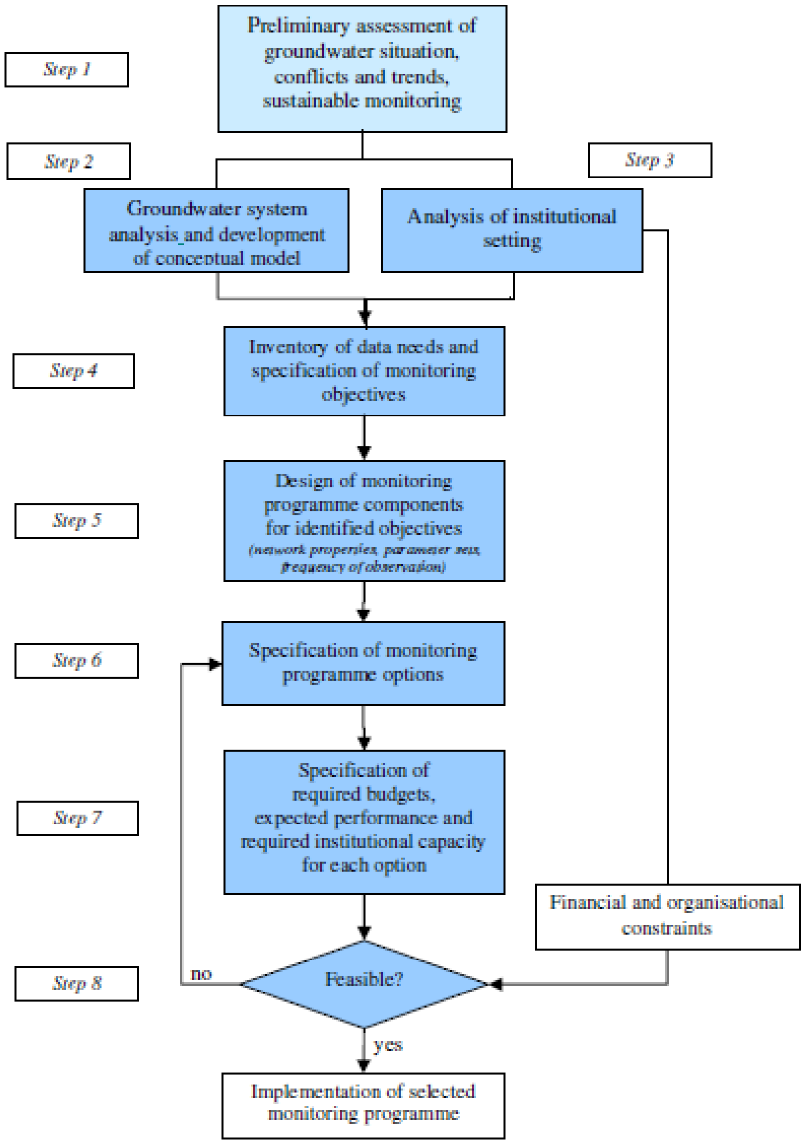


Figure 3-8: Schematic of the steps for designing a groundwater monitoring programme (IGRAC, 2008)

Groundwater Monitoring in the CORB: A Case of Namibia, Botswana, and Angola

In Southern Africa, groundwater is a primary source of water for domestic use and supporting livelihood activities; notwithstanding its vitality in sustaining ecosystems such as wetlands. Dependence on this invisible resource within the regions as in many parts of Africa is on the rise due to population increase and immense pressures owed to climate change and variability. Therefore, many discussions within the Water Sector in the Southern African Development Community (SADC) are centred on sustainable management of groundwater resources.

Groundwater monitoring in the Cubango Okavango River Basin (CORB) is limited to the Okavango Delta in Botswana only, where budget and institutional difficulties hinder its efficiency. In Angola, most of the work in the CORB is focused on the inventory of all geological, hydrological, and hydrogeological data from various institutions. In Namibia, the Geohydrology Division of the Department of Water Affairs (DWA) has established a representative groundwater monitoring network observation system (Figure 3-9). The network comprises 600 monitoring boreholes country-wide distributed within different groundwater rock bodies with various groundwater potential. To successfully evaluate water levels in the delineated groundwater potential bodies, 75 monitoring boreholes referred to as Master Stations (MS) were selected from the 600 boreholes. Water level loggers have been installed in monitoring boreholes and data is downloaded from these manually during field visits. Selected Master Stations have been installed with telemetry stations and they are capable of transmitting data remotely.

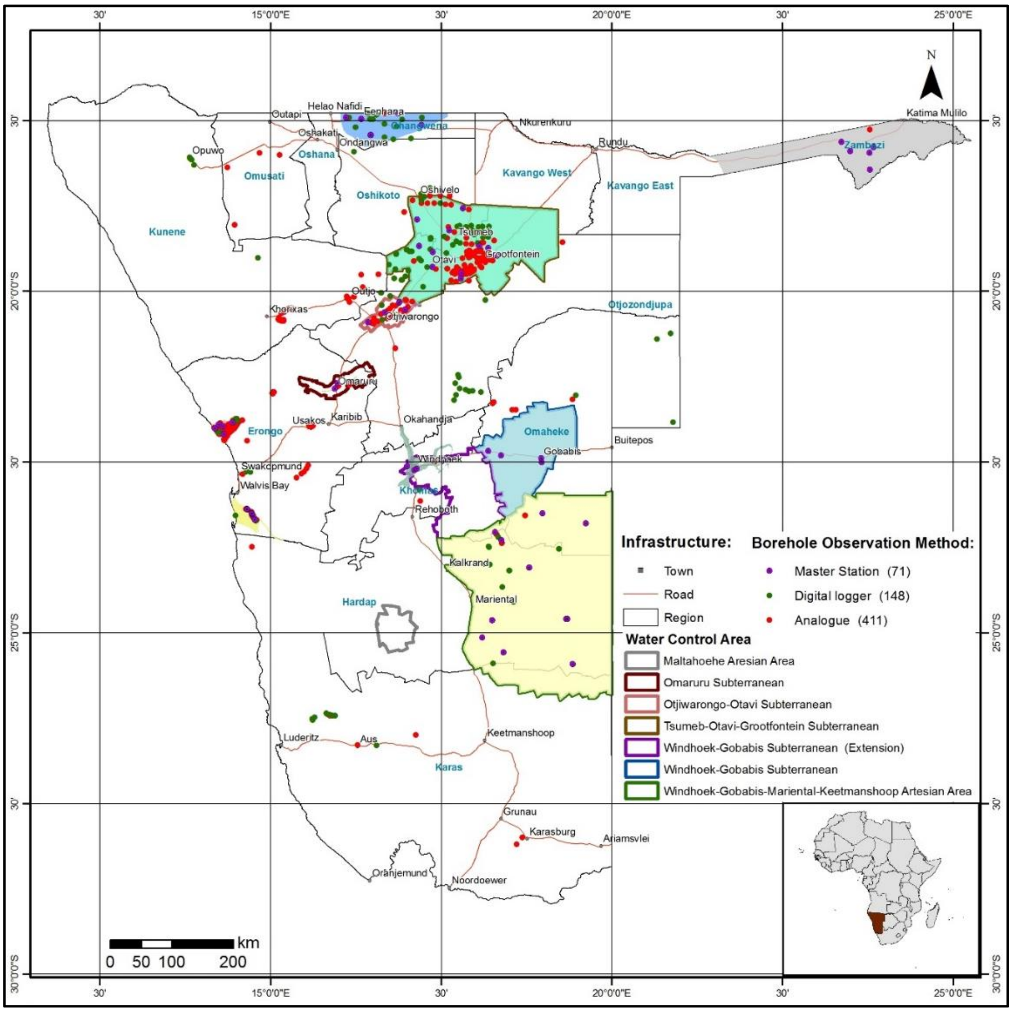


Figure 3-9: Groundwater monitoring network in Namibia and the Water Control Areas (MAWLR, 2021)

There are currently no monitoring boreholes in the KE and KW; there are only water supply boreholes supplying the villages and towns. However, in the larger Okavango-Omatako Basin, there are some 15 monitoring boreholes in the southwest of the basin. Most of the water supply boreholes were drilled by the Directorate of Rural Water Supply and Co-ordination, which has been mandated to implement rural water supply in rural communities on communal land. The rest of the boreholes are NAMWATER

Schemes which supply the towns of Rundu, Nkurenkuru, and larger settlements. Groundwater resources serve mostly the communities living in the interior, while those in proximity to the river utilize surface water.

Water quality problems in certain locations where livestock drink from the River have rendered surface water utilization by the NAMWATER difficult. Purifying contaminated surface water is costly, and a cheaper alternative would be the use of groundwater. A study by Water Surveys Botswana (2011) began the preliminary analysis in the design of a groundwater level and quality monitoring network for the KE and KW for the DWRM (Table 3-3). Based on that study, a visual siting of localities for the drilling of monitoring wells by DWRM (Beukes & Masule, 2014) was initialized.

Table 3-3: Locations suggested for groundwater level monitoring (Water Surveys Botswana, 2011)

Site Number	Location	Aquifer	Selection Criteria
1	Nkunrenkuru	Shallow Kalahari	Okavango River recharge near rainfall station
1a	Nkunrenkuru adjacent site 1	Deeper Kalahari	Relationship of shallow and deeper aquifers
2	Bangani	Shallow Kalahari	Okavango River recharge
2a	Bangani adjacent site 2	Deeper Kalahari	Relationship of shallow and deeper aquifers
3	South Mangetti Farms	Deeper Kalahari	Recharge from dolomites, near rainfall station
4	North Mangetti Farms	Deeper Kalahari	Regional flow path and tracking indications of nitrate pollution
5	Central regime 3	Middle Kalahari	Recharge
6	Southwest Regime 3A	Middle Kalahari	Regional flow regime from area 3 to 3a
7	Rundu	Shallow Kalahari	Inter relationship Okavango River and Kalahari
8	Rundu	Palaeo Okavango channels	Monitor large abstraction effects, probably 3 boreholes required
9	Confluence Omatako & Okavango	Shallow Kalahari	Assess recharge
10, 11, 12		Middle Kalahari	Regional flow regime

The work done by these studies provides a good basis for the design of a monitoring network. However, the design of a comprehensive and efficient monitoring network considers many other factors that have not been outlined in these studies. These factors include outlining clearly the monitoring objectives, defining information needs, data storage/interpretation of collected data, dissemination procedures, and management information and actions thereafter (AGW-Net, 2015). In terms of groundwater quality monitoring, the Water Surveys Botswana (2011) study suggested that a total of 600 boreholes should be sampled to provide a basis for groundwater quality monitoring, and thereafter a representative network should be designed. The study presented should provide a detailed framework for both groundwater level and quality monitoring, including the above information.

4 METHODOLOGY

4.1 Field Research

An inventory of geochemistry data from the Kavango Regions was conducted by compiling drilling reports from the two regions and querying the GROWAS II Database. The database records 771 boreholes with chemistry data from the regions out of the 994 boreholes captured. Of these 771 records, only 97 borehole records, spatially distributed over the two regions have lithology data and borehole construction/design information. Lithology data and borehole design were used to determine which boreholes to sample, based on the aquifer penetrated.

Moreover, other types of essential data listed below were obtained from various Ministries/Agencies and private institutions in Windhoek. These include:

- shapefiles for the Kavango West and East Regions: Namibia Statistics Agency
- land-use data and shapefiles: Ministry of Lands and Resettlement (merged to MAWLR as of 2020)
- climate data: Meteorological Services of Namibia, Hydrology Division at DWAF
- groundwater data (quality, quantity, borehole yields, pump test data, rest water levels, abstraction data): GROWAS II at DWAF, NAMWATER, SLR Environmental Consulting (Namibia) Pty Ltd; Directorate of Water Supply and Sanitation Coordination (DWSSC)
- Geological data (borehole rock chips, lithology logs): Ministry of Mines and Energy (MME)

4.1.1 Sampling Procedure for Major Ions and Heavy Metals

The field sampling campaign was conducted during the wet period, from 22 to 26th March 2020. A total of 22 samples for both hydrochemistry and stable isotope analyses were collected from boreholes, a well, and the Okavango River, a pond, and rain samples across the KE and KW. Forty-one (41) samples were obtained from the newly drilled DWSSC Drought Relief boreholes in the two regions, conducted during the period December 2019 to April 2020.

The sampling points were selected from boreholes penetrating the Kalahari Aquifers and are spatially distributed across the two regions. The pond and well were sampled impromptu to determine connectivity with groundwater; as well as to ascertain chemistry due to their daily usage. The boreholes sampled were installed with solar-powered submersible pumps and occasionally electrical-powered pumps. The boreholes were sampled directly from a valve at the top of the borehole. DWSSC boreholes are communal water points that are used daily by the local communities. Geographical sampling locations collected by the use of a handheld GPS and borehole data are shown in Table 5-3.

Before sampling, the boreholes were purged for 5 minutes whilst measuring the physical parameters temperature, EC, TDS, and pH by use of the Hach portable instruments (HQ40D Portable Multi Meter, HQ40D conductivity meter, and HQ40D pH meter) (Figure 4-1 A). Parameter stabilization occurred after 5 minutes of pumping. Subsequently, a second EC reading was recorded after a further 10 minutes of pumping. The water level was measured in each borehole with an electrical contact gauge. The cation and anion samples were collected in 1 litre polyethylene bottles supplied by the NamWater Laboratory in Windhoek.

The samples were stored immediately in cooler boxes after sampling and transferred to a refrigerator at the end of each day. Labels were prepared to indicate the name of the sampler, sample number, WW number (borehole number), date, time, Division, the purpose of analysis, location/origin of the sample. For each sample, a sampling protocol (Appendix B) was completed in detail with on-site determinants such as odour, colour, and turbidity which were determined qualitatively. DO was not determined in the field as the DO probe was not functional. Furthermore, alkalinity was not determined due to a lack of reagents to complete titration in the field. These parameters were measured at the laboratory; the results are seen in Table 5-3. The cation samples were filtered through 0.45 μm filters and subsequently preserved with nitric acid whereas, anion samples were kept cool using a cooler box and refrigerator until analysed in the laboratory.

4.1.2 Sampling Procedure for Stable Isotopes

In total, 24 samples for stable isotopes (oxygen-18 and deuterium) were collected at the locations visited, including 4 samples collected from rainfall collectors at Rundu, Mashare, and Ndonga Linena Agricultural Development Centres (ADC's), Okavango River samples, and 2 duplicates (tap water). These rain collectors are completely sealed, thus limiting the evaporation of precipitation. The precipitation samples were collected every 24 hours. The samples were collected in 50 ml glass bottles and stored in cooler boxes with cooling packs and transferred to the refrigerator at the end of each day. The glass bottles were filled to the top and air bubbles were expelled. The bottles were carefully sealed to prevent any evaporation during transport.

4.2 Laboratory Methods

Chemical analyses were conducted at the NamWater Laboratory in Windhoek, Namibia. Twenty-nine hydrochemical parameters and Sodium Adsorption Ratio (SAR), water quality classification, and usability for stock watering were analysed in this study. The stable isotope samples were analysed at the UNAM Laboratory. The methods used at the Analytical and NamWater Laboratories are summarized in Table 4-1. All methods are based on the American Water Works Association Standard methods.

Table 4-1: Methods used for general water quality analysis at the Analytical and NamWater Laboratories

Parameter	Method number	Section	Type of Method
pH	4500	B	Electrometric Method
EC	2510	B	Field Method
TDS (determined)			Calculation
Colour	2120	B	Visual Comparison
Turbidity	2130	B	Nephelometric
Sodium as Na	3120	B	Inductively Coupled Plasma (ICP) Method
Potassium as K	3120	B	Inductively Coupled Plasma (ICP) Method
Calcium as Ca as CaCo3	3120	B	Inductively Coupled Plasma (ICP) Method
Magnesium as Mg as CaCO3	3120	B	Inductively Coupled Plasma (ICP) Method
Total Hardness as CaCO3			Calculation
Iron as Fe	3120	B	Inductively Coupled Plasma (ICP) Method
Manganese as Mn	3120	B	Inductively Coupled Plasma (ICP) Method
Chloride as Cl	4500	E	Automated Ferricyanide Method
Sulphate as $SO^{2-}4$	4500	G	Automated Methylthymol Blue Method
Fluoride as F	4500	C	Ion Selective Electrode method
Nitrate as N/ NO3	4500	F	Automated Cadmium Reduction Method
Nitrite as N/ as NO2	4500	F	Automated Cadmium Reduction Method
T-Total Alkalinity as CaCO3/$CO^{2}3$	2320	B	Titration Method
P-Alkalinity CaCO3/HCO3	2320	B	Titration Method
Silica as SiO2	4500	E	Molybdate-Reactive Silica
Copper as Cu	3120	B	Inductively Coupled Plasma (ICP) Method
Zinc as Zn	3120	B	Inductively Coupled Plasma (ICP) Method
Lead as Pb	3120	B	Inductively Coupled Plasma (ICP) Method
Arsenic as As	3120	B	Inductively Coupled Plasma (ICP) Method
Cadmium as Cd	3120	B	Inductively Coupled Plasma (ICP) Method
Ammonia as NH4	3120	B	Inductively Coupled Plasma (ICP) Method
Langelier Index			
Raznar Index			
Stability pH			
Corrosivity ratio			

4.2.1 Charge Balance Error

In any hydrochemical interpretation, it is necessary to check the accuracy of the laboratory chemical analyses and if the condition of electroneutrality has been met, in which the sum of the equivalent weight of cations equates to the sum of the equivalent weight of anions. This control was carried out by calculating the charge balance error (CBE) for all ions for all 63 samples (including DWSSC samples), based on equation 5 (Hiscock, 2005):

$$\text{Charge Balance Error (\%)} = \frac{\Sigma cations - \Sigma anions}{\Sigma cations + \Sigma anions} \times 100 \qquad \textbf{eq.5}$$

4.2.2 Stable Isotopes Analysis

The stable isotopes of $\delta^{18}O$ and $\delta^{2}H$ were analysed using the Los Gatos DLT-100 which uses Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS) (Figure 4-1 D), at the University of Namibia. The analyser has an internal computer (Linux OS) that stores data on an internal hard disk drive. A 100 to 1000 µL Variable Volume Single Channel Pipette fitted with 100 to 1000 µL filtered pipette tips was used to inject the sample into 1.5 ml screw neck glass vials (Figure 4-1 F), which were immediately closed with Teflon lined screw caps on the Autosampler tray. Hamilton 7701.2 N CTC 1.2 µL syringes were used to inject the sample, through the screw cap into the Autosampler (Figure 4-1 E). The injection port of the Autosampler is heated to vaporise the sample under vacuum. This water vapour travels down the transfer line and into the pre-evacuated mirror chamber to begin the analysis. The LGR software automatically applies calibration standard measurements during a sample run to graphically display all the results, and to diagnose instrument operation. It further comprises Spectral Contamination Identifier (SCI) technology, which accurately quantifies and corrects for the presence of any organic matter in the water sample.

The standards used in the analysis were VSMOW2 and VSLAP2. Analyses are given in per mil (‰) against the international standard Vienna Standard Mean Ocean Water (V-SMOW), normalized to V-SMOW/SLAP scale, defined below:

$$\delta_x = \left(\frac{R_x - R_{std}}{R_{std}}\right) \times 1000 \text{ ‰} \qquad \textbf{eq.6}$$

R_x: isotope ratio of $^2H/^1H$ or $^{18}O/^{16}O$ of the sample

R_{std}: isotope ratio of the standard

If $\delta_x>0$; R_x is heavier than R_{std} and if $\delta_x<0$; R_x is lighter than R_{std}

4.2.3 Tritium Analysis

Tritium was analysed at the iThemba Environmental Isotope Laboratory in South Africa. The samples were collected in 500 ml bottles and sent from Windhoek, Namibia to South Africa. The iThemba Labs analysis methodology as provided by the lab is summarized below.

The samples were distilled and subsequently enriched by electrolysis. The electrolysis cells consist of two concentric metal tubes, which are insulated from each other. The outer anode, which is also the container, is of stainless steel. The inner cathode is of mild steel with a special surface coating. Approximately, 500 ml of the water sample, having first been distilled and containing sodium hydroxide, was introduced into the cell. A direct current of about 10 to 20 ampere was then passed through the cell, which was initially cooled because of the heat generation. After several days, the electrolyte volume was reduced to 20 ml. The volume reduction (up to about 25 times) produced a corresponding tritium enrichment factor of about 20. Samples of standard known tritium concentration (spikes) were subsequently run in one cell of each batch to ascertain the enrichment attained. For liquid scintillation counting, samples were prepared by directly distilling the enriched water sample from the now highly concentrated electrolyte. 10 ml of the distilled water sample was mixed with 11 ml Ultima Gold and placed in a vial in the analyser, which counted 2 to 3 cycles of 4 hours each. Detection limits are 0.2 TU for enriched samples.

4.2.4 Software

Numerous software was utilized in producing graphs and maps to understand the geochemical processes affecting the chemical composition of the PKAs. Microsoft Excel was utilized in producing all the climate graphs, scatter plots, bar charts, Collins Diagram, Gibbs Plot, Wilcox Diagram, Pie Chart, and variation diagrams. GW_Chart software was used to draw the Piper Diagram utilized in determining the groundwater types in the Regions. ArcGIS and Surfer 11 were used to produce the location map, hydrogeological and geology maps, as well as the spatial distribution maps of measured chemical parameters and stable isotopes.

4.2.5 Analyses Limitations

The long duration storage times for the geochemistry samples against the prescribed times (Water Research Commission [WRC], 2017) presents an important limitation in the study. Samples must be stored not longer than prescribed to ascertain accuracy in interpretations. Another significant limitation is that there is no documentation of the sampling procedures used by similar studies conducted in the study area, which has made it difficult to assess existing geochemical data. The DWA has since established Groundwater Sampling Operations Procedures based on WRC (2017), which would guide future research and work in Hydrogeochemistry in the study area. There is no baseline for isotope studies in the study area, or it is not well documented.

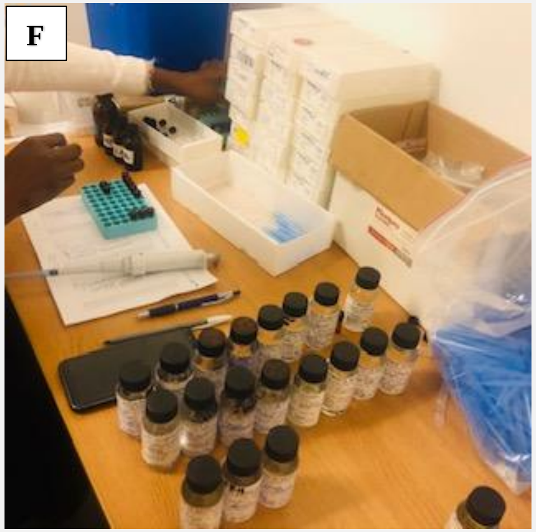


Figure 4-1: A-B Preparation of sampling equipment (Hach HQ40D Multi Meter Kit). Boreholes are installed with a solar-powered pump. The valve at the top of the borehole was opened with a wrench. An electrical contact gauge was used to measure the water level C. Sampling from a well with a bucket pulley. D-E. LGR Isotope Analyzer at the UNAM Laboratory in Windhoek F. Stable isotope samples being injected into the tray for analyses.

5 RESULTS AND DISCUSSION

5.1 Hydrogeochemistry Results

The following section describes the hydrochemical condition of the groundwater of the Primary Kalahari Aquifers according to the physicochemical parameters, ion concentrations and ion ratios. The groundwater is classified according to its usability for domestic use, stock watering, and irrigation. Sampled borehole locations are seen in Figure 5-1.

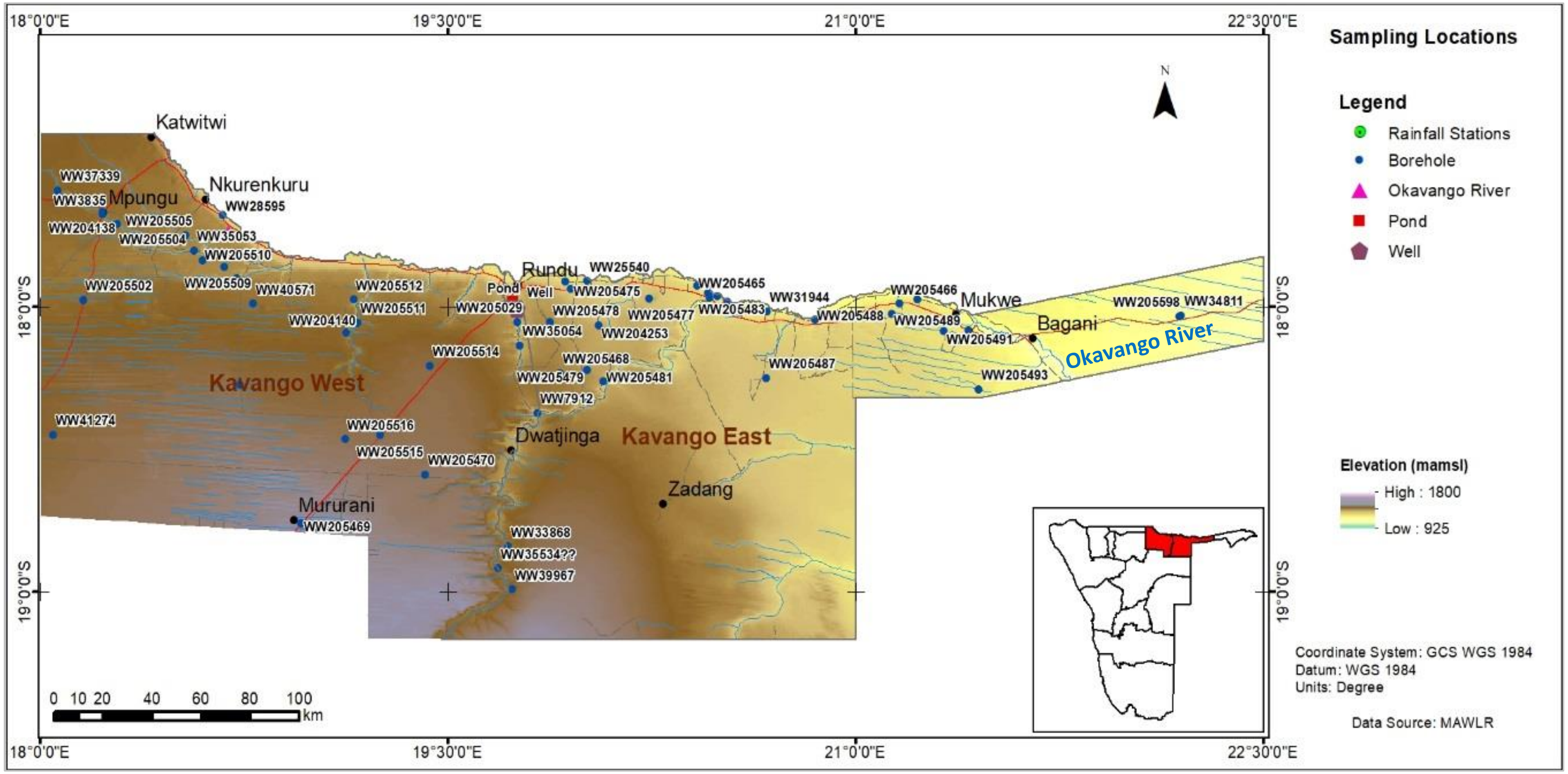


Figure 5-1: Sampling locations in the KW and KE Regions

5.1.1 Charge Balance Error (CBE) and Physicochemical Parameters

The CBE (Appendix C) of the 22 JIN sample analyses show an average of -0.94%, whereas the DWSSC samples results show an average of 0.73%. The overall accuracy of the data is confirmed, with 58/63 (92%) samples in the range of -5 to 5% and 5/63 (8%) samples in the range of 5 to 10%. The former includes 1 analysis from the Okavango River, 1 from a well, and 1 from a pond. Figure 5-2 shows that there is a poor correlation between TDS and CBE, where R^2 = -0.61%. High TDS values in the range 994 to 5828 mg/l have a CBE averaging 0.03%. CBE above 5% may be due to a number of discrepancies, such as mishandling of samples and improper storage; poor or no filtration during sampling, and failure to accurately measure field parameters of pH, Eh, EC in the field.

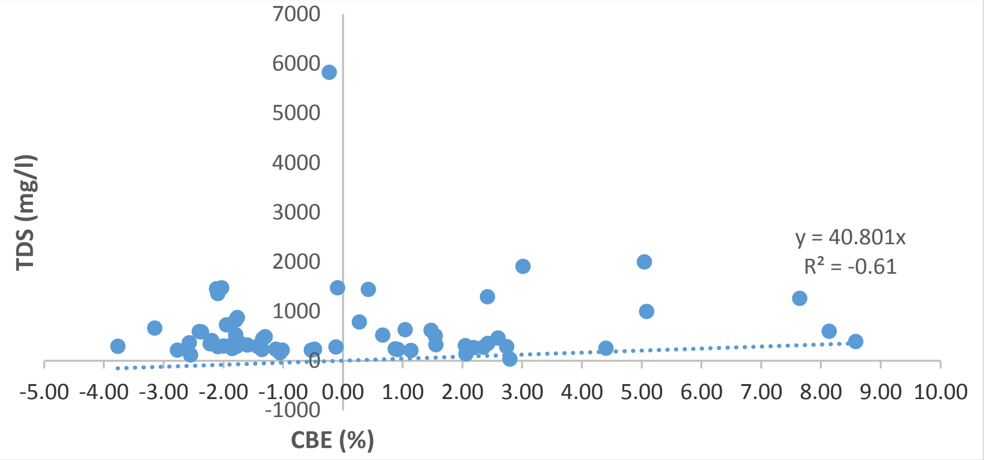


Figure 5-2: Charge Balance Error (CBE) vs TDS for all samples collected (groundwater and surface water)

Based on the Water Act (1956), water is classified into:

- GROUP A: water with an excellent quality
- GROUP B: water with acceptable quality
- GROUP C: water with low health risk
- GROUP D: water with high health risk, or water unsuitable for human consumption

In the study area, 82.5% of the groundwater and surface water analyses are classified as Group A and B, respectively. This translates to groundwater in wide areas of the two Kavango Regions to be safely usable for domestic water and livestock watering, as well as water supply without treatment. In the north-western parts of the Kavango West Region, groundwater quality deteriorates to Groups C and D (Figure 5-3), exceeding the quality limits set in the Drinking Water Guidelines (Table 5-1). 7.9% of samples are Group C and 9.5% are Group D.

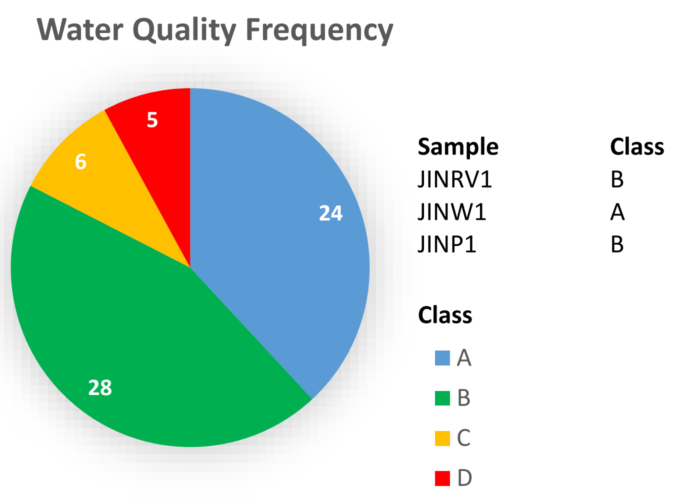


Figure 5-3: Water quality frequency distribution based on the DWA Drinking Water Guidelines and classification. The numbers in the chart refer to the number of samples in each class out of 63.

Table 5-1: Drinking Water Guidelines: Limits for aesthetic, physical, and inorganic determinants

DETERMINANTS	UNITS	LIMITS FOR GROUPS			
		A	B	C	D*
Colour	mg/l Pt**	20			
Conductivity	mS/m @25 °C	150	300	400	400
Total hardness	mg/l $CaCO_3$	300	650	1300	1300
Turbidity	N.T.U***	1	5	10	10
Chloride	mg/l Cl	250	600	1200	1200
Chlorine (free)	mg/l Cl	0,1- 5,0	0,1 – 5,0	0,1 – 5,0	5,0
Fluoride	mg/l F	1,5	2,0	3,0	3,0
Sulphate	mg/l SO_4	200	600	1200	1200
Copper	µg/l Cu	500	1000	2000	2000
Nitrate	mg/l N	10	20	40	40
Hydrogen Sulphide	µg/l H_2S	100	300	600	600
Iron	µg/l Fe	100	1000	2000	2000
Manganese	µg/l Mn	50	1000	2000	2000
Zink	mg/l Zn	1	5	10	10
pH****	pH-unit	6,0 – 9,0	5,5 – 9,5	4,0 – 11,0	4,0 – 11,0

* All values greater than the figure indicated.
** Pt = Platinum Units
*** Nephelometric Turbidity Units
**** The pH limits of each group exclude the limits of the previous group

Temperature

The temperature of groundwater is an important parameter as it has a significant influence on the condition of the water, such as the solubility of ions as well as the pH (Holting, 1996, as cited in Lohe & Hoeben, 2014). The physical and chemical parameters of groundwater and surface water samples were measured in the field. The temperature of the collected groundwater samples ranges between 24.5 to 35.8 °C and averages 27.4 °C, much higher than the average air temperature of 20 °C as reported by (Mendelsohn & El Obeid, 2004). A minimum temperature of 24.5 °C was recorded at borehole WW7912 at Ncaute in the KE, and a maximum temperature of 35.8 °C was recorded at Sharukwe in the KE in the borehole WW205029. The groundwater temperature does not show a large variation from the average, amounting to 2.9 °C; with the exemption of the individual maximum value at Sharukwe. The spatial distribution of the groundwater temperature across the KE and KW does not show a specific pattern (Tables 5-2 and 5-3).

Table 5-2: Characteristics of the 22 sampled boreholes including temperature values

BH ID	Location	BH Depth (m)	Water Level (mbgl)	Initial Yield (m^3/h)	Sampling Date	Analysis Date	Longitude	Latitude	Temp. (°C)	pH	On-site Determinants	
											EC (µS/cm)	TDS (mg/l)
WW28595	Kahenge	38.2	6.7	18.0	23/03/2020	27/05/2020	18.67380	-17.67680	26.6	8.16	N/A	N/A
WW25540	Sambiu	60.0	11.4	15.0	23/03/3020	27/05/2020	20.03190	-17.90710	27.4	9.3	1237	343
WW31944	Nyangana	62.0	12.0	25.0	23/03/2020	27/05/2020	20.67540	-18.01510	27.3	7.69	538	262
WW35053	Yinsu Clinic	119.0	65.1	12.9	24/03/2020	27/05/2020	18.56750	-17.80018	27.3	9.69	1687	845
WW37339	Mukekete	176.6	64.7	10.2	24/03/2020	27/05/2020	18.06740	-17.58948	26.8	8.34	944	463
WW41274	Bravo	125.0	85.8	4.2	24/03/2020	27/05/2020	18.04867	-18.44797	27.7	7.3	1087	540
WW3835	Mpungu	195.0	ND	ND	24/03/2020	27/05/2020	18.23225	-17.67326	26.2	7.97	451	218
WW205029	Sharukwe Clinic	146.0	4.5	12.0	25/03/2020	27/05/2020	19.75740	-18.05130	35.8	7.72	335	161
WW35054	Ncuncuni	84.0	9.5	24.8	25/03/2020	27/05/2020	19.76682	-18.13428	26.1	7.22	303	146
WW7912	Ncaute	57.6	6.1	24.5	25/03/2020	27/05/2020	19.83067	-18.37084	24.5	8.11	374	180
WW33868	Klein Karakuwisa	172.6	12.7	15.0	25/03/2020	27/05/2020	19.72279	-18.84035	26.6	8.5	790	384
WW35524	Satoka	ND	ND	ND	25/03/2020	27/05/2020	19.04602	-18.47760	25.5	7.84	499	235
WW39967	Zadang	117.0	13.9	23.0	25/03/2020	27/05/2020	19.73580	-18.99097	26.3	7.5	724	352
River	Kandjimi Murangi	River	ND	ND	23/03/2020	27/05/2020	18.69466	-17.73780	27.4	8.06	363	17
Pond	Mavandje	Pond	ND	ND	26/03/2020	27/05/2020	19.74059	-17.98063	26.2	8.37	748	367
Well	Mavandje	Well	ND	ND	25/03/2020	27/05/2020	19.75395	-18.0077	25.5	7.68	583	283
WW34811	Omega	90.0	45.2	5.0	14/03/2020	27/05/2020	22.20030	-18.02780	27.6	7.35	1972	ND
WW40567	Tcalikawa	180.0	97.0	1.8	11/03/2020	27/05/2020	18.73762	-18.27320	29.2	7.389	602	ND
WW40571	Desi	120.0	79.0	12.0	11/03/2020	27/05/2020	18.78484	-17.98756	27.9	7.19	841	ND
WW204140	Shinunga Toring	106.0	11.0	6.0	18/03/2020	27/05/2020	20.30251	-18.18076	27.8	7.36	211	ND
WW204253	Rupetho	54.0	13.0	15.0	13/03/2020	27/05/2020	21.65588	-18.14476	27.6	7.27	488	ND
WW204138	Tcausha	90.0	20.9	12.0	18/03/2020	27/05/2020	18.23060	-17.66450	27.1	7.6	523	ND

Table 5-3: Hydrogeochemistry results for all samples

BH ID	Sample ID	Sample ID NamWater	Location	Longitude	Latitude	pH	Conductivity (mS/m)	TDS (mg/l)	CO_3^{2-} (mg/l)	HCO_3^- (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	SO_4^{2-} (mg/l)	NO_3^- (mg/l)	NO_2^- (mg/l)	SiO_2 (mg/l)	F^- (mg/l)	Cl^- (mg/l)	Total Alkalinity as $CaCO_3$(mg/l)	Phenolphthalein Alkalinity	Total Hardness as $CaCO_3$ (mg/l)
WW28595	JINNAM1	DS56071	Kahenge	18.67380	-17.67680	7.6	33.6	225	0.0	200.08	9	2	2	0.5	0.1	7	0.1	1	164	0	142
WW25540	JINNAM2	DS56072	Sambiu	20.01390	-17.90710	8.9	215.0	1441	15.6	427.00	360	3	220	0.5	0.1	17	1.9	125	376	44	7
WW31944	JINNAM3	DS56073	Nyangana	20.67540	-18.01510	7.4	52.3	350	0.0	307.44	41	4	4	0.5	0.1	64	0.3	1	252	0	157
WW35053	JINBH1	DS56074	Yinsu Clinic	18.56750	-17.80018	9.4	187.4	1256	60.3	521.60	350	3	35	0.5	0.1	21	2.1	65	528	148	7
WW37339	JINBH2	DS56075	Mukekete	18.06740	-17.58948	8.1	107.9	723	0.0	622.20	195	15	10	0.5	0.1	27	0.5	6	510	0	68
WW41274	JINBH3	DS56076	Bravo	18.04867	-18.44797	7.4	122.8	823	0.0	563.64	160	13	16	2.3	0.1	43	1.4	65	462	0	193
WW3835	JINBH4	DS56077	Mpungu	18.23225	-17.67326	7.7	51.4	344	0.0	280.60	53	11	2	0.5	0.1	56	0.6	1	230	0	97
WW205029	JINBH5	DS56078	Sharukwe Clinic	19.75740	-18.05130	7.6	38.3	257	0.0	209.84	20	3	6	0.5	0.1	46	0.3	1	172	0	128
WW35054	JINBH6	DS56079	Ncuncuni	19.76682	-18.13428	7.2	36.9	247	0.0	207.40	8	2	1	0.5	0.1	55	0.2	1	170	0	148
WW7912	JINBH7	DS56080	Ncaute	19.83067	-18.37084	7.8	42.4	284	0.0	234.24	12	4	1	0.5	0.1	44	0.1	1	192	0	157
WW33868	JINBH8	DS56081	Klein Karakuwisa	19.72279	-18.84035	8.1	72.1	483	0.0	346.48	126	5	11	1.7	0.1	16	0.8	15	284	0	32
WW35534	JINBH9	DS56082	Satoka	19.68625	-18.91755	7.7	44.5	298	0.0	248.88	18	7	1	0.5	0.1	49	0.1	1	204	0	152
WW39967	JINBH10	DS56083	Zadang	19.73580	-18.99097	7.5	65.5	439	0.0	317.20	30	7	2	0.5	0.1	58	0.1	17	260	0	206
WW34811	AK8	DS56087	Omega	22.19917	-18.02855	8.0	202.0	1353	0.0	678.32	290	9	160	1.4	0.1	76	0.6	150	556	0	258
WW40567	AK4	DS56088	Tcalikawa	18.73762	-18.27320	8.3	60.6	406	2.7	297.00	54	7	1	0.5	0.1	21	0.1	24	248	0	146
WW40571	AK2	DS56089	Desi	18.78484	-17.98756	7.8	87.3	585	0.0	466.04	70	18	3	0.5	0.1	57	0.4	7	382	0	204
WW204140	AK20	DS56090	Shinunga Toring	19.12800	-18.08860	8.0	217.0	1454	0.0	419.68	360	9	230	3.2	0.1	27	0.6	220	344	0	67
WW204253	AK7	DS56091	Rupetho	20.05700	-18.06440	7.7	50.6	339	0.0	292.80	19	3	2	0.5	0.1	71	0.2	1	240	0	192
WW204138	AK21	DS56092	Tcausha	18.23060	-17.66450	8.0	53.5	358	0.0	268.40	75	2	25	0.5	0.1	57	0.5	8	220	0	85
Okavango River	JINRV1	DS56084	Kandjimi Murangi	18.69466	-17.73780	6.9	4.5	30	0.0	24.40	4	1	1	0.5	0.1	16	0.1	1	20	0	14
Pond	JINP1	DS56085	Mavandje	19.74059	-17.98063	8.0	86.2	578	0.0	502.64	80	22	2	0.5	0.1	97	1.6	10	412	0	213
Well	JINW1	DS56086	Mavandje	19.75395	-18.00770	7.5	67.9	455	0.0	283.04	8	12	14	9.4	0.1	72	0.7	1	232	0	239
WW205492	DWSSC1	AnaLab	Dingandu	21.41687	-18.08193	6.7	48.3	292	0.0	358.68	9.2	5.6	2	0.5	0.01	0.04	0.1	2	294	0	264
WW205493	DWSSC2	AnaLab	Shamagumbo	21.45333	-18.28850	6.8	39.2	225	0.0	262.30	5.5	1	3	1	0.01	0.08	0.3	4	215	0	216
WW205491	DWSSC3	AnaLab	Muthindiko	21.32676	-18.08403	6.8	28.2	163	0.0	198.86	5.1	1.6	1	0.5	0.01	0.03	0.2	3	163	0	153
WW205490	DWSSC4	AnaLab	Mayara	21.22730	-17.97158	6.7	48.7	293	0.0	364.78	14	2.9	3	0.6	0.01	0.12	0.1	6	299	0	254
WW205489	DWSSC5	AnaLab	Sharuhenga	21.13369	-18.02338	6.8	35.3	213	0.0	269.62	2.5	1.8	1	0.5	0.01	0.01	0.1	2	221	0	206
WW205488	DWSSC6	AnaLab	Makena	20.85101	-18.04393	6.9	33.5	214	0.0	224.48	48	2.6	12	0.5	0.01	0.02	0.2	6	184	0	93
WW205487	DWSSC7	AnaLab	Gcorodani	20.67258	-18.24781	7.0	54.7	364	0.0	378.20	105	3.7	21	0.5	0.01	0.01	1.1	13	310	0	103
WW205486	DWSSC8	AnaLab	Ngandaro	20.47869	-18.00684	8.6	104.3	629	7.3	399.90	249	1.7	110	1.1	0.07	0.01	0.7	57	340	0	4
WW205485	DWSSC9	AnaLab	Shitemo	20.52944	-17.97998	7.2	22.4	119	0.0	134.20	0.01	4.6	0.1	1	0.5	26	11	11	110	0	103

Sample ID	Sample ID NamWater	Location	Longitude	Latitude	Ca^{2+} as Ca (mg/l)	Mg^{2+} as Mg (mg/l)	Fe^{2+} (mg/l)	Mn^{2+} (mg/l)	Cu^{2+} (mg/l)	Zn^{2+} (mg/l)	Cd^{2+} (mg/l)	Pb^{2+} (mg/l)	As^{2+} (mg/l)	Turbidity NTU	Colour	NH_4^+ (mg/l)	TDS 180 deg.C (mg/l)	WQ Classification	Stock-Watering
JINNAM1	**DS56071**	**Kahenge**	18.67380	-17.67680	40	10	0.04	0.32	0.01	0.02	0.01	0.02	0.01	0.74	1	0.09	238	B	SU
JINNAM2	**DS56072**	**Sambiu**	20.01390	-17.90710	1	1	0.01	0.01	0.02	0.01	0.01	0.02	0.06	0.48	1	0.00	1262	B	SU
JINNAM3	**DS56073**	**Nyangana**	20.67540	-18.01510	36	16	0.06	0.03	0.01	0.01	0.01	0.02	0.01	0.36	3	0.00	330	A	SU
JINBH1	**DS56074**	**Yinsu Clinic**	18.56750	-17.80018	1	1	0.01	0.01	0.01	0.01	0.01	0.02	0.27	0.24	1	0.00	1071	C	SU
JINBH2	**DS56075**	**Mukekete**	18.06740	-17.58948	12	9	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.29	1	0.04	621	B	SU
JINBH3	**DS56076**	**Bravo**	18.04867	-18.44797	32	27	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.35	1	0.03	716	B	SU
JINBH4	**DS56077**	**Mpungu**	18.23225	-17.67326	17	13	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.27	1	0.00	315	A	SU
JINBH5	**DS56078**	**Sharukwe Clinic**	19.75740	-18.05130	41	6	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.19	1	0.01	234	A	SU
JINBH6	**DS56079**	**Ncuncuni**	19.76682	-18.13428	54	3	0.05	0.01	0.01	0.02	0.01	0.02	0.01	0.82	1	0.00	249	A	SU
JINBH7	**DS56080**	**Ncaute**	19.83067	-18.37084	46	10	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.22	1	0.05	246	A	SU
JINBH8	**DS56081**	**Klein Karakuwisa**	19.72279	-18.84035	6	4	0.02	0.01	0.01	0.03	0.01	0.02	0.01	0.27	1	0.00	442	B	SU
JINBH9	**DS56082**	**Satoka**	19.68625	-18.91755	44	10	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.15	1	0.00	274	A	SU
JINBH10	**DS56083**	**Zadang**	19.73580	-18.99097	64	11	0.01	0.01	0.01	0.06	0.01	0.02	0.01	0.19	1	0.00	382	A	SU
AK8	**DS56087**	**Omega**	22.19917	-18.02855	40	38	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.19	1	0.03	1207	B	SU
AK4	**DS56088**	**Tcalikawa**	18.73762	-18.27320	35	14	0.01	0.01	0.01	0.39	0.01	0.02	0.01	0.21	1	0.03	261	B	SU
AK2	**DS56089**	**Desi**	18.78484	-17.98756	35	28	0.01	0.01	0.01	0.11	0.01	0.02	,0.01	0.18	1	0.03	480	A	SU
AK20	**DS56090**	**Shinunga Toring**	19.12800	-18.08860	15	7	0.01	0.01	0.01	0.03	0.01	0.02	0.01	0.49	1	0.04	1245	B	SU
AK7	**DS56091**	**Rupetho**	20.05700	-18.06440	45	19	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.28	1	0.02	273	A	SU
AK21	**DS56092**	**Tcausha**	18.23060	-17.66450	19	9	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.19	1	0.02	306	A	SU
JINRV1	**DS56084**	**Kandjimi Murangi**	18.69466	-17.73780	4	1	0.26	0.01	0.01	0.01	0.01	0.02	0.01	0.59	18	0.01	57	B	SU
JINP1	**DS56085**	**Mavandje**	19.74059	-17.98063	30	33	0.01	0.01	0.01	0.02	0.01	0.02	0.01	1.1	28	0.12	568	B	SU
JINW1	**DS56086**	**Mavandje**	19.75395	-18.00770	84	7	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.26	1	0.27	524	A	SU
DWSSC1	**AnaLab**	**Dingandu**	21.41687	-18.08193	76	18	0.08	0.04	ND	ND	ND	ND	ND	8.6	ND	ND	ND	C	SU
DWSSC2	**AnaLab**	**Shamagumbo**	21.45333	-18.28850	65	13	0.25	0.08	ND	ND	ND	ND	ND	0.25	ND	ND	ND	B	SU
DWSSC3	**AnaLab**	**Muthindiko**	21.32676	-18.08403	38	14	0.02	0.03	ND	ND	ND	ND	ND	1.2	ND	ND	ND	B	SU
DWSSC4	**AnaLab**	**Mayara**	21.22730	-17.97158	59	26	0.06	0.12	ND	ND	ND	ND	ND	1.2	ND	ND	ND	B	SU
DWSSC5	**AnaLab**	**Sharuhenga**	21.13369	-18.02338	56	16	0.01	0.01	ND	ND	ND	ND	ND	0.3	ND	ND	ND	A	SU
DWSSC6	**AnaLab**	**Makena**	20.85101	-18.04393	26	6.9	0.38	0.02	ND	ND	ND	ND	ND	3.2	ND	ND	ND	B	SU
DWSSC7	**AnaLab**	**Gcorodani**	20.67258	-18.24781	18	14	0.04	0.01	ND	ND	ND	ND	ND	1.3	ND	ND	ND	B	Su
DWSSC8	**AnaLab**	**Ngandaro**	20.47869	-18.00684	1	0.4	0.57	0.01	ND	ND	ND	ND	ND	11	ND	ND	ND	D	SU
DWSSC9	**AnaLab**	**Shitemo**	20.52944	-17.97998	26	9.3	2.40	0.20	ND	ND	ND	ND	ND	6.7	ND	ND	ND	B	SU

BH ID	Sample ID	Sample ID NamWater	Location	Longitude	Latitude	pH	Conductivity (mS/m)	TDS (mg/l)	CO_3^{2-} (mg/l)	HCO_3^- (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	SO_4^{2-} (mg/l)	NO^-_3 (mg/l)	NO^-_2 (mg/l)	SiO_2 (mg/l)	F^- (mg/l)	Cl^- (mg/l)	Total Alkalinity as $CaCO_3$ (mg/l)	Phenolphthalein Alkalinity	Total Hardness as $CaCO_3$ (mg/l)
WW205484	DWSSC10	AnaLab	Mbarena	20.49414	-17.96048	7.0	64.7	384	0.0	298.90	55	2.1	6	17	0.01	0.01	0.3	22	245	0	230
WW205477	DWSSC11	AnaLab	Dausima	20.24166	-17.96892	6.8	31.6	212	0.0	222.04	20	2.6	2	0.5	0.01	0.01	0.1	7	182	0	146
WW205474	DWSSC12	AnaLab	Draai ya Kamuncaya	19.93398	-17.90869	8.0	148.4	994	0.0	517.28	387	2.5	192	0.5	0.01	0.01	1.6	102	424	0	10
WW205476	DWSSC13	AnaLab	Tyeye Teya	20.08186	-17.94499	7.4	37.3	250	0.0	228.14	35	2.5	10	0.5	0.01	0.01	0.3	8	187	0	150
WW205479	DWSSC14	AnaLab	Lirarambi	20.01406	-18.22144	6.7	98.4	659	0.0	697.84	125	29	1	0.5	0.01	0.02	0.6	12	572	0	247
WW205480	DWSSC15	AnaLab	Mutwekombahe	20.01080	-18.32051	6.8	47.7	320	0.0	329.40	8.6	15	1	0.5	0.01	0.01	0.7	3	270	0	249
WW205481	DWSSC16	AnaLab	Shakamba 2	20.07414	-18.26012	7.5	116.7	782	0.0	597.80	241	8.4	57	3.1	0.01	0.01	1.1	82	490	0	139
WW205478	DWSSC17	AnaLab	Shimpanda no.2	19.87722	-18.05190	6.8	45.7	306	0.0	315.98	42	7.4	1	0.5	0.11	0.01	0.2	3	259	0	176
WW205453	DWSSC18	AnaLab	Shighuru	20.41931	-17.92347	7.3	105.1	616	0.0	549.00	183	5.3	31	8.9	0.04	0.01	0.8	37	450	0	155
WW205483	DWSSC19	AnaLab	Ndonga Linena	20.45857	-17.94988	7.2	105.9	591	0.0	427.00	78	4.7	1	25	0.03	0.01	0.2	67	350	0	373
WW205475	DWSSC20	AnaLab	Kambowo Teya	19.95461	-17.93542	7.4	74.9	502	0.0	369.66	158	3.1	77	0.5	0.01	0.01	0.9	29	303	0	93
WW205598	DWSSC21	AnaLab	Omega	22.19100	-18.03194	6.8	219.5	1471	0.0	671.00	386	11	346	1.6	0.54	0.05	0.5	285	550	0	460
WW205502	DWSSC22	DS55941	Heha	18.15953	-17.97457	7.7	52.5	291.8	0.0	312.30	80	7	1	0.5	0.1	25	0.1	1	256	0	38
WW205503	DWSSC23	DS55942	Kavango village	18.12988	17.89947	9.0	344.0	1905.6	71.2	1548.50	810	5	125	0.5	0.1	20	10.1	95	1388	172	14
WW205504	DWSSC24	DS55943	Ngandu	18.28489	-17.70759	9.1	377.0	1995.9	56.6	977.90	830	8	250	0.5	0.1	20	5.1	340	896	136	9
WW205505	DWSSC25	DS55944	Dikweya	18.53584	-17.74687	7.8	38.1	234.6	0.0	224.48	46	4	4	0.5	0.1	39	0.2	1	184	0	83
WW205506	DWSSC26	DS55945	Nsivi	18.65596	-17.80690	8.3	39.8	229	2.0	220.40	79	3	5	0.5	0.1	24	0.3	1	184	4	12
WW205507	DWSSC27	DS55946	Ndombe Za Matala	18.72405	-17.89786	7.9	248.0	1289.7	0.0	524.60	430	10	210	0.5	0.1	37	0.5	290	430	0	165
WW205508	DWSSC28	DS55947	Mahahe	18.64023	-17.91756	7.5	168.7	871	0.0	312.32	260	9	70	0.5	0.1	27	0.2	300	256	0	80
WW205509	DWSSC29	DS55948	Namkupa	18.68000	-17.85778	7.9	926.0	5828	0.0	409.92	2000	16	2080	4.8	0.1	21	1.7	1440	336	0	151
WW205510	DWSSC30	DS55949	Mafugu	18.59810	-17.83656	8.6	271.0	1472.1	10.3	564.00	540	6	270	0.5	0.1	19	2	340	480	14	10
WW205511	DWSSC31	DS55950	Gcana	19.16955	-18.05451	7.6	47.2	286.9	0.0	263.52	29	5	4	0.5	0.1	59	0.1	5	216	0	173
WW205512	DWSSC32	DS55951	Sainca	19.15484	-17.97250	7.7	41.3	263.3	0.0	239.12	15	6	1	0.5	0.1	67	0.5	1	196	0	80
WW205513	DWSSC33	DS55952	Masiro	19.26802	17.88131	7.3	48.1	279	0.0	290.36	13	5	1	0.5	0.1	39	0.1	2	238	0	208
WW205514	DWSSC34	DS56178	Gcigcau	19.43606	-18.20585	7.5	22.2	132.3	0.0	122.00	6	4	1	0.7	0.1	29	0.1	1	100	0	90
WW205515	DWSSC35	DS56179	Mauguva	19.25213	-18.44941	8.5	35.0	205	2.8	189.60	39	18	1	0.6	0.1	29	0.3	1	160	0	60
WW205516	DWSSC36	DS56180	Eharo	19.12310	-18.46381	8.1	70.0	519.4	0.0	524.60	180	20	5	0.7	0.1	9	0.4	26	430	0	63
WW205470	DWSSC37	DS55846	Likorera	19.41779	-18.58831	7.7	46.9	314	0.0	278.16	23	5	5	1.2	0.1	46	0.6	4	228	0	178
WW205469	DWSSC38	DS55845	Mururani	18.96216	-18.75947	7.6	78.4	525	0.0	517.28	61	28	10	1.7	0.1	31	0.5	9	424	0	268
WW205468	DWSSC39	DS55844	Mpuma	19.91446	-18.23115	7.7	40.2	269	0.0	251.32	7	3	1	1.3	0.1	48	0.1	1	206	0	202
WW205466	DWSSC40	DS55843	Kangono Teya	21.16383	-17.98697	7.5	35.3	237	0.0	209.84	2	1	4	1.2	0.1	52	0.2	1	172	0	178
WW205465	DWSSC41	DS55842	Ndonga Linena	20.46317	-17.96621	7.3	51.8	347	0.0	297.68	10	3	4	3.2	0.1	88	0.4	2	244	0	243

BH ID	Sample ID	Sample ID NamWater	Location	Longitude	Latitude	Ca^{2+} as Ca (mg/l)	Mg^{2+} as Mg (mg/l)	Fe^{2+} (mg/l)	Mn^{2+} (mg/l)	Cu^{2+} (mg/l)	Zn^{2+} (mg/l)	Cd^{2+} (mg/l)	Pb^{2+} (mg/l)	As^{2+} (mg/l)	Turbidity NTU	Colour	NH_4^+ (mg/l)	TDS 180 deg.C (mg/l)	WQ Classification	Stock-Watering
WW205484	**DWSSC10**	**AnaLab**	**Mbarena**	20.49414	-17.96048	51	25	0.01	0.01	ND	ND	ND	ND	ND	0.35	ND	ND	ND	B	SU
WW205477	**DWSSC11**	**AnaLab**	**Dausima**	20.24166	-17.96892	32	16	0.01	0.01	ND	ND	ND	ND	ND	0.55	ND	ND	ND	A	SU
WW205474	**DWSSC12**	**AnaLab**	**Draai ya Kamuncaya**	19.93398	-17.90869	2	1.2	0.07	0.01	ND	ND	ND	ND	ND	2	ND	ND	ND	B	SU
WW205476	**DWSSC13**	**AnaLab**	**Tyeye Teya**	20.08186	-17.94499	32	17	0.03	0.01	ND	ND	ND	ND	ND	0.95	ND	ND	ND	A	SU
WW205479	**DWSSC14**	**AnaLab**	**Lirarambi**	20.01406	-18.22144	41	35	0.22	0.02	ND	ND	ND	ND	ND	17	ND	ND	ND	D	SU
WW205480	**DWSSC15**	**AnaLab**	**Mutwekombahe**	20.01080	-18.32051	55	27	0.01	0.01	ND	ND	ND	ND	ND	0.55	ND	ND	ND	A	SU
WW205481	**DWSSC16**	**AnaLab**	**Shakamba 2**	20.07414	-18.26012	26	18	0.06	0.01	ND	ND	ND	ND	ND	3.5	ND	ND	ND	B	SU
WW205478	**DWSSC17**	**AnaLab**	**Shimpanda no.2**	19.87722	-18.05190	39	19	0.02	0.01	ND	ND	ND	ND	ND	0.65	ND	ND	ND	A	SU
WW205453	**DWSSC18**	**AnaLab**	**Shighuru**	20.41931	-17.92347	29	20	0.14	0.14	ND	ND	ND	ND	ND	5.5	ND	ND	ND	C	SU
WW205483	**DWSSC19**	**AnaLab**	**Ndonga Linena**	20.45857	-17.94988	72	47	0.04	0.01	ND	ND	ND	ND	ND	1.8	ND	ND	ND	C	SU
WW205475	**DWSSC20**	**AnaLab**	**Kambowo Teya**	19.95461	-17.93542	26	6.7	0.06	0.01	ND	ND	ND	ND	ND	2.3	ND	ND	ND	B	SU
WW205598	**DWSSC21**	**AnaLab**	**Omega**	22.19100	-18.03194	67	71	ND	0.01	ND	ND	ND	ND	ND	1.1	ND	ND	ND	B	SU
WW205502	**DWSSC22**	**DS55941**	**Heha**	18.15953	-17.97457	15	7	0.01	0.01	ND	ND	ND	ND	ND	0.65	11	ND	351.8	A	SU
WW205503	**DWSSC23**	**DS55942**	**Kavango village**	18.12988	17.89947	4	1	0.57	0.01	ND	ND	ND	ND	ND	0.45	92	ND	2304.8	D	US
WW205504	**DWSSC24**	**DS55943**	**Ngandu**	18.28489	-17.70759	2	1	0.1	0.01	ND	ND	ND	ND	ND	12.8	24	ND	2525.9	D	SU
WW205505	**DWSSC25**	**DS55944**	**Dikweya**	18.53584	-17.74687	18	9	0.92	0.01	ND	ND	ND	ND	ND	10.7	39	ND	255.3	B	SU
WW205506	**DWSSC26**	**DS55945**	**Nsivi**	18.65596	-17.80690	3	1	0.18	0.01	ND	ND	ND	ND	ND	9.2	24	ND	266.7	B	SU
WW205507	**DWSSC27**	**DS55946**	**Ndombe Za Matala**	18.72405	-17.89786	31	21	0.07	0.01	ND	ND	ND	ND	ND	10	19	ND	1661.6	C	SU
WW205508	**DWSSC28**	**DS55947**	**Mahahe**	18.64023	-17.91756	32	17	0.05	0.01	ND	ND	ND	ND	ND	19	19	ND	1130.3	B	SU
WW205509	**DWSSC29**	**DS55948**	**Namkupa**	18.68000	-17.85778	27	20	0.03	0.01	ND	ND	ND	ND	ND	2.1	20	ND	6204.2	D	US
WW205510	**DWSSC30**	**DS55949**	**Mafugu**	18.59810	-17.83656	4	1	0.01	0.01	ND	ND	ND	ND	ND	15	15	ND	1815.7	C	SU
WW205511	**DWSSC31**	**DS55950**	**Gcana**	19.16955	-18.05451	29	24	0.11	0.01	ND	ND	ND	ND	ND	1.9	15	ND	316.2	B	SU
WW205512	**DWSSC32**	**DS55951**	**Sainca**	19.15484	-17.97250	32	21	0.06	1.40	ND	ND	ND	ND	ND	13	13	ND	276.7	A	SU
WW205513	**DWSSC33**	**DS55952**	**Masiro**	19.26802	17.88131	60	14	0.01	0.01	ND	ND	ND	ND	ND	1.3	12	ND	322.3	A	SU
WW205514	**DWSSC34**	**DS56178**	**Gcigcau**	19.43606	-18.20585	16	12	0.15	0.02	ND	ND	ND	ND	ND	10.4	1	ND	148.7	B	SU
WW205515	**DWSSC35**	**DS56179**	**Mauguva**	19.25213	-18.44941	9	9	0.16	0.02	ND	ND	ND	ND	ND	5.6	1	ND	234.5	B	SU
WW205516	**DWSSC36**	**DS56180**	**Eharo**	19.12310	-18.46381	7	11	0.03	0.01	ND	ND	ND	ND	ND	2.8	1	ND	469	B	SU
WW205470	**DWSSC37**	**DS55846**	**Likorera**	19.41779	-18.58831	48	14	0.01	0.02	0.01	0.01	0.01	0.02	ND	1.4	8	ND		A	SU
WW205469	**DWSSC38**	**DS55845**	**Mururani**	18.96216	-18.75947	47	36	0.02	0.01	0.01	0.01	0.01	0.02	ND	21.9	11	ND		A	SU
WW205468	**DWSSC39**	**DS55844**	**Mpuma**	19.91446	-18.23115	64	10	0.01	0.01	0.01	0.01	0.01	0.02	ND	0.74	7	ND		A	SU
WW205466	**DWSSC40**	**DS55843**	**Kangono Teya**	21.16383	-17.98697	51	12	0.01	0.02	0.01	0.01	0.01	0.02	ND	0.55	11	ND		A	SU
WW205465	**DWSSC41**	**DS55842**	**Ndonga Linena**	20.46317	-17.96621	54	26	0.01	0.01	0.01	0.01	0.01	0.02	ND	0.49	12	ND		A	SU

pH

pH affects the solubility and ion concentrations of most dissolved substances in water, with the exception of ions such as Na^+, K^+, NO_3^- and Cl^-. In turn, dissolved substances/ions affect the pH level, such as waters with a high content of carbonates will shift the pH level into the alkaline range. pH values for the 22 JIN and AK samples (Table 5-2) measured in the field range between 7.2 and 9.7 with an average of 8.45. pH values measured in the lab for all 63 samples range between 6.7 to 9.4 and averages 7.6, placing it in the i.e. slightly acidic to slightly alkaline range (Figure 5-4).

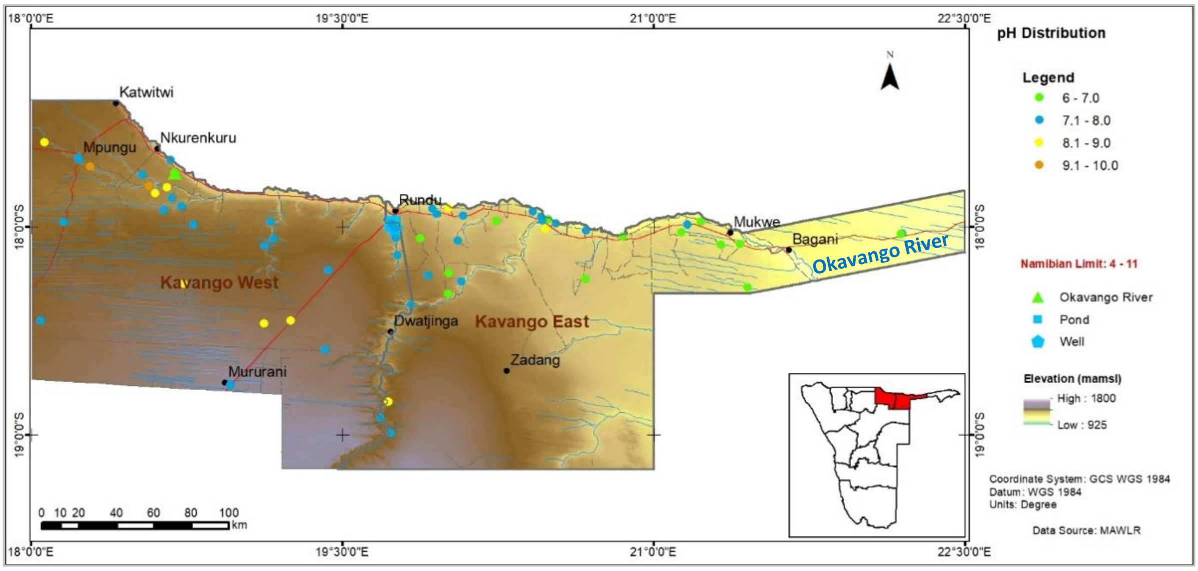


Figure 5-4: Map of pH concentrations in the study area

The highest pH value of 9.4 was recorded at Yinsu Clinic (WW35053) situated in the northern part of the Kavango West Region. Groundwater is slightly alkaline towards the southern parts of the KE and KW and more so in the northern parts of the KW. In the northeast of Kavango East and groundwater south of Rundu, pH values are in the slightly acidic-neutral range. Overall, the pH range of groundwater in the two regions is largely within the optimum pH range for drinking water of 6.5 to 8.5 (World Health Organisation [WHO], 2018). In this range, the concentration of heavy metals in groundwater is low averaging 0.12 mg/l for iron and 0.05 mg/l manganese (Figure 5-5).

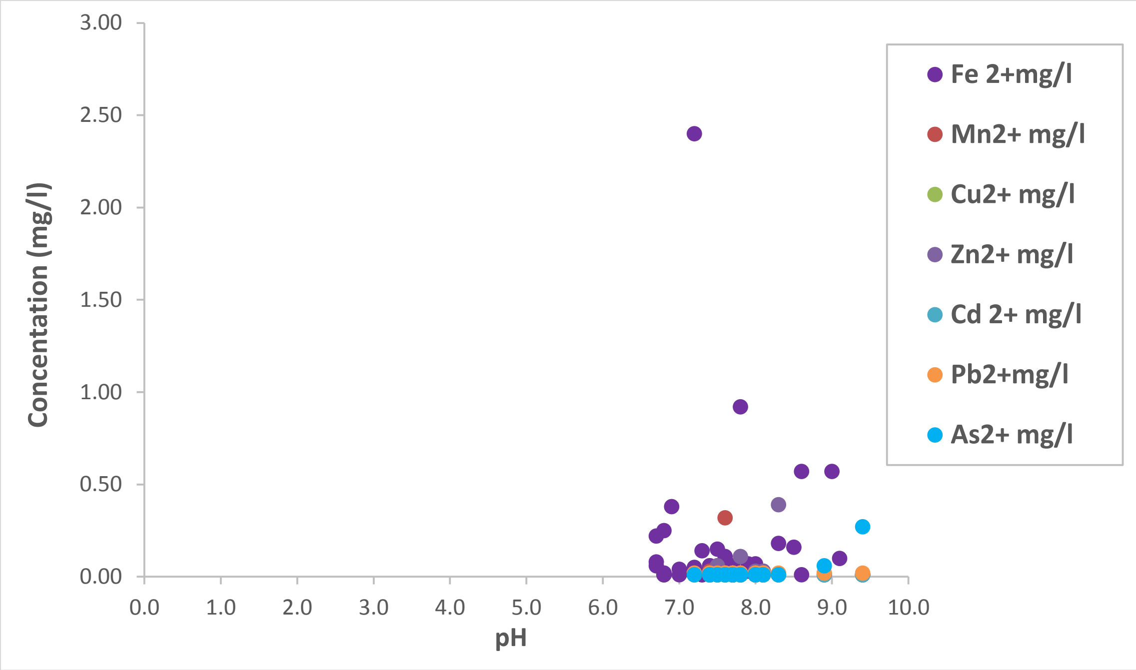


Figure 5-5: pH vs Heavy metals

Only 7.9% of the analyses fall out of the acceptable pH range, observed in groundwater in the northwest KW.

Total Dissolved Solids (TDS)

TDS provides a good indication of the salinity of groundwater, with the lowest values reflecting potable useable water, whilst higher values are associated with high salinity. Water with TDS values above 2600 mg/l is not fit for human consumption and above 5000 mg/l is detrimental for animals (Mendelsohn et al., 2013). The WHO Guidelines for Drinking Water Quality (World Health Organization, 2017) do not specify the limit for TDS values in drinking water, citing that it is not of health concern at levels found in drinking water. However, high levels >1000 mg/l affect the palatability and acceptability of drinking water by consumers. No limit has been set for TDS in the Namibian Guidelines for Drinking Water (Water Act, 1956; Water Resources Management Act, 2013).

TDS values in groundwater within the KE and KW (Figure 5-6 & 5-7 A) range between 30 to 5828 mg/l, the latter occurring at the Namkupa village in the KW. High TDS levels >1000 mg/l are concentrated in the north-central parts of the Kavango West Region along Omuramba Mpungu, with discrete high values in proximity to Rundu and at Omega in the far northeast in the KE Region. Towards the southern parts of the two regions and along the political border, TDS values range between 30 to 600 mg/l.

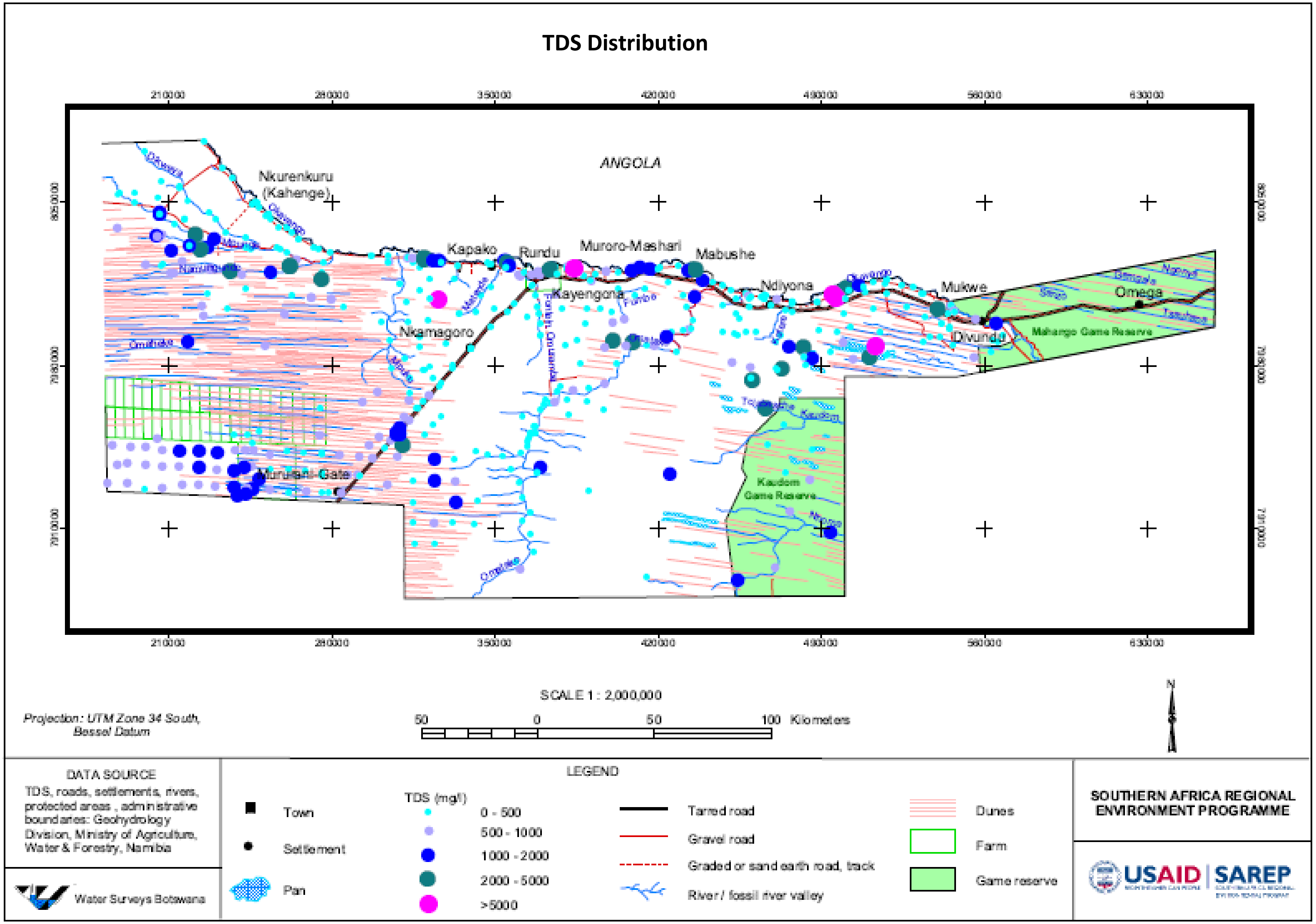
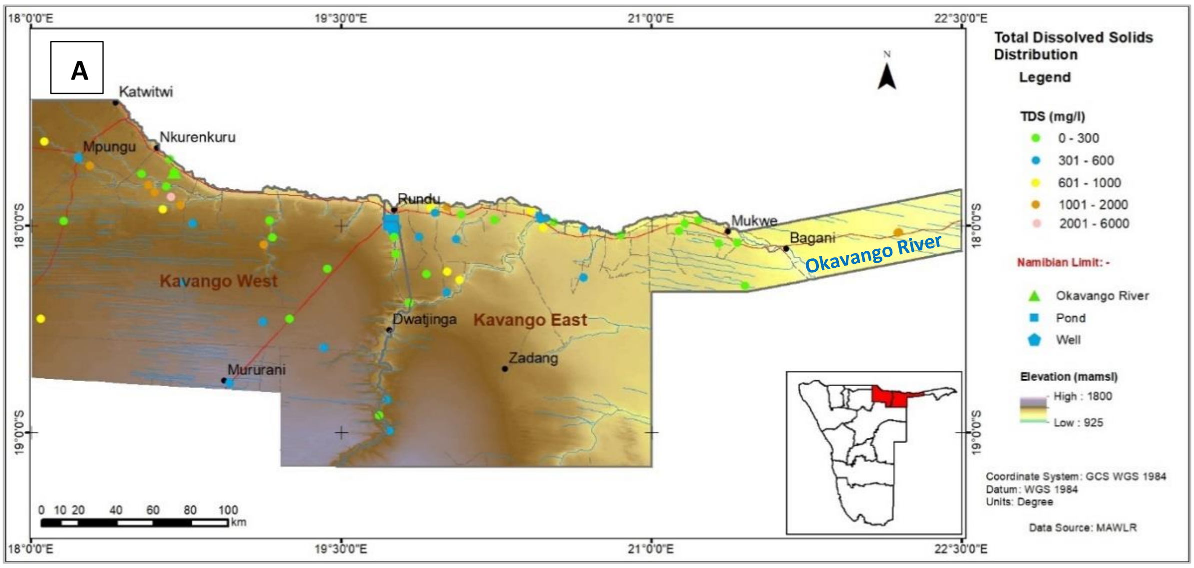
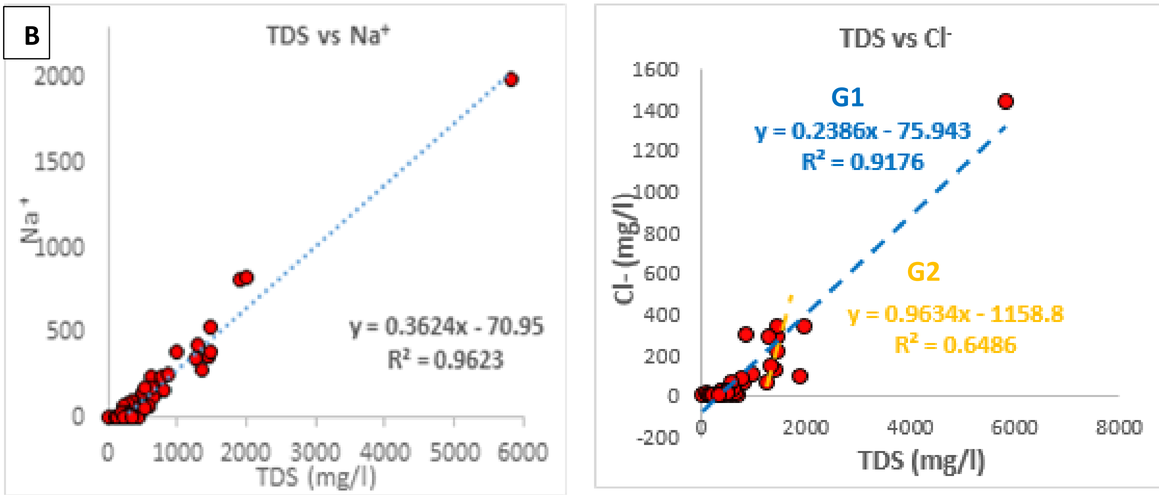


Figure 5-6: TDS distribution in KE and KW regions (Water Surveys Botswana, 2011)

BIWAC (2002) and Water Surveys Botswana (2011) report elevated TDS in the northeast and north-west Kaudom Park, along the Okavango River, and in the Mangetti Block. Groundwater with such high TDS levels (1000-10 000 mg/l) is categorized as brackish (Hiscock, 2005). Overall, the average TDS in groundwater is calculated as 646 mg/l, which is generally considered to be freshwater (TDS < 1000 mg/l).





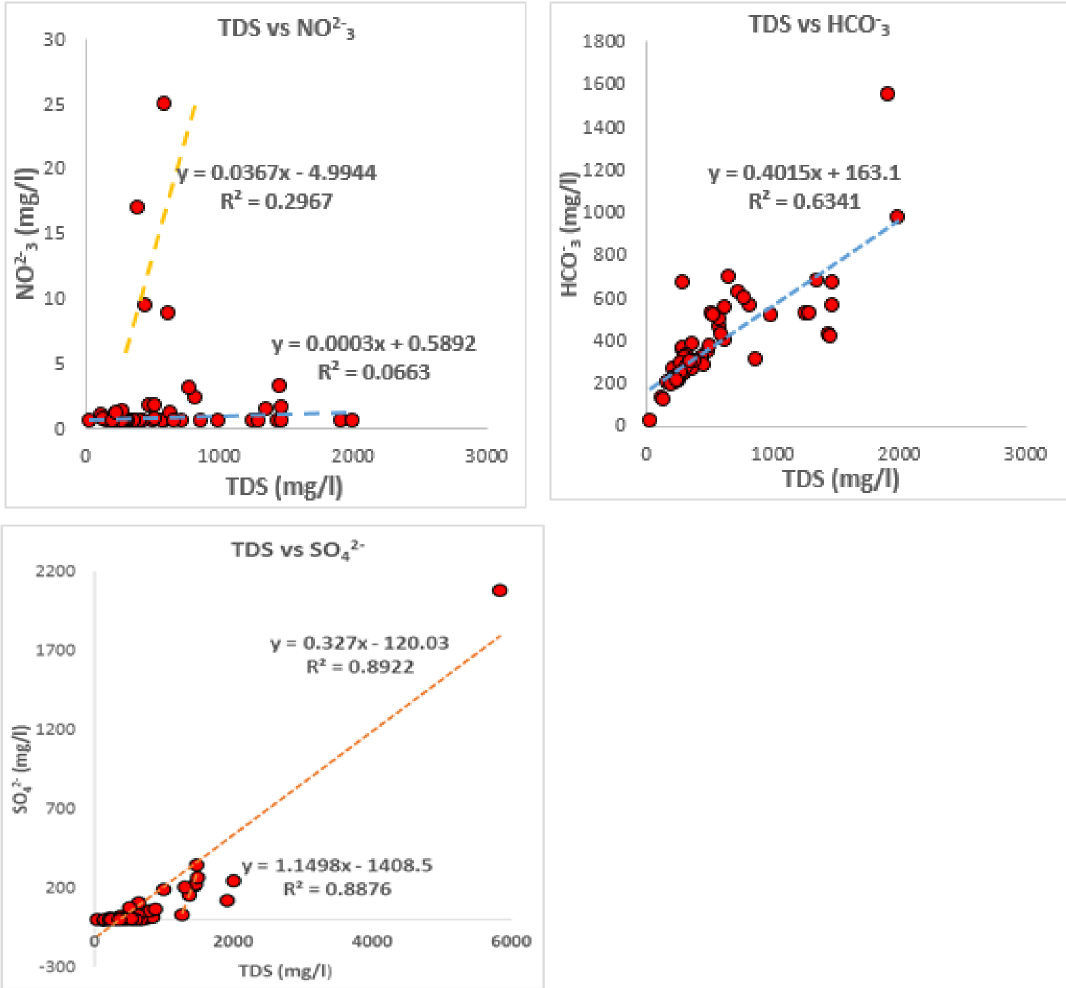


Figure 5-7: A) Map of the TDS distribution in the KE and KW B) Variation diagrams of TDS vs nitrate, carbonate, sodium, and chloride based on mg/l

The variation diagrams presented above (Figure 5-7 B) indicate that there is a strong linear positive relationship between TDS and sodium and chloride ions in groundwater analyses. This is shown by R^2 = 0.96 (96%) for the graph TDS vs Na^+. The graph TDS vs Cl^- shows two trends described by R^2 = 0.9176 (92%), named Group 1 (G1) and a second trend R^2 = 0.6486 (65%), named Group 2 (G2). In this graph, TDS ranges between 1256 to 1472 mg/l and chloride ranges between 65 to 340 mg/l. For the G1 analyses, high chloride values are not the largest contributor to high TDS. Elevated sodium concentrations in the range of 290 to 540 mg/l and sulphate in the range of 35 to 346 mg/l contribute to a higher TDS concentration. This means with an increase in Cl^-, there is a smaller increase in TDS values. For the G2 analyses, the trendline is described well by a linear equation, where an increase in chloride is directly proportional to an increase TDS.

The graph of TDS vs NO_3^{2-} also has two trends, with G1, R^2 = 0.2967 (30%) and G2, R^2 = 0.0663. This clearly shows that there is a poor correlation between TDS and nitrate concentrations in groundwater. The graph of TDS vs SO_4^{2-} shows that there is a good correlation between TDS and sulphate concentrations in groundwater. The correlation ratio for all samples is R^2 = 0.89 (89%). The graph of TDS vs HCO_3^- shows that variation in TDS is poorly explained by bicarbonate with R^2 = 0 (0%).

In summary, based on the analyses performed, TDS in groundwater in KE and KW is largely controlled by the three ions, sodium, chloride and sulphate.

Electrical Conductivity (EC)

In the study area, most boreholes with depths >100 m are more mineralized with EC values ranging from 700 to 9260 μS/cm (70-926 mS/m); whereas boreholes drilled to depths between 35 to 100 m show an average EC value of only 435 μS/cm (43.5 mS/m). In the graph of EC vs TDS, the regression line gives R^2 = 0.99% (Figure 5-8). Across the KW and KE, electrical conductivity ranges between 45 to 9260 μS/m (4.5-926 mS/m), the latter detected in the borehole WW205509 at the Namkupa village in north-central KW (Figure 5-9). In the sampled open pond at Mavandje which is accessible to livestock and people, EC values are higher than those in water from the hand-dug well (enclosed, hence inaccessible to livestock) and the Okavango River. These values are 862 μS/cm (86.2 mS/m), 679 μS/cm (67.9 mS/m) and 45 μS/cm (4.5 mS/m), respectively.

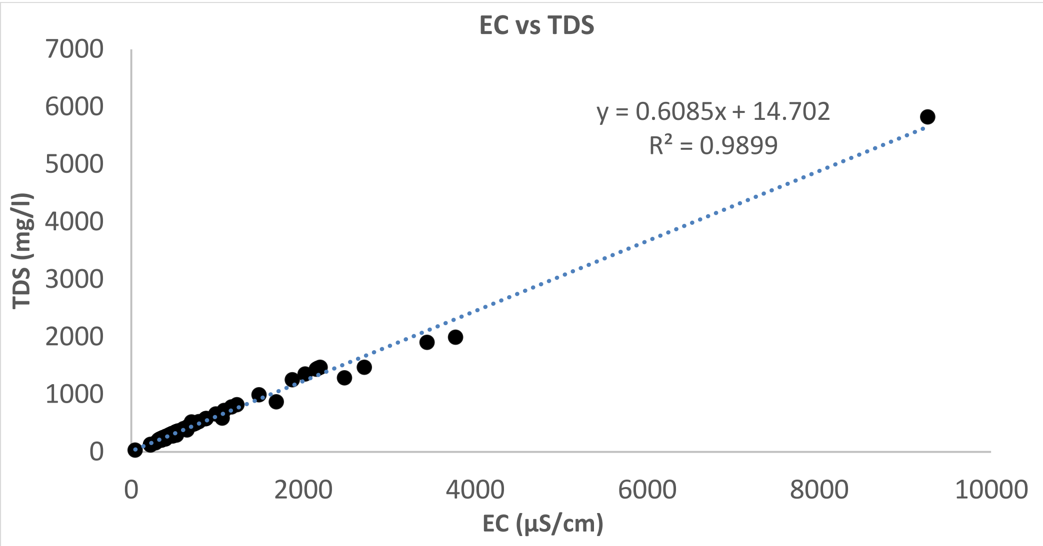


Figure 5-8: EC vs TDS plot for all water samples

Overall, based on the types of water derived by Rhoades (1992, as cited in Rusydi, 2017), groundwater in the north-central KW is characterised as type 3: moderately saline with EC values >2000 μS/cm (>200 mS/m). Towards the western parts of KW and the eastern parts of KE, groundwater is nonsaline (type 1,<700 μS/cm) and slightly saline (type 2, 700-2000 μS/cm). Further to the northeast of the KE along the Zambezi arm, groundwater is characterised as fresh.

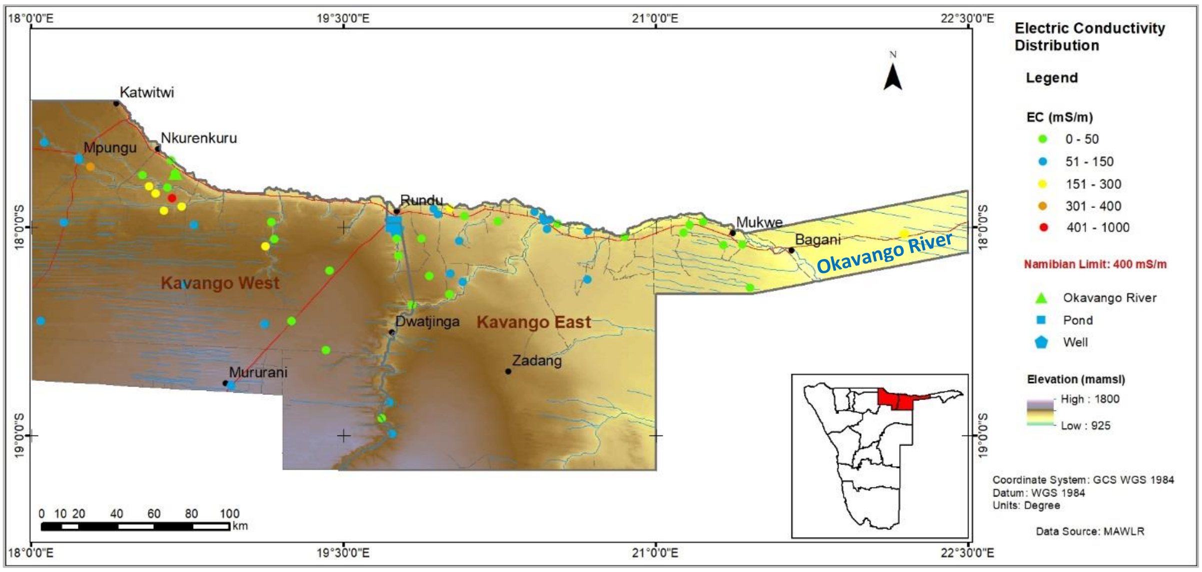


Figure 5-9: Map of EC in the study area

Total Hardness

Based on Hiscock (2005) total hardness is an important property for water users, indicative of the capacity of water to bind soap to form lather. According to the source, water hardness is predominantly caused by the alkaline earth metals calcium and magnesium. The source of these ions is commonly sedimentary rocks such as limestone and dolomite, which produce Ca, Mg and HCO_3^- by silicate weathering. Depending on factors such as pH and alkalinity, WHO (2017) points out that groundwater with a hardness above >100 mg/l can be troublesome, at 200 mg/l it is termed hard water and causes the scaling of appliances during heating, and above 500 mg/l it is not aesthetically appealing.

WHO (2011) categorizes water with total hardness as $CaCO_3$ less than 60 mg/l as soft, 60 to 120 mg/l as moderately hard, 120 to 180 mg/l as hard, and greater than 180 mg/l very hard (McGowan, 2000, as cited in WHO, 2011). The limit as per the DWA Guidelines for Drinking Water Quality is 1300 mg/l for Group D. Total hardness in the KE and KW ranges between 4 to 460 mg/l, the latter is present in groundwater at Omega farther to the east of the KE. Across the two regions, total hardness averages 143.5 mg/l and is classified predominantly as hard water (120-180 mg/l). Overall, based on the DWA guidelines groundwater in the KE and KW is within the upper limit of Group A which is 650 mg/l, inclusive of surface waters in the river and open pond.

Turbidity

Turbidity describes the cloudiness of water resultant from suspended particles such as clay and silts, chemical precipitates, micro-organisms as well as plant debris (WHO, 2017). Turbidity in groundwater is mostly caused by natural geological factors. Surface waters generally have higher turbidity in comparison to groundwater, except in shallow wells or poorly designed boreholes. Groundwater with turbidity levels above 4 NTU will appear milky white, muddy, red-brown, or black with suspended particles (WHO, 2017).

Turbidity in groundwater from the study area ranges between 0.15 to 21.9 NTU and averages 3.5 NTU. Highly turbid groundwater occurs predominantly in the KW, with 6 boreholes averaging 14.1 NTU, and in the KE, two boreholes recorded an average of 14 NTU (see Table 5-3). Boreholes in which groundwater has turbidity above 10 NTU are not suitable for human consumption as per the NamWater guidelines, which are based on the Water Act (1956). The Okavango River analysis is 0.59 NTU and the pond 1.1 NTU. The low turbidity in the river is due to dilution and little impact from local activities and livestock. The pond is utilized daily by the community for both livestock drinking and human consumption and washing of clothes.

5.1.2 Major Ions Geochemistry

The concentration of the chemical constituents present in natural groundwater depends on numerous processes and conditions, which include the availability and solubility of minerals, as well as the geology, geochemical environment which affects pH and Eh, as well as exchange processes (Freeze & Cherry, 1979). Major ions geochemistry results are seen in Table 5-4.

The concentrations of the alkali ions (Na^+ and K^+) range between 0.01 to 2000 mg/l and 1 to 29 mg/l, with average values of 164.4 mg/l and 6.87 mg/l, respectively. The alkaline earth ions Ca^{2+} and Mg^{2+} have concentrations ranging 1 to 84 mg/l and 0.4 to 71 mg/l with mean values of 32.1 mg/l and 15.2 mg/l, respectively. The dominant anion in the boreholes is bicarbonate HCO_3^- with concentrations ranging 24.40 to -1548.5 mg/l, with an average of 378 mg/l. Concentrations of other anions are Cl^- (1-1440 mg/l), F^- (0.1-11 mg/l), NO_2^- (0.01-0.54 mg/l), NO_3^- (0.5-25 mg/l), SO_4^{2-} (0.1-2080 mg/l), NH_4^+ (0-0.27 mg/l). Average values for these anions are 69 mg/l, 0.9 mg/l, 0.1.mg/l, 1.7 mg/l, 77.7 mg/l and 0.02 mg/l.

Therefore, the order of relative abundance for major ions expressed as average meq/l for all groundwater samples is Na^+ (6.88 meq/l) > HCO_3^- (6.11 meq/l) > Cl^- (1.95 meq/l) > Ca^{2+} (1.62 meq/l) > SO_4^{2-} (1.55 meq/l) > Mg^{2+} (1.24 meq/l) >Si^{2+} (0.46 meq/l). The river, pond and well samples have concentrations for HCO_3^-,Cl^-, SO_4^{2-}, NO_3^-, F,- Na^+, Ca^{2+},K^+ and Mg^{2+} with ranges of 24.4 to 502.6 mg/l, 1 to 10 mg/l, 1 to 14 mg/l, 0.1 to 1.6 mg/l, 4 to 80 mg/l, 4 to 84 mg/l, 1 to 22 mg/l and 1 to 34 mg/l. Average values are 270 mg/l, 4 mg/l, 5.7 mg/l, 3.47 mg/l, 0.8 mg/l, 30.7 mg/l, 39.3 mg/l, 11.7 mg/l and 14 mg/l, respectively (Figure 5-10 and Table 5-4).

The dominant anion and cation in these two sources are HCO_3^- and Ca^{2+}. The concentrations of the major ions above in the river sample are lower than 5 mg/l with only HCO_3^- at 24.4 mg/l. Overall, major ions concentrations in all groundwater samples are within the limits as set out in the Namibian Guidelines for Drinking Water Quality (Water Act, 1956) as well as the limits set by the World Health Organization. The exceptions are 2 borehole samples with sulphate and chloride levels above the 1200 mg/l limit and 3 other samples with fluoride above the Namibian and WHO limits of 3.0 mg/l and 1.5 mg/l, respectively (WHO, 2018).

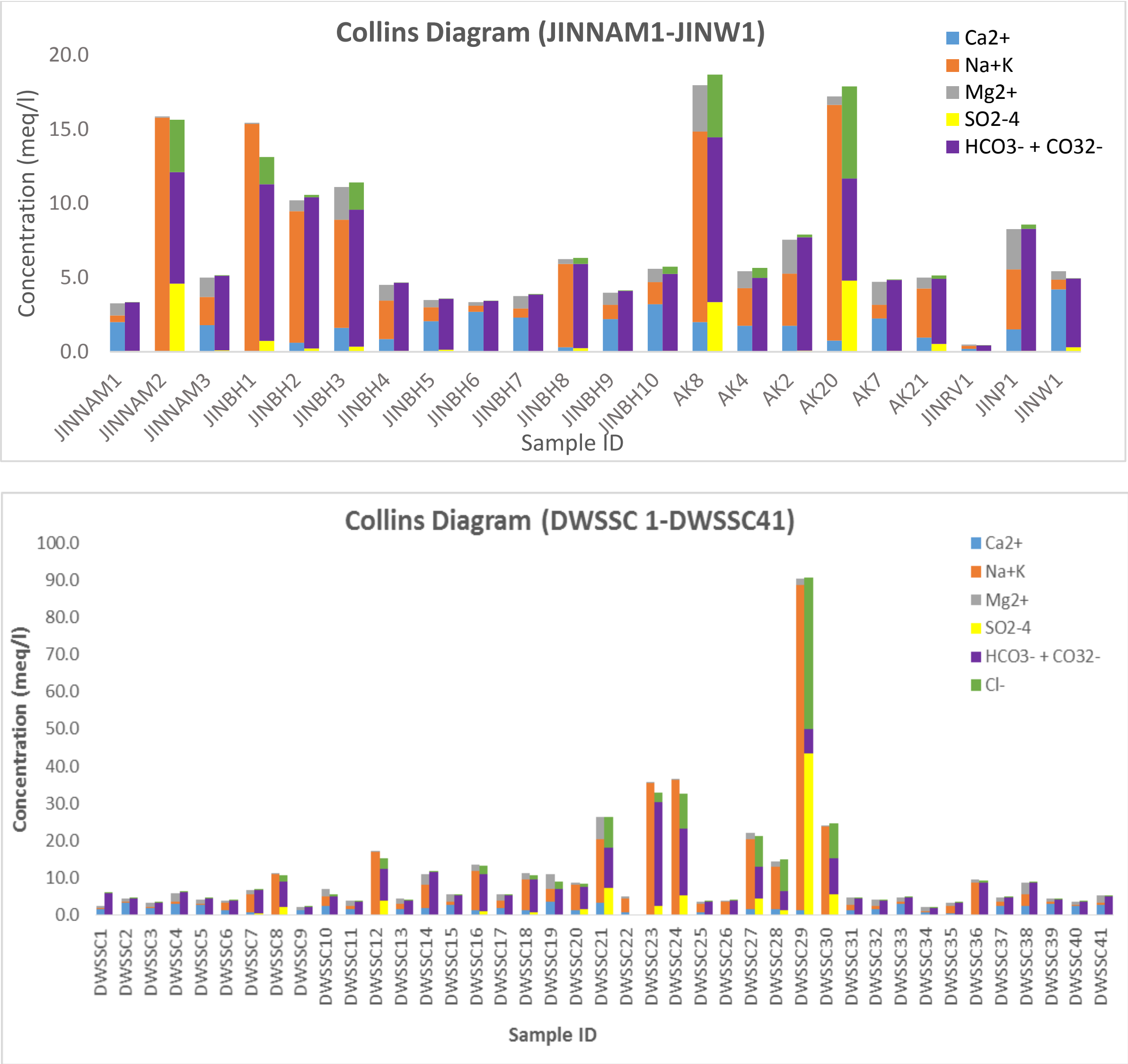


Figure 5-10: Collins Diagram displaying major ion chemistry in the samples collected in meq/l

Table 5-4: Major ions geochemistry results

BH ID	Sample ID	Location	Longitude	Latitude	pH	EC (μS/cm)	TDS (mg/l)	EC (mS/m)	T-Alkalinity as CaCO3 (mg/l	Total Hardness as CaCO3 mg/l	Na^+ (mg/l)	Ca^{2+} as Ca (mg/l)	Mg^{2+} as Mg (mg/l)	SO^{2-}_4 (mg/l)	Cl^- (mg/l)	HCO^-_3 (mg/l)	SiO_2 (mg/l)
WW28595	JINNAM1	Kahenge	18.67380	-17.67680	7.6	336	225	33.6	164	142	9	40	10	2	1	200.08	7
WW25540	JINNAM2	Sambiu	20.01390	-17.90710	8.9	2150	1441	215.0	376	7	360	1	1	220	125	427.00	17
WW31944	JINNAM3	Nyangana	20.67540	-18.01510	7.4	523	350	52.3	252	157	41	36	16	4	1	307.44	64
WW35053	JINBH1	Yinsu Clinic	18.56750	-17.80018	9.4	1874	1256	187.4	528	7	350	1	1	35	65	521.60	21
WW37339	JINBH2	Mukekete	18.06740	-17.58948	8.1	1079	723	107.9	510	68	195	12	9	10	6	622.20	27
WW41274	JINBH3	Bravo	18.04867	-18.44797	7.4	1228	823	122.8	462	193	160	32	27	16	65	563.64	43
WW3835	JINBH4	Mpungu	18.23225	-17.67326	7.7	514	344	51.4	230	97	53	17	13	2	1	280.60	56
WW205029	JINBH5	Sharukwe Clinic	19.75740	-18.05130	7.6	383	257	38.3	172	128	20	41	6	6	1	209.84	46
WW35054	JINBH6	Ncuncuni	19.76682	-18.13428	7.2	369	247	36.9	170	148	8	54	3	1	1	207.40	55
WW7912	JINBH7	Ncaute	19.83067	-18.37084	7.8	424	284	42.4	192	157	12	46	10	1	1	234.24	44
WW33868	JINBH8	Klein Karakuwisa	19.72279	-18.84035	8.1	721	483	72.1	284	32	126	6	4	11	15	346.48	16
WW35534	JINBH9	Satoka	19.68625	-18.91755	7.7	445	298	44.5	204	152	18	44	10	1	1	248.88	49
WW39967	JINBH10	Zadang	19.73580	-18.99097	7.5	655	439	65.5	260	206	30	64	11	2	17	317.20	58
WW34811	AK8	Omega	22.19917	-18.02855	8.0	2020	1353	202.0	556	258	290	40	38	160	150	678.32	76
WW40567	AK4	Tcalikawa	18.73762	-18.27320	8.3	606	406	60.6	248	146	54	35	14	1	24	297.00	21
WW40571	AK2	Desi	18.78484	-17.98756	7.8	873	585	87.3	382	204	70	35	28	3	7	466.04	57
WW204140	AK20	Shinunga Toring	19.12800	-18.08860	8.0	2170	1454	217.0	344	67	360	15	7	230	220	419.68	27
WW204253	AK7	Rupetho	20.05700	-18.06440	7.7	506	339	50.6	240	192	19	45	19	2	1	292.80	71
WW204138	AK21	Tcausha	18.23060	-17.66450	8.0	535	358	53.5	220	85	75	19	9	25	8	268.40	57
Okavango River	JINRV1	Kandjimi Murangi	18.69466	-17.73780	6.9	45	30	4.5	20	14	4	4	1	1	1	24.40	16
Pond	JINP1	Mavandje	19.74059	-17.98063	8.0	862	578	86.2	412	213	80	30	34	2	10	502.64	97
Well	JINW1	Mavandje	19.75395	-18.00770	7.5	679	455	67.9	232	239	8	84	7	14	1	283.04	72
WW205492	DWSSC1	Dingandu	21.41687	-18.08193	6.7	483	292	48.3	294	264	9.2	30	4	2	2	358.68	0.04
WW205493	DWSSC2	Shamagumbo	21.45333	-18.28850	6.8	392	225	39.2	215	216	5.5	65	13	3	4	262.30	0.08
WW205491	DWSSC3	Muthindiko	21.32676	-18.08403	6.8	282	163	28.2	163	153	5.1	38	14	1	3	198.86	0.03
WW205490	DWSSC4	Mayara	21.22730	-17.97158	6.7	487	293	48.7	299	254	14	59	26	3	6	364.78	0.12
WW205489	DWSSC5	Sharuhenga	21.13369	-18.02338	6.8	353	213	35.3	221	206	2.5	56	16	1	2	269.62	0.01
WW205488	DWSSC6	Makena	20.85101	-18.04393	6.9	335	214	33.5	184	93	48	26	6.9	12	6	224.48	0.02
WW205487	DWSSC7	Gcorodani	20.67258	-18.24781	7.0	547	364	54.7	310	103	105	18	14	21	13	378.20	0.01
WW205486	DWSSC8	Ngandaro	20.47869	-18.00684	8.6	1043	629	104.3	340	4	249	1	0.4	110	57	399.90	0.01
WW205485	DWSSC9	Shitemo	20.52944	-17.97998	7.2	224	119	22.4	110	103	0.01	26	9.3	0.1	11	134.20	26

WW205484	**DWSSC10**	**Mbarwena**	20.49414	-17.96048	7.0	647	384	64.7	245	230	55	51	25	6	22	298.90	0.01
WW205477	**DWSSC11**	**Dausima**	20.24166	-17.96892	6.8	316	212	31.6	182	146	20	32	16	2	7	222.04	0.01
WW205474	**DWSSC12**	**Draai ya Kamuncaya**	19.93398	-17.90869	8.0	1484	994	148.4	424	10	387	2	1.2	192	102	517.28	0.01
WW205476	**DWSSC13**	**Tyeye Teya**	20.08186	-17.94499	7.4	373	250	37.3	187	150	35	32	17	10	8	228.14	0.01
WW205479	**DWSSC14**	**Lirarambi**	20.01406	-18.22144	6.7	984	659	98.4	572	247	125	41	35	1	12	697.84	0.02
WW205480	**DWSSC15**	**Mutwekombahe**	20.01080	-18.32051	6.8	477	320	47.7	270	249	8.6	55	27	1	3	329.40	0.01
WW205481	**DWSSC16**	**Shakamba 2**	20.07414	-18.26012	7.5	1167	782	116.7	490	139	241	26	18	57	82	597.80	0.01
WW205478	**DWSSC17**	**Shimpanda no.2**	19.87722	-18.05190	6.8	457	306	45.7	259	176	42	39	19	1	3	315.98	0.01
WW205453	**DWSSC18**	**Shighuru**	20.41931	-17.92347	7.3	1051	616	105.1	450	155	183	29	20	31	37	549.00	0.01
WW205483	**DWSSC19**	**Ndonga Linena**	20.45857	-17.94988	7.2	1059	591	105.9	350	373	78	72	47	1	67	427.00	0.01
WW205475	**DWSSC20**	**Kambowo Teya**	19.95461	-17.93542	7.4	749	502	74.9	303	93	158	26	6.7	77	29	369.66	0.01
WW205598	**DWSSC21**	**Omega**	22.19100	-18.03194	6.8	2195	1471	219.5	550	460	386	67	71	346	285	671.00	0.05
WW205502	**DWSSC22**	**Heha**	18.15953	-17.97457	7.7	525	291.8	52.5	256	38	80	15	7	1	1	671.00	25
WW205503	**DWSSC23**	**Kavango village**	18.12988	17.89947	9.0	3440	1905.6	344.0	1388	14	810	4	1	125	95	1548.50	20
WW205504	**DWSSC24**	**Ngandu**	18.28489	-17.70759	9.1	3770	1995.9	377.0	896	9	830	2	1	250	340	977.90	20
WW205505	**DWSSC25**	**Dikweya**	18.53584	-17.74687	7.8	381	234.6	38.1	184	83	46	18	9	4	1	224.48	39
WW205506	**DWSSC26**	**Nsivi**	18.65596	-17.80690	8.3	398	229	39.8	184	12	79	3	1	5	1	220.40	24
WW205507	**DWSSC27**	**Ndombe Za Matala**	18.72405	-17.89786	7.9	2480	1289.7	248.0	430	165	430	31	21	210	290	524.60	37
WW205508	**DWSSC28**	**Mahahe**	18.64023	-17.91756	7.5	1687	871	168.7	256	80	260	32	17	70	300	312.32	27
WW205509	**DWSSC29**	**Namkupa**	18.68000	-17.85778	7.9	9260	5828	926.0	336	151	2000	27	20	2080	1440	409.92	21
WW205510	**DWSSC30**	**Mafugu**	18.59810	-17.83656	8.6	2710	1472.1	271.0	480	10	540	4	1	270	340	564.00	19
WW205511	**DWSSC31**	**Gcana**	19.16955	-18.05451	7.6	472	286.9	47.2	216	173	29	29	24	4	5	263.52	59
WW205512	**DWSSC32**	**Sainca**	19.15484	-17.97250	7.7	413	263.3	41.3	196	80	15	32	21	1	1	239.12	67
WW205513	**DWSSC33**	**Masiro**	19.26802	17.88131	7.3	481	279	48.1	238	ND	13	60	14	1	2	290.36	39
WW205514	**DWSSC34**	**Gcigcau**	19.43606	-18.20585	7.5	222	132.3	22.2	100	90	6	16	12	1	1	122.00	29
WW205515	**DWSSC35**	**Mauguva**	19.25213	-18.44941	8.5	350	205	35.0	160	60	39	9	9	1	1	189.60	29
WW205516	**DWSSC36**	**Eharo**	19.12310	-18.46381	8.1	700	519.4	70.0	430	63	180	7	11	5	26	524.60	9
WW205470	**DWSSC37**	**Likorera**	19.41779	-18.58831	7.7	469	314	46.9	228	178	23	48	14	5	4	278.16	46
WW205469	**DWSSC38**	**Mururani**	18.96216	-18.75947	7.6	784	525	78.4	424	268	61	47	36	10	9	517.28	31
WW205468	**DWSSC39**	**Mpuma**	19.91446	-18.23115	7.7	402	269	40.2	206	202	7	64	10	1	1	251.32	48
WW205466	**DWSSC40**	**Kangongo Teya**	21.16383	-17.98697	7.5	353	237	35.3	172	178	2	51	12	4	1	209.84	52
WW205465	**DWSSC41**	**Ndonga Linena**	20.46317	-17.96621	7.3	518	347	51.8	244	243	10	54	26	4	2	297.68	88

A very important objective of this study is to show the spatial distribution of major and minor ions in the Kavango East and West Regions. This is shown in the maps below which provide an overview of the chemistry analyses in 2D.

Sodium

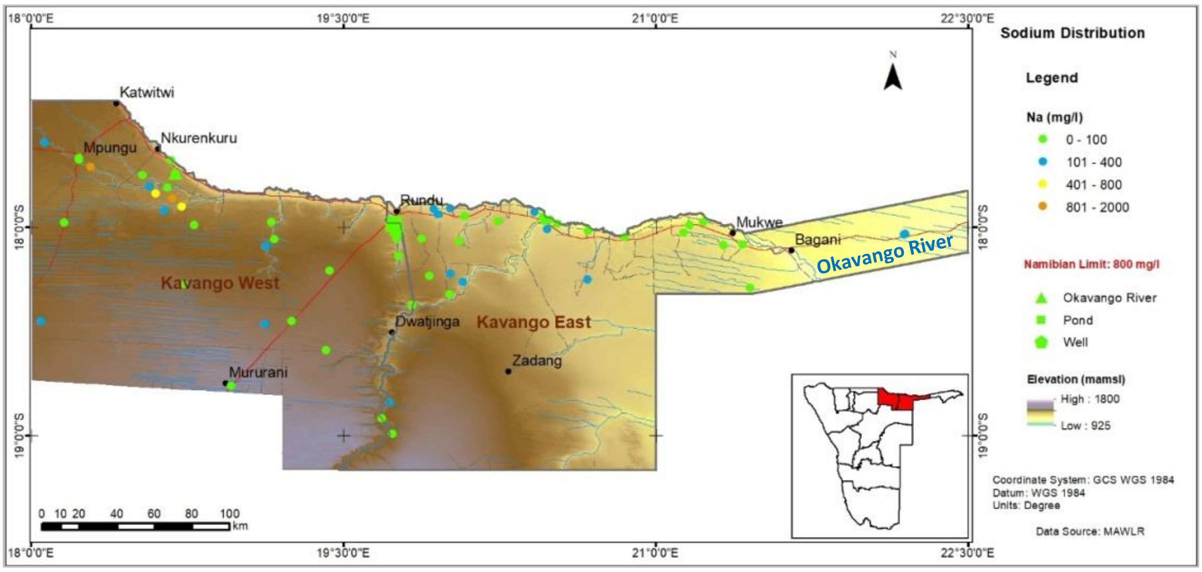


Figure 5-11: Map of sodium concentrations in the KE and KW Regions

Sodium (Figure 5-11) is predominantly found in halite (NaCl), plagioclase feldspars such as albite ($NaAlSi_3O_8$), and other sodium minerals. Spatially, concentrations of sodium in groundwater in the KE and KW are below the restrictive level of 800 mg/l (Water Act, 1956). Only two out of sixty (2/60) groundwater analyses, WW205503 (Kavango Village) and WW205509 (Namkupa) in the north-east and north-central Kavango West have elevated sodium levels above this limit. WW205509 has 2000 mg/l Na^+ and 1440 mg/l Cl^-, making it brackish. Sodium may be sourced from clay minerals within the Kalahari succession, such as Na-montmorillonite. In sandstones and siltstones also making up the PKAs, sodium is a component of un-weathered mineral grains and is present as a cement or crystal residue of pore solution.

Potassium

Concentration of potassium in groundwater in the two regions (Figure 5-12) are very low, not amounting to more than 30 mg/l across all the boreholes sampled. The lowest concentrations of ≤ 5 mg/l are observed along the Okavango River, with a slight increase in levels in the range of 6 to 15 mg/l inland and towards the northwest of KW and south of the KW. Sufficed to say that potassium levels increase in a south-westerly direction from the Mukwe Constituency in the northeast KE. Discrete points at Mururani (WW205469), Lirarambi (WW205479), and the pond at Mavandje to the south of Rundu, have potassium content >21 mg/l but <30 mg/l.

Potassium levels are much lower than sodium levels spatially, which is the usual case due to the limited mobility of potassium. Potassium in groundwater is released from silicate weathering of silicate minerals such as feldspar and micas.

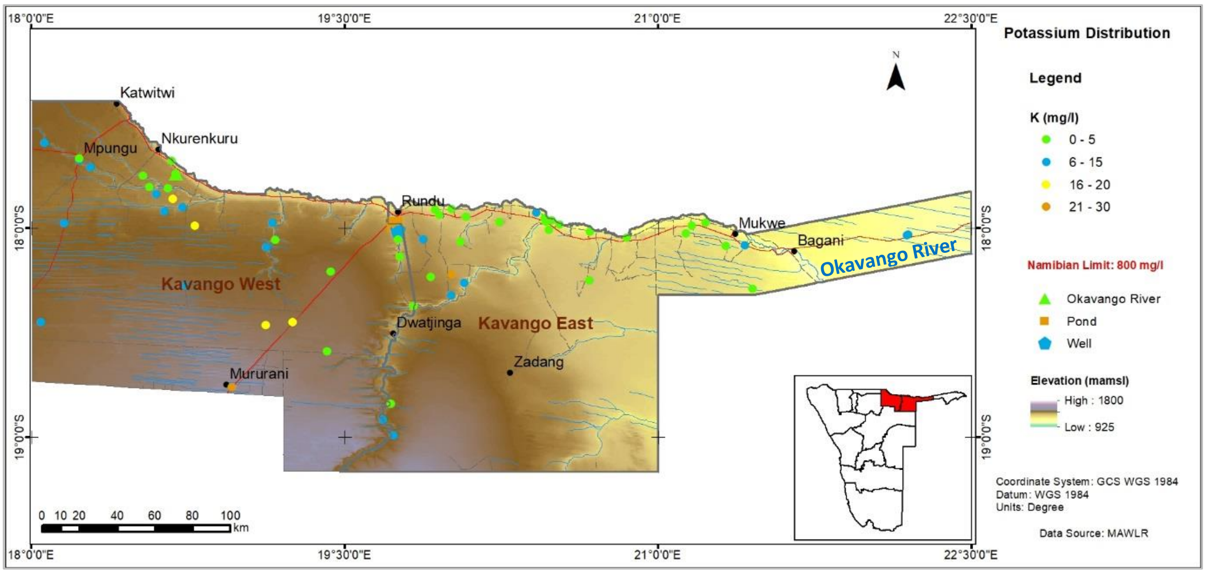


Figure 5-12: Map of potassium concentrations in the KE and KW Regions

Calcium

Calcium concentrations across the KE and KW (Figure 5-13) are below the Namibian limit of 400 mg/l (Water Act, 1956). The highest concentrations >61 to 100 mg/l occur in discrete locations in the northeast and proximal to Rundu and in borehole WW39967 in the south along the political border between the regions. The maximum concentrations are 84 mg/l in the hand-dug well at Mavandje and 76 mg/l at Ndonga Linena (WW205483) in the Kavango East. A minimum value of 1 mg/l occurs at Ngandaro (WW205486), Sambiu (WW25540), and at Yinsu Clinic (WW35053). Calcium concentrations increase spatially from the north-west KW towards the south of the KW (higher concentrations) and then north-east of the KE. Calcium in groundwater is due to water-rock interactions with carbonates such as calcite and dolomite, calcareous cement between sand grains, or calcrete layers interbedded between sandstone and sand deposits across the study area (Appendix A) and clay. Sulphate minerals such as gypsum and anhydrite found at some localities are also potential sources of calcium.

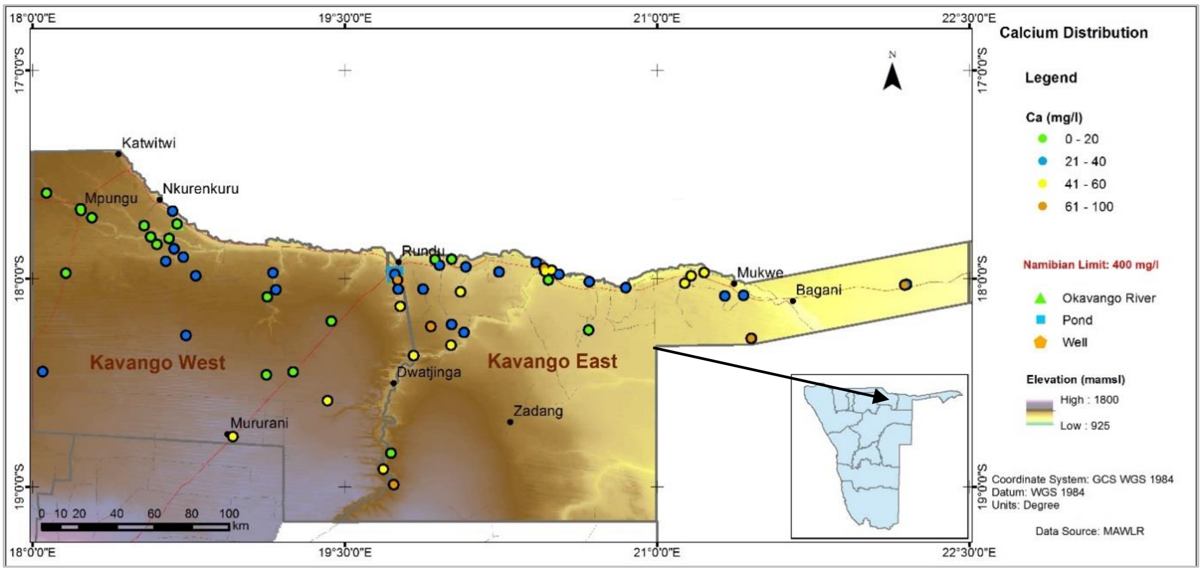


Figure 5-13: Map of calcium concentrations in the KE and KW Regions

Magnesium

The magnesium concentrations in groundwater (Figure 5-14) are slightly lower than calcium and much lower than sodium. There is no specific trend in the spatial distribution of magnesium in the aquifers. Minimum values of 0.4 mg/l occur at Ngandaro (WW205486) and 1 mg/l is present in the borehole at Namkupa, Yinsu Clinic, Kavango village, Ngandu, Nsivi; Mafugu as well as in the Okavango River sample collected at Kandjimi Murangi. A maximum concentration of 71 mg/l was measured at Omega in the far northeast of the KE.

All groundwater analyses inclusive of the well and the pond samples do not contain magnesium exceeding the limit of 200 mg/l (Water Act, 1956). Magnesium just like calcium and sodium is a common constituent of fresh groundwater (Hiscock, 2005). The sample analysis from Bravo which is located in the area southwest of KW shows no appreciable amounts of magnesium, amounting to only 27 mg/l. Groundwater in this area is expected to show higher levels of magnesium (and calcium) as groundwater is understood to be recharged from the carbonates of the OTM. This study shows no evidence of this yet. Sources of magnesium could instead be micas in sandstone and clay, as well weathering of basalt, the latter outcropping just east/south-east of Rundu. Magnesium is favoured by sorbing minerals such as clay, over calcium, thus its lower content in groundwater.

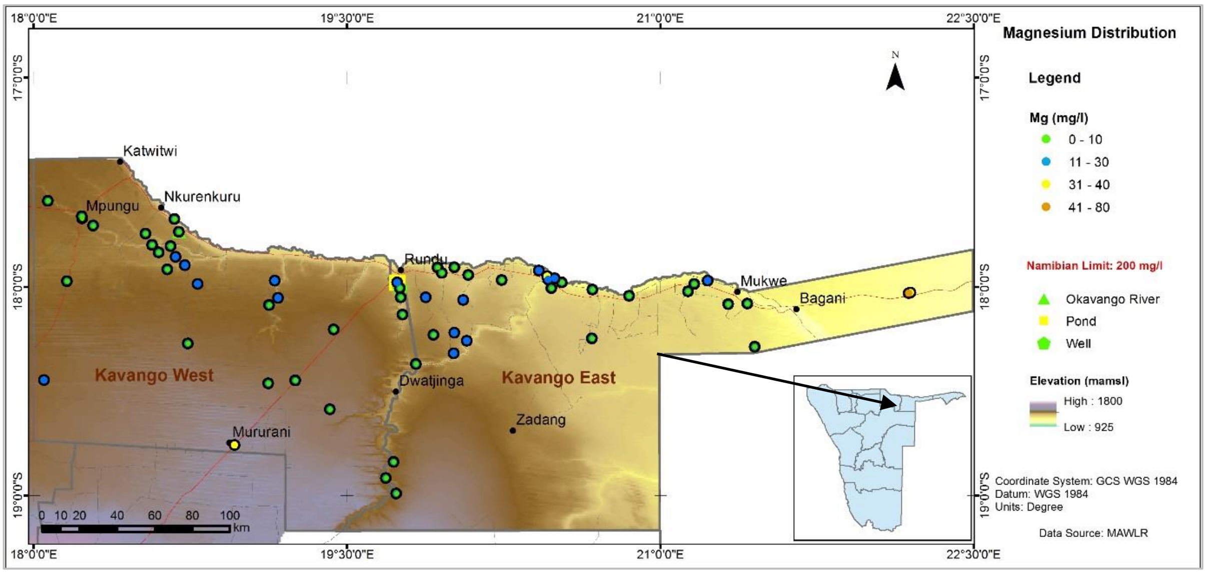


Figure 5-14: Map of magnesium concentrations in the KE and KW Regions

5.1.3 Major Anions Geochemistry

Carbonate and Bicarbonate

Carbonate rocks such as limestone and dolostone consist mostly of the minerals calcite and dolomite, with minor amounts of clay (Freeze and Cherry, 1979). Limestone is intersected in some boreholes in the KE, namely (WW35532, Lat: -18.1933, Long: 21.1297) at a thickness of 56 m. This borehole was not sampled for this study. Thick calcrete layers (Appendix A) are intersected in boreholes in the Kavango West region, reaching thicknesses up to 55 m in borehole WW37339 at Mukekete, 32 m in the boreholes WW205029 (Sharukwe) and WW40571 (Desi).

pH determines the type of alkalinity in water. Total alkalinity is resultant from carbonates, bicarbonates, and hydroxides. In the graph Figure 5-15, a positive correlation between bicarbonate and total alkalinity is observed with R^2 = 96 %. An increase in bicarbonate results in an increase in total alkalinity.

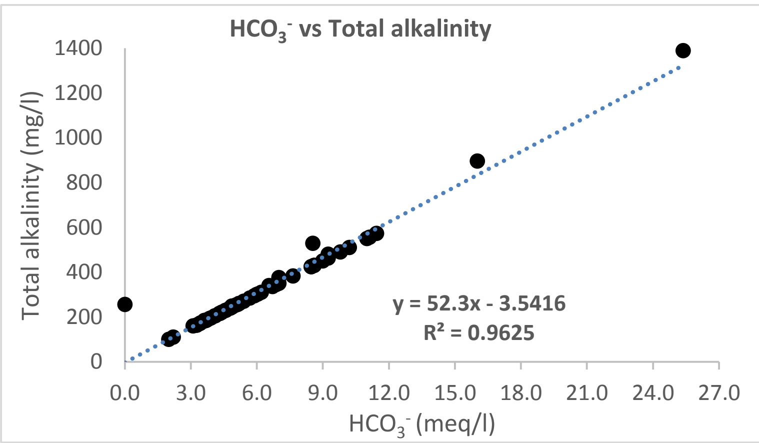


Figure 5-15: Bicarbonate vs total alkalinity

The pH of groundwater analyses in the study area is predominantly in the neutral-slightly alkaline realm. In this range, bicarbonate alkalinity is predominant (Figure 5-16 A), resultant from bicarbonate ions. As pH increases, the species of alkalinity changes. In localities where pH is above 8.3, carbonate species progressively enter the system (Figure 5-16 B). This shift is observed in 8 boreholes where pH ranges from 8.3 to 9.4. Carbonate concentrations in these boreholes averages 3.63 mg/l (0.8 meq/l) as opposed to an average of 384.5 mg/l (6.3 meq/l).

Bicarbonate is a major constituent of groundwater, occurring at >5 mg/l (Freeze & Cherry, 1979). The maximum bicarbonate concentration of 1548.5 mg/l was recorded at Kavango Village in the north-central KW and the minimum value of 24.4 mg/l is from the Okavango River sample analyses at Kandjimi Murangi (Figure 5-17). Thirty-one out of sixty (31/60) samples have bicarbonate above 300 mg/l. Bicarbonate has no adverse effects on human health, however, above 300 mg/l it is reported to lead to kidney stones in the presence of higher concentrations of calcium, especially in dry climates (Mostafa et al., 2017).

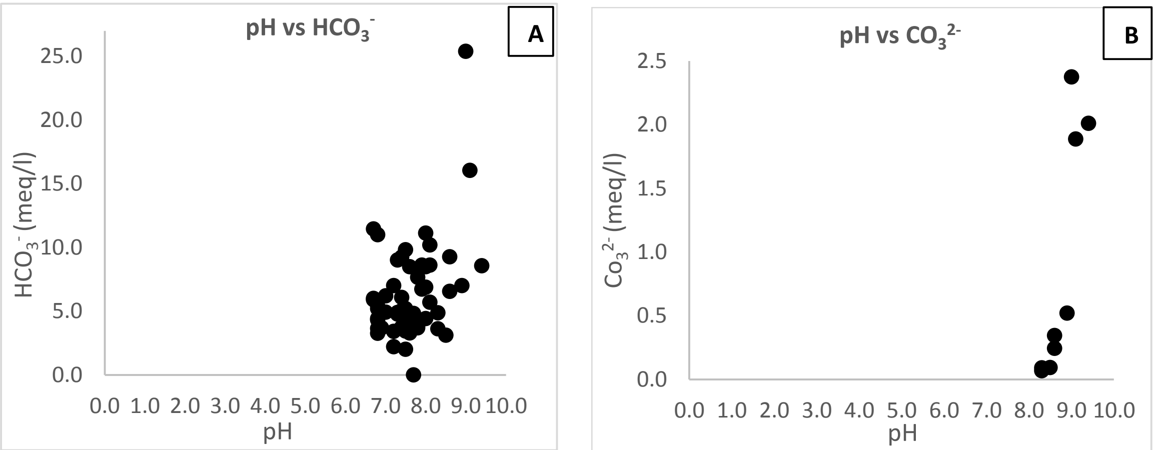


Figure 5-16: A) pH vs bicarbonate B) pH vs carbonate

There is no specific pattern in the spatial distribution of bicarbonate in the study area, except where slightly high amounts occur in the north-central parts of KW; accounting for high TDS values in the area.

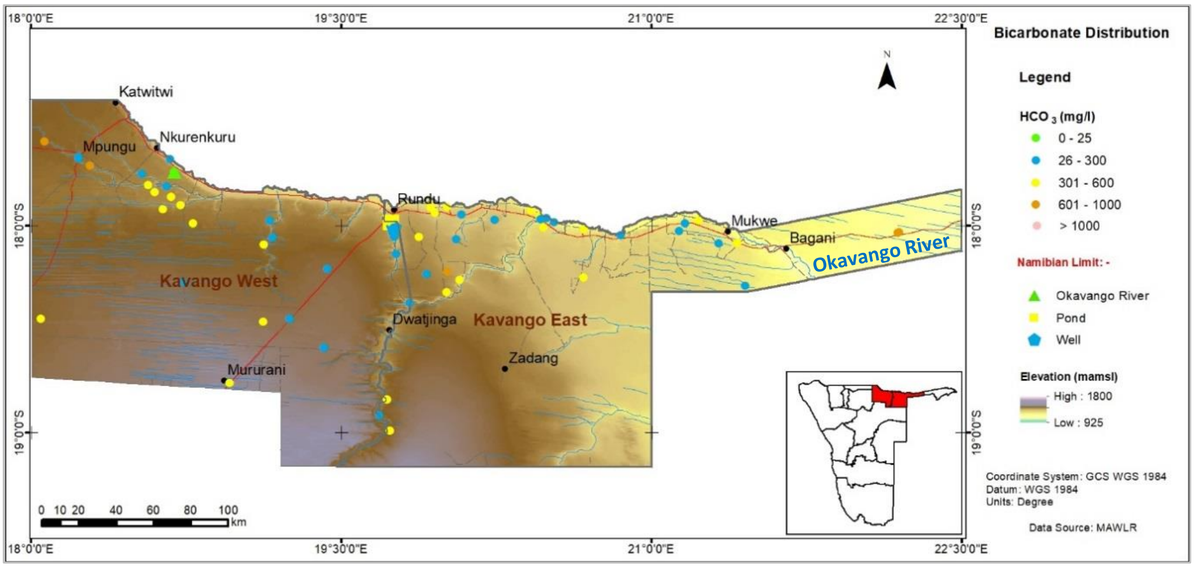


Figure 5-17: Map of bicarbonate concentrations in the KE and KW Regions

Carbonate concentrations are very low and occur in the range between 0 to 71.2 mg/l (Figure 5-18). Fifty out of sixty (50/60) samples have 0 mg/l of carbonate content, amounting to 85% of all samples. The pond, river, and well samples also contain 0% carbonate.

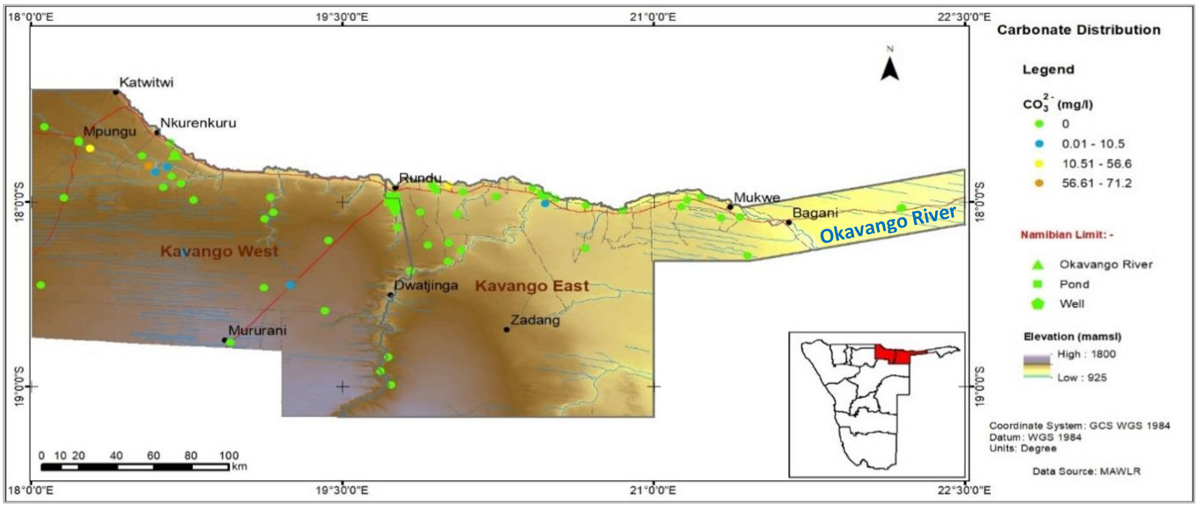


Figure 5-18: Map of carbonate concentrations in the KE and KW Regions

Sulphate

The PKAs are characterised by low sulphate concentrations (Figure 5-19) in the north-east of the KE and inland towards the south-west of the KW, as well as along the Omuramba-Omatako tributary. High concentrations are found in the northwest and north-central locations in the KW, where 1 sample (WW205509, 2080 mg/l, Namkupa) exceeds the permitted limit of 1200 mg/l sulphate in drinking water (Water Act, 1956; Water Resources Management Act, 2013). Namkupa village is located southwest of Nkurenkuru.

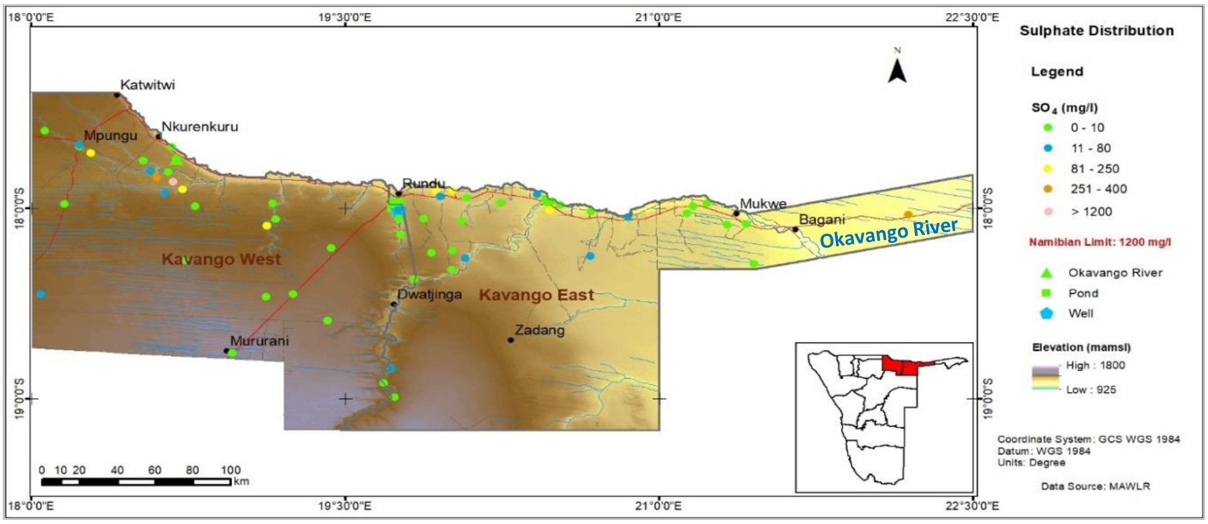


Figure 5-19: Map of sulphate concentrations in the KE and KW Regions

Two out of sixty (2/60) groundwater samples from the farther north-west and farther northeast have sulphate contents higher than 250 mg/l (WW205510, Mafugu) and up to 370 mg/l (WW205598, Omega). Both these boreholes are deep; drilled to 140 m below ground level. Fifty-seven out of sixty (57/60) samples equating to 95% of the samples contain sulphate below 192 mg/l.

Sulphate in groundwater may be sourced from runoff from fertilized land used for agriculture; however, there is no correlation between sites of elevated sulphate concentrations and sites of irrigation from the samples presently collected. This lack of correlation was also noted by Water Surveys Botswana (2011). The same study reports that elevated sulphate content may be due to the dissolution of evaporates. The researcher postulates that sulphate is sourced from geology as a component of feldspar and possibly gypsum ($CaSO_4.2H_2O$. If sourced from anthropogenic sources, more sampling is required to prove the concept. According to Mostafa et al. (2017), sulphide oxidation during chemical weathering may also contribute to high sulphate in groundwater.

Chloride

Chloride concentrations (Figure 5-20) are much higher in the KW than in the KE, with the highest value above the allowable drinking water limit of 1200 mg/l (Water Act, 1956; Water Resources Management Act, 2013) at Namkupa (WW205509, 1440 mg/l). Chloride is the second dominant anion in groundwater in the KE and KW after bicarbonate, contributing to the higher TDS (Figure 5-6 & 5-7) concentrations occurring in the north-central parts of KW. Chloride is a major constituent of fresh groundwater, usually present at greater than 5 mg/l (Freeze & Cherry, 1979).

The average chloride concentration in groundwater is 72.2 mg/l. Twenty out of sixty (20/60) groundwater samples, which equate to 33 % of all samples contain Cl^- ≤5 mg/l. Twenty-four out of sixty (24/60) (40%) comprise Cl^- in the range 6 to 95 mg/l. Nine out of sixty (9/60) groundwater samples contain chloride in the range 101 to 350 mg/l; of these 4 locations in the KW contain higher concentrations (290-340 mg/l) than those recorded in the 5 boreholes in the KE (102-285 mg/l). The river and well samples both contain 1 mg/l of chloride, while the pond contains 10 mg/l. Admixture of old mineralized groundwater is a potential source of chloride; as well as the weathering of soils and dissolution of evaporite minerals. Overall, chloride concentrations in the regions are low, even in areas in proximity to Governmental Green Schemes.

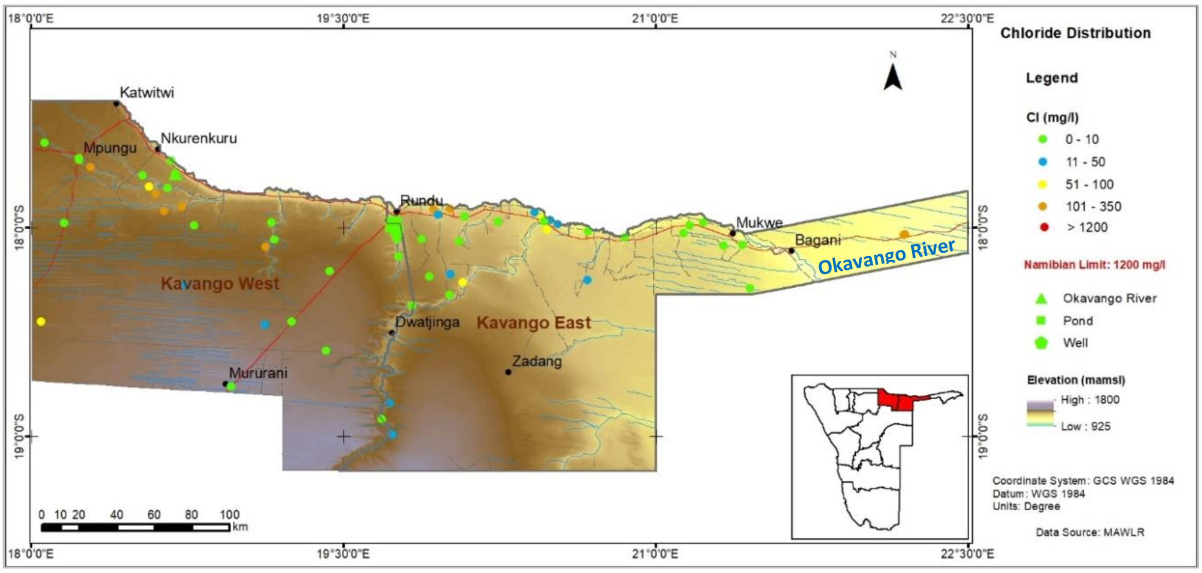


Figure 5-20: Map of chloride concentrations in the KE and KW Regions

Fluoride

Discrete locations of elevated fluoride (Figure 5-21) above the stipulated limit of 3.0 mg/l (Water Resources Management Act, 2013) occur at Shitemo (WW205485, 11 mg/l); Kavango Village (WW205503, 10.1 mg/l) and Ngandu (WW205504, 5.1 mg/l).

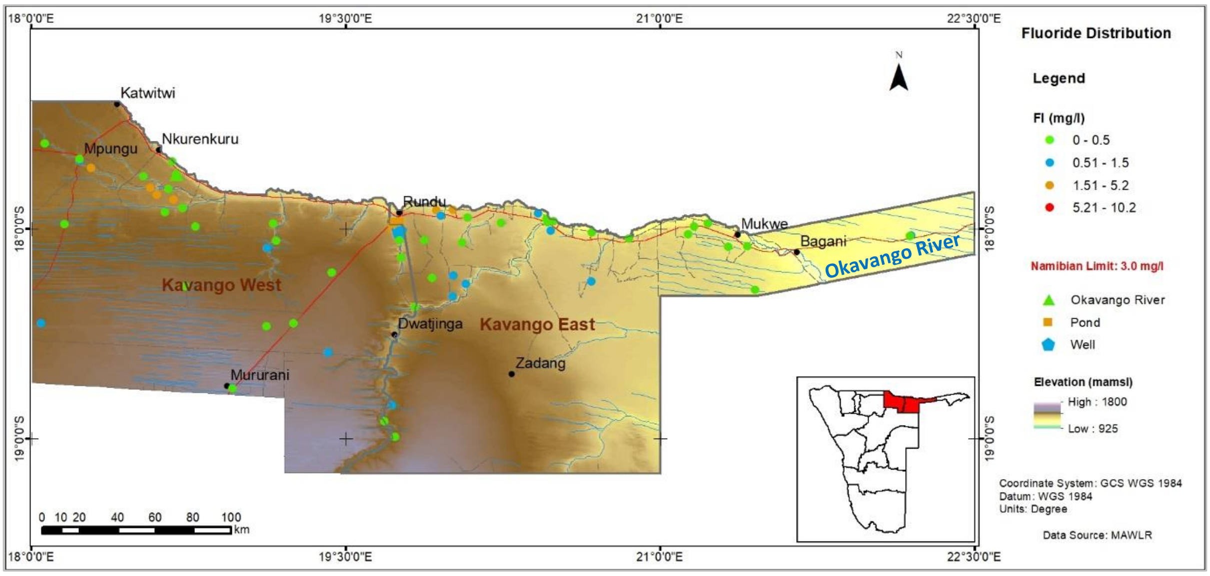


Figure 5-21: Map of fluoride concentrations in the KE and KW Regions

Groundwater from these boreholes is not safe for human consumption over a prolonged period, and defluoridation is necessary. The limit of fluoride in drinking water is 1.5 mg/l (WHO, 2018). Elevated fluoride in drinking water between 3 to 6 mg/l causes damage to skeletal tissues over time. Fifty-one out of sixty (51/60) groundwater samples have a fluoride content below 1.5 mg/l, which equates to 85% of all samples. Five out of sixty (5/60) samples have fluoride content in the range of 1.6 to 2.1 mg/l; making up 8.3 % of the total samples. The Okavango River, pond, and well samples contain 0.1 mg/l, 1.6 mg/l, and 0.7 mg/l, respectively.

There is no specific pattern in the spatial distribution of fluoride in the KE and KW, it is, however, very closely related to locations with high chloride concentrations (Figure 5-20). Groundwater at Rundu and east of the town, and largely in the north-central parts of the KW have >1.5 mg/l of fluoride. Fluoride enters groundwater from the weathering of minerals such as fluorite, mica, and apatite; the latter from fertilizers. Groundwater analyses from boreholes in proximity to the Okavango River contain fluoride well below the acceptable limit. Fluoride in groundwater may be sourced from geology.

Nitrate and Nitrite

Nitrate and nitrite are inorganic parameters that serve as contaminants in groundwater when present at levels above the recommended limit of 40 mg/l (Water Act, 1956) and 50 mg/l (WHO, 2018). Hiscock (2005) outlines the fixation of nitrogen into the soil in the nitrogen cycle. Nitrogen may be sourced directly from the atmosphere, from the precipitation of nitrogen compounds such as ammonium and nitrate, and from anthropogenic sources such as fertilizers, pesticides, and sewage water.

Nitrogen undergoes processes of ammonification to form ammonium, nitrification to form nitrite, and further nitrification by aerobic processes to form nitrate, which is leached into groundwater. Across the KE and KW, nitrate in groundwater (Figure 5-22) is lower than the restrictive level averaging 1.7 mg/l. Only three out of sixty (3/60) boreholes samples have concentrations in the range 8 to 25 mg/l, and the rest contain less than 5 mg/l nitrates.

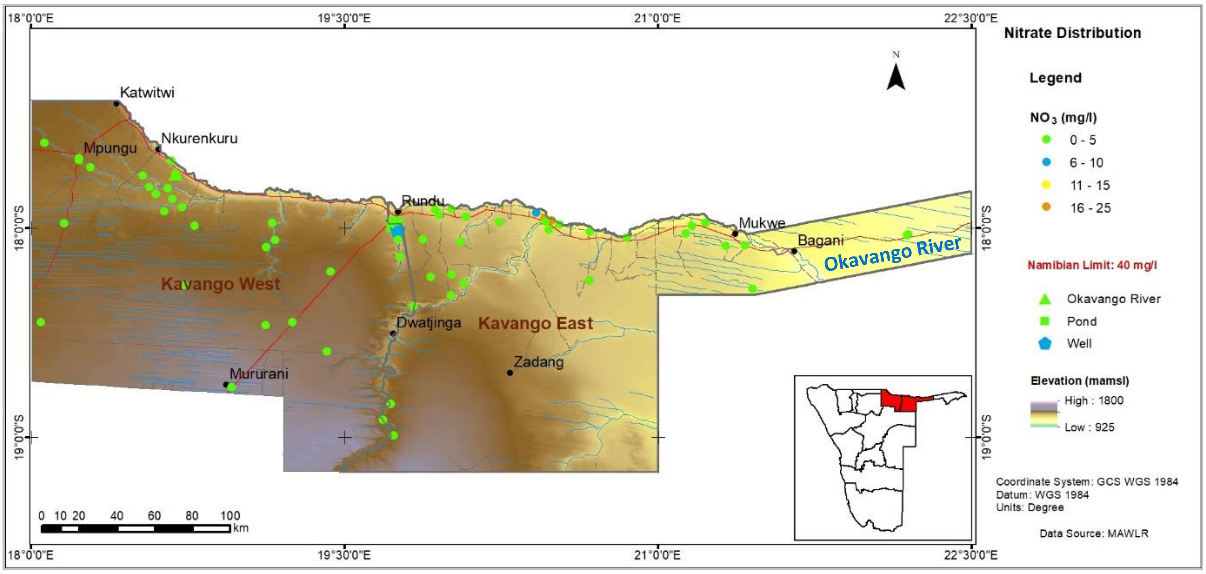


Figure 5-22: Map of nitrate concentrations in the KE and KW Regions

Nitrite concentrations in all samples inclusive of the pond, river, and hand-dug well are less than 1 mg/l (Figure 5-23). Water in the hand-dug well at Mavandje contains 9.4 mg/l nitrate, which is interestingly higher than that in the open pond (0.5 mg/l). The highest level of nitrate (25 mg/l) recorded in borehole WW205483 at Ndonga Linena is possibly associated with the Ndonga Linena Irrigation Agricultural Project. The source of the nitrate can only be fertilizers and pesticides applied to the soil. Woodland of *Acaciaerioloba* (Camelthorn) and *Terminalia sericia* species which are predominant (Burke, 2002) in this part of the country can be associated with fixing nitrogen in roots into the soil.

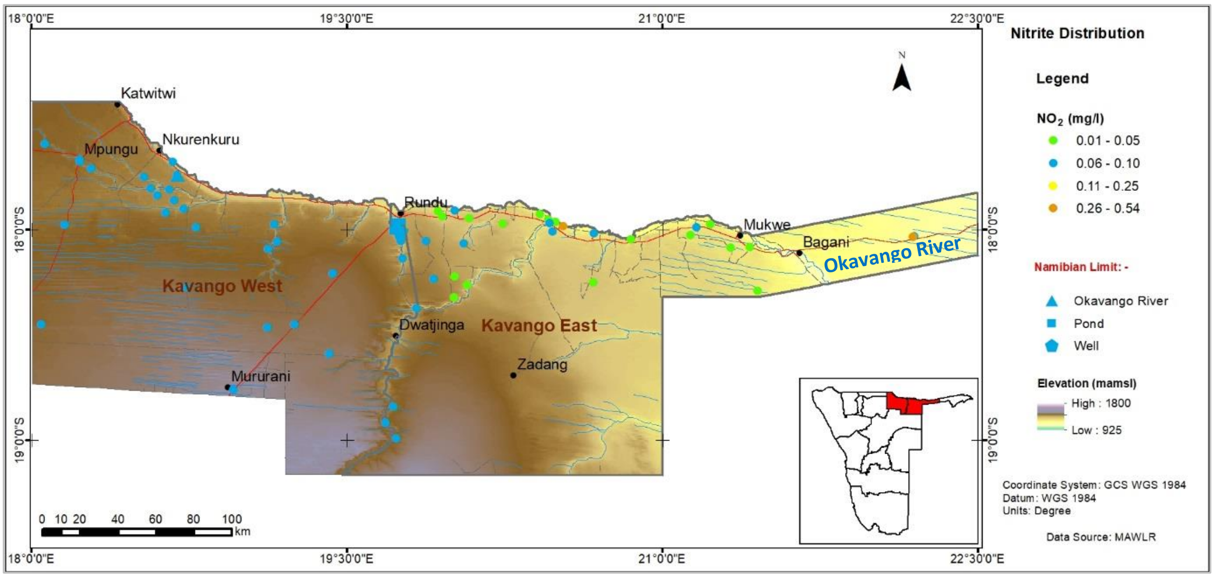


Figure 5-23: Map of nitrite concentrations in the KE and KW Regions

5.1.4 Metals

Overall, concentrations of heavy metals of Fe^{2+}, Mn^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}, $Pb^{2+}$and As^{2+} (Figure 5-5) in the Primary Kalahari Aquifers are relatively low and of no health concern. The average values for these metals in groundwater are 0.12 mg/l, 0.05 mg/l, 0.01 mg/l, 0.04 mg/l, 0.01 mg/l, 0.02 mg/l and 0.03 mg/l, respectively. In the borehole WW205485 at Shitemo, 2.4 mg/l iron is recorded. Elevated concentrations of manganese are recorded in borehole WW205512 (Sainca) at 1.40 mg/l in the KW. The acceptable limit of manganese in drinking water is 2 mg/l (Water Resources Management Act, 2013). The WHO (2018) has not set a limit for manganese in drinking water, stating that it is not of health concern at levels normally causing problems in drinking water. WHO further states that manganese concentrations above 0.1 mg/l cause aesthetic issues such as taste impacts and staining laundry. The source of manganese in the aquifer is likely the weathering of minerals in sediment, such as biotite and hornblende (Chilton, 1996), the latter from basalt east of Rundu.

Ion Ratios

Sodium Adsorption Ratio

Irrigation schemes in the two regions utilize the surface waters of the Okavango River. On the other hand, groundwater can be an equally important source for agricultural purposes. For this reason, numerous studies including the CRAVE Project (DWRM, 2018) have looked into the potential of abstracting groundwater for climate-resilient agriculture.

The salinity hazard and sodium hazard are expressed as:

$$\text{SAR} = \frac{Na^{2+}}{\sqrt{(Ca^{2+}+Mg^{2+})/2}} \qquad \textbf{eq.7}$$

were ionic concentrations are in meq/l (Richards, 1954).

SAR is important in the consideration of the usability of groundwater for irrigation (Al-ahmadi, 2013). Other parameters to consider are soil texture and structure, drainage conditions, amount of gypsum in the soil, chloride concentrations, and the irrigation method (Hiscock, 2005). A spatial distribution map of SAR in the study area is seen in Figure 5-24.

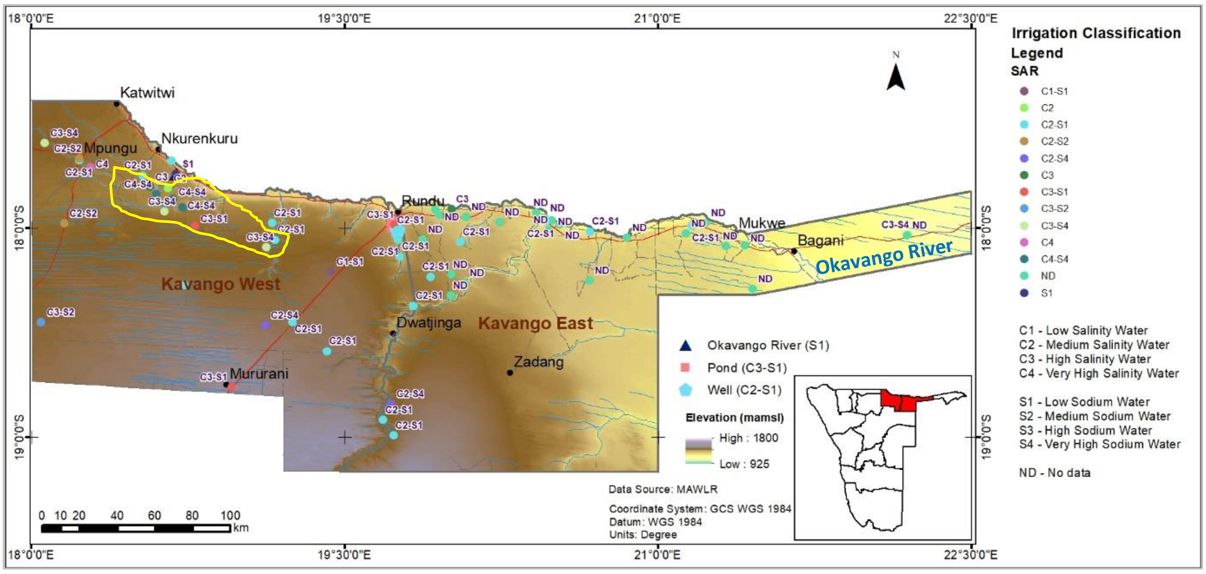


Figure 5-24: Map of SAR classification in the KE and KW Regions

The salinity hazard is related to high concentrations of soluble salts in the aquifer, and it is proportional to EC and TDS. Excess salt in the water that is added to the soil increases the osmotic pressure of the soil leading to plant wilting (Zaman et al., 2018). Four classes are established in the classification of salinity hazard seen in Table 5-5:

Table 5-5: Salinity hazard in the study area (Bauder et al., 2011)

Hazard	Dissolved Salt content EC (µS/cm)	No. of Analyses
None – Water for which no detrimental effects will usually be noticed.	750	39
Some – Water that may have detrimental effects on sensitive crops.	750-1500	10
Moderate – Water that may have adverse effects on many crops, thus requiring careful management practices	1500-3000	8
Severe – Water that can be used for salt-tolerant plants on permeable soils with careful management practices.	3000-7500	3

salinity hazard is highest in the north-central parts of the KW along the Omuramba Mpungu tributary and close to Rundu. These levels of salinity [C3-C4] in groundwater are due to high TDS in the range of 1290 to 5828 mg/l and elevated chloride (65-1440 mg/l) (Figure 5-25 A). The CRAVE Report (DWRM, 2018) describes elevated TDS levels in boreholes along the Okavango River resultant from high sulphate and nitrate concentrations, thus causing the salinity hazard. In this study, a correlation is seen between high TDS and chloride levels, rather than between TDS and nitrate concentrations. It is therefore concluded that salinity hazard in the Primary Kalahari Aquifers is resultant from high chloride concentrations and high sulphate concentrations only.

The sodium hazard is highest (S4) in the same parts of north-central KW as stated above, and results from high levels of sodium up to 2000 mg/l. The irrigation standard for sodium is in the range of 100 to 400 mg/l (DWRM, 2018). Three groundwater analyses from the boreholes WW205503, WW205509, and WW 205510 are classed as unsuitable for irrigation purposes (Figure 5-25 B). Six groundwater analyses (WW25540, WW34811, WW204140, WW205598, WW205507, and WW205510) based on the Wilcox diagram are classified as doubtful to unsuitable for irrigation purposes due to elevated (above 2000-3000 µS/cm) EC concentrations.

A majority (60%) of the groundwater analyses are classed as excellent to good for irrigation. A total of 30 %, which accounts for 18/60 groundwater analyses are classified as good to permissible for irrigation purposes. The analysis from the pond is classed as good to permissible and the well is classed as excellent quality water for irrigation. In summary, groundwater in the larger parts of the KE and KW is suitable for irrigation purposes, with the exception of groundwater in the areas of Namkupa, Kavango village, and Ndombe za Matala in the KW where irrigation would be unsuitable.

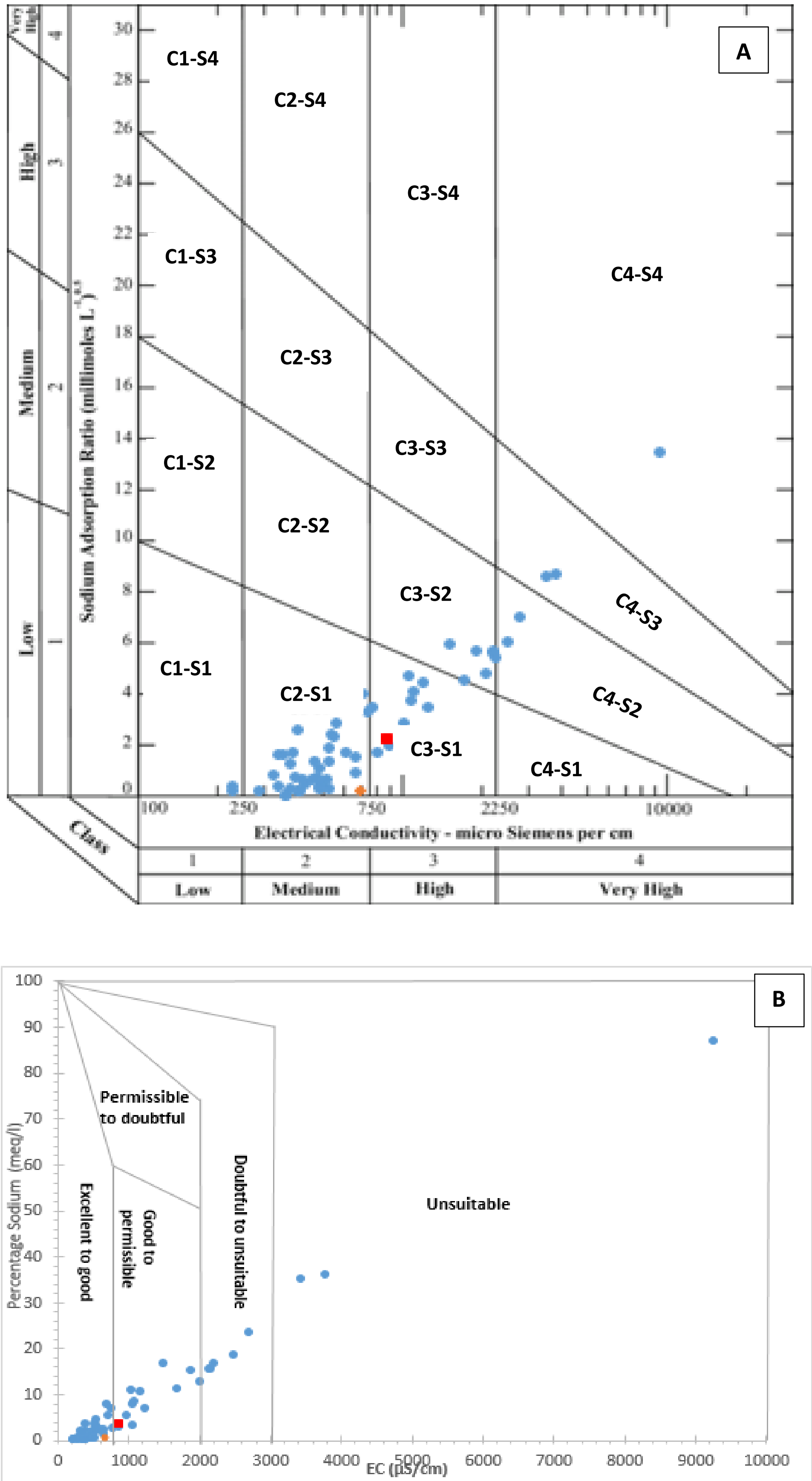


Figure 5-25: A) Classification of samples according to salinity hazard and sodium hazard based on the modified US Salinity Laboratory diagram by (Zaman et al., 2018), B) Wilcox diagram

Usability for Human Consumption

The groundwater of the Kalahari Aquifers is largely suitable for human consumption with mainly excellent quality groundwater (Group A), except in discrete localities where it is classified as Group D i.e.in the villages of Ngandu, Namkupa, and Kavango Village in the northern and north-central Kavango West and Lirarambi and Ngandaro in the Kavango East (Figure 5-26). The two boreholes in the KE, WW205479, and WW205486 are recorded to have high turbidity, 17 NTU and 11 NTU, which surpass the limit of 10 NTU (Water Act, 1956).

In the former villages in the KW, D-parameters are fluoride (10.1 mg/l), sodium (830 mg/l and 2000 mg/l), sulphate (2080 mg/l) and conductivity (3440 µS/cm, 3777 µS/cm and 9260 µS/cm) recorded in the boreholes WW205503, WW205504 and WW205509, rendering groundwater unsuitable for human consumption.

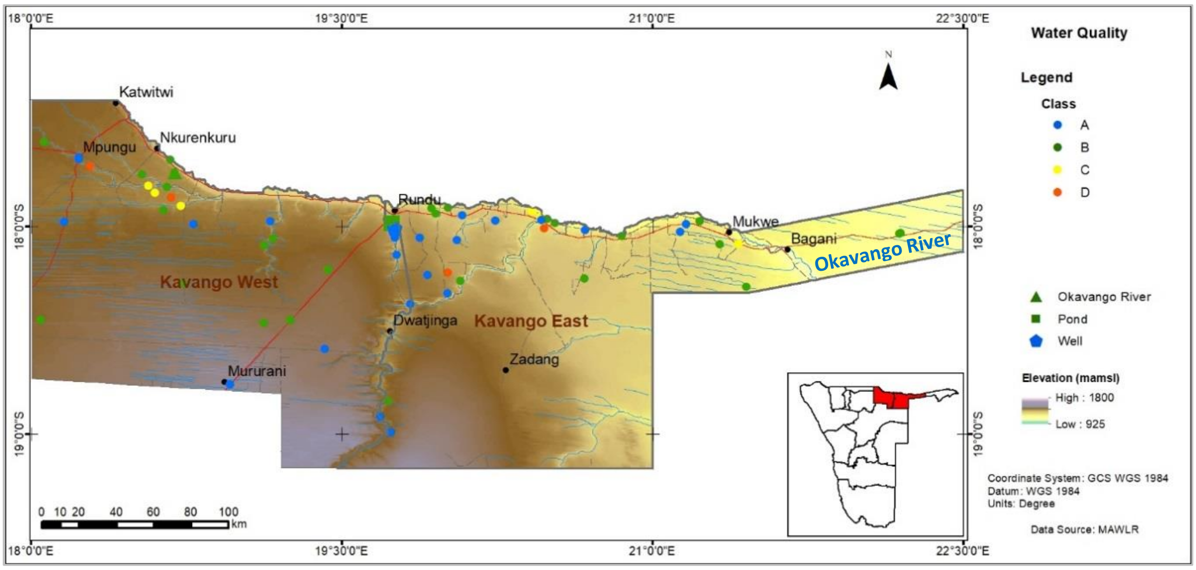


Figure 5-26: Map showing the usability of groundwater for human consumption in the KE and KW Regions

Groundwater is of excellent quality along the border between the two regions, and as you move inland to the east and west of the political border, the quality degrades to groundwater with good quality and then reaches northwards to low health risk water.

Usability for Livestock-watering

Less strict requirements are set for the usability of groundwater for livestock watering in relation to those set for water for human consumption. Groundwater across the KE and KW is predominantly suitable for livestock watering (Figure 5-27).

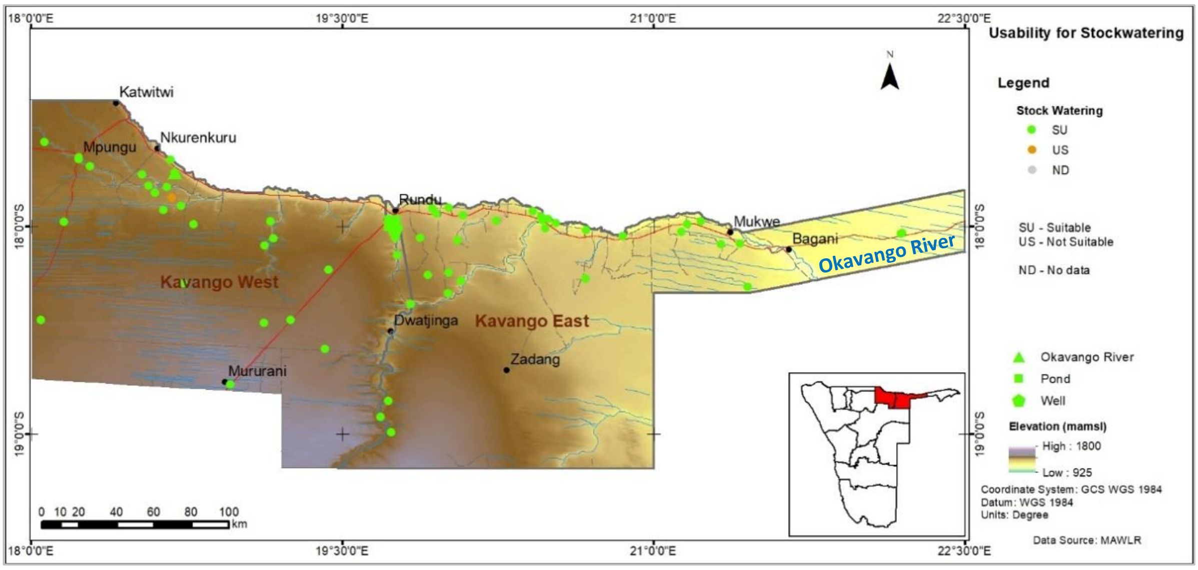


Figure 5-27: Map showing the usability of groundwater for livestock watering in the KE and KW Regions

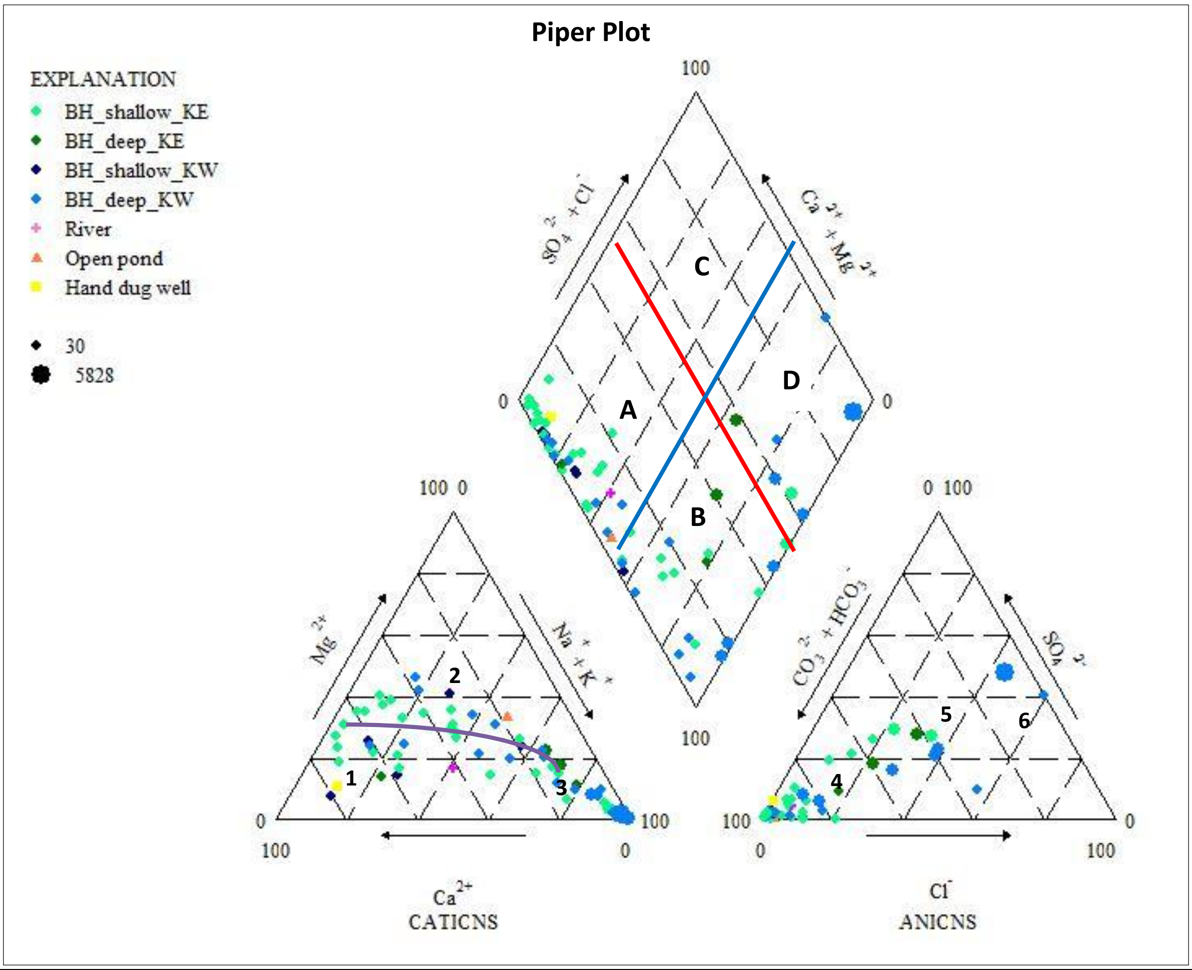
Only two out of sixty (2/60) groundwater analyses exceed the maximum limit for livestock watering on the basis of high fluoride, conductivity, and sulphate concentrations. The 1 borehole is located at the Kavango village (WW205503) and the other at Namkupa (WW205509) as seen in the previous section.

5.1.5 Geochemical Processes in groundwater

Hydrochemical Trends

The Piper plot developed by Piper (1944) is one of the most effective graphics used for determining the sources of dissolved constituents in waters, geochemical evolution of groundwater and surface waters, and related geochemical problems. It gives details on the similarities and differences in the composition of waters by means of classifying different chemical water types, as well as basic conclusions on mixing, precipitation/solution, and ion exchange reactions.

Based on the classification of water table depths (refer to Chapter 3) in the two Kavango Regions BIWAC (2002), the boreholes sampled are classified into shallow (0-40 m water table depth) and deep (>40->100 m water table depth) boreholes for the discussion of the Piper Plot (Figure 5-28). Four classes are discoursed i.e. i) shallow boreholes in the KW ii) deep boreholes in the KW iii) shallow boreholes in the KE and iv) deep boreholes in the KE.



Water Types
A: Calcium-Magnesium bicarbonate type
B: Mixed Type
C: Sodium bicarbonate type
D: Sodium chloride sulphate type & Sodium chloride type (saline waters)

Mineral &rock sources: gypsum, calcite, dolomite, basalt, and shale

Dominant cations
1: Calcium type
2: No dominant type
3. Sodium & potassium type

Dominant anions
4. Bicarbonate type
5: No dominant type
6. Chloride type

A+B: Weak acids exceed strong acids
C+D: Strong acids exceed weak acids
A+C: Alkaline earths exceed alkalies
B+D: Alkalies exceed alkaline earths

Figure 5-28: Piper plot displaying the hydrogeochemical facies of the samples collected in meq/l. The numbers in the key refer to the numbers in the Plot

More than 95% of the groundwater and surface water samples plotted in the bottom half of the diamond. Groundwater samples plotted near the left corner of the diamond are rich in Ca^{2+} + Mg^{2+} and HCO_3^-, resulting in Ca^{2+}-Mg^{2+}-HCO_3^- type. These include 17/27 shallow boreholes in the KE, 4/27 shallow boreholes in the KW, 5/27 deep boreholes in the KE including Dingandu (WW205514, RWL: 43.7 m b g l), and 1 deep borehole (WW205492, RWL: 50-60 m b g l) in the KW at the Gcigcau village. The hand-dug well is juxtaposed with the groundwater samples on the Piper plot, which suggests similar hydrochemical facies and sources. The well in this case is fed by groundwater. The open pond and river samples are likewise Ca^{2+}-Mg^{2+} -HCO_3^- type as expected of freshwaters. Ca^{2+}-Mg^{2+}-HCO_3^- water type relates to recently recharged groundwater in the early stages of hydrochemical evolution (Sidibe et al., 2019). This type of water is characterised by low salinity, which is the case in the shallow boreholes in the KE. The exceptions are two shallow groundwater analyses from the KE with TDS 1441 mg/l and 1454 mg/l.

Groundwater samples plotting in the lower corner of the diamond are composed of alkali carbonates and are classified as Na^+-HCO_3^- type. It is observed that 6/14 shallow borehole analyses in the KE, 0 shallow boreholes (WW205511, Gcana village, RWL: 26.5 m b g l) analysis in the KW, 1 deep borehole (WW205481, Shakamba 2 village, RWL: 59.8 m b g l) analysis in the KE and 7/14 deep borehole analyses in the KW are in this class. A total of 57% of the samples classified as Na^+-HCO_3^- water type are from deep boreholes. Na^+-HCO_3^- type waters are dynamically coordinated waters of the basin underflow regime (NGDC, 1991). Groundwaters of this type are reportedly dominant in the study area and occur spatially across the two regions (NGDC, 1991). This provides evidence of the regional continuity of the Kalahari aquifers across the regions. Due to the thinning out of the Kalahari towards the KE, groundwater of this type occurs in shallow boreholes in the KE, whilst in the KW, groundwater of this type occurs in the deeper boreholes with deeper water tables. It could also be true that this water type points to a particular aquifer, which is shallower in the KE and is intersected east and south-east of Rundu.

Five out of eleven (5/11) shallow borehole analyses in the KE, 3/11 deep borehole analyses in the KW, 1 shallow borehole analysis in the KW, 1 deep borehole analysis in the KE, and the sample from the pond are classified as Ca-Na^+-HCO_3^- type waters. Groundwaters of this type are termed mixed type and are a result of mixing processes.

Groundwater analyses plotting in the right-hand corner of the diamond plot are considered saline and comprise Na^++K^+ and Cl^-+SO_4^{2-}. These samples are classified as Na^+-Cl^- type and Na^+-Cl^--SO_4^{2-} type. Only 1 groundwater analysis from a deep borehole in KW (WW205502, RWL at 68.3 m b g l) at Heha village is classified as Na^+-Cl^- type. Five out of eight (5/8) deep borehole analyses in the KW, 1 deep borehole analysis from the KE, and 2 shallow borehole analyses in the KE are classified as Na^+-Cl^--SO_4^{2-} water type. The latter shallow boreholes (WW25540, depth: 60 m b g l, RWL: 11.4 m b g l) are at Sambiu east of Rundu along the Okavango River and at Shinunga Toring (WW204140, depth: 106 m, RWL: 11 m b g l), respectively. Based on the deep borehole depths and shallow RWL in these two boreholes, confining conditions may occur in these localities. Shallow groundwater may be affected by evaporation processes which are typical of a semi-arid to arid climate.

Water Surveys Botswana (2011) reports that high evaporation and evapotranspiration in the study area has led to salt concentration in the sediments due to the unsaturated water flux, and infiltrating waters could be saline. The production of halite through evaporation and its latter dissolution is thus a possible source of salinity in these areas of Sambiu and Shinunga Toring, where faults are absent.

In the KW, saline groundwater found in the deep boreholes drilled in Namkupa, Ndombe za Matala and others, of the type Na^{+}-Cl^{-}-SO_4^{2-} is fault-controlled. In this area, BIWAC (2002) stated that flows from the Lower Kalahari aquifer move upwards through these faults and mix with the fresh groundwater of the Middle Kalahari aquifer. Na^{+}-Cl^{-}-SO_4^{2-} character groundwater has undergone longer residence times and stagnation, which results from limited groundwater flow within the aquifer, as a function of hydraulic gradient and aquifer transmissivity. TDS levels for Na^{+}-Cl^{-}-SO_4^{2-} and Na^{+}-Cl^{-} groundwater types across the regions range between >871 to >5000 mg/l. A water type cumulative bar graph is presented in Figure 5-29.

BIWAC (2002) describes three sources of recharge (refer to section 1.3.2) for the multi-layered Kalahari Aquifer System and two discharge points in the Damara Sequence meta-sedimentary outcrops both in the Kaudom Park and proximate to the Okavango River at Andara.

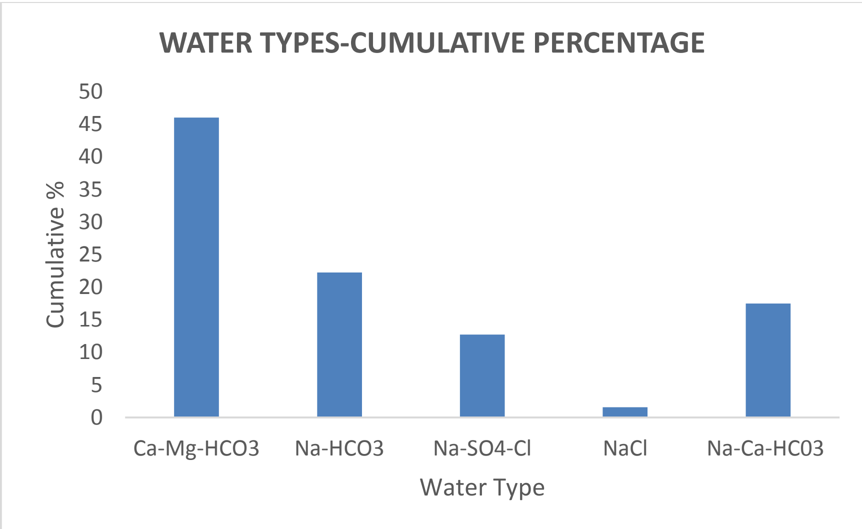


Figure 5-29: Cumulative percentage of water types in the study area

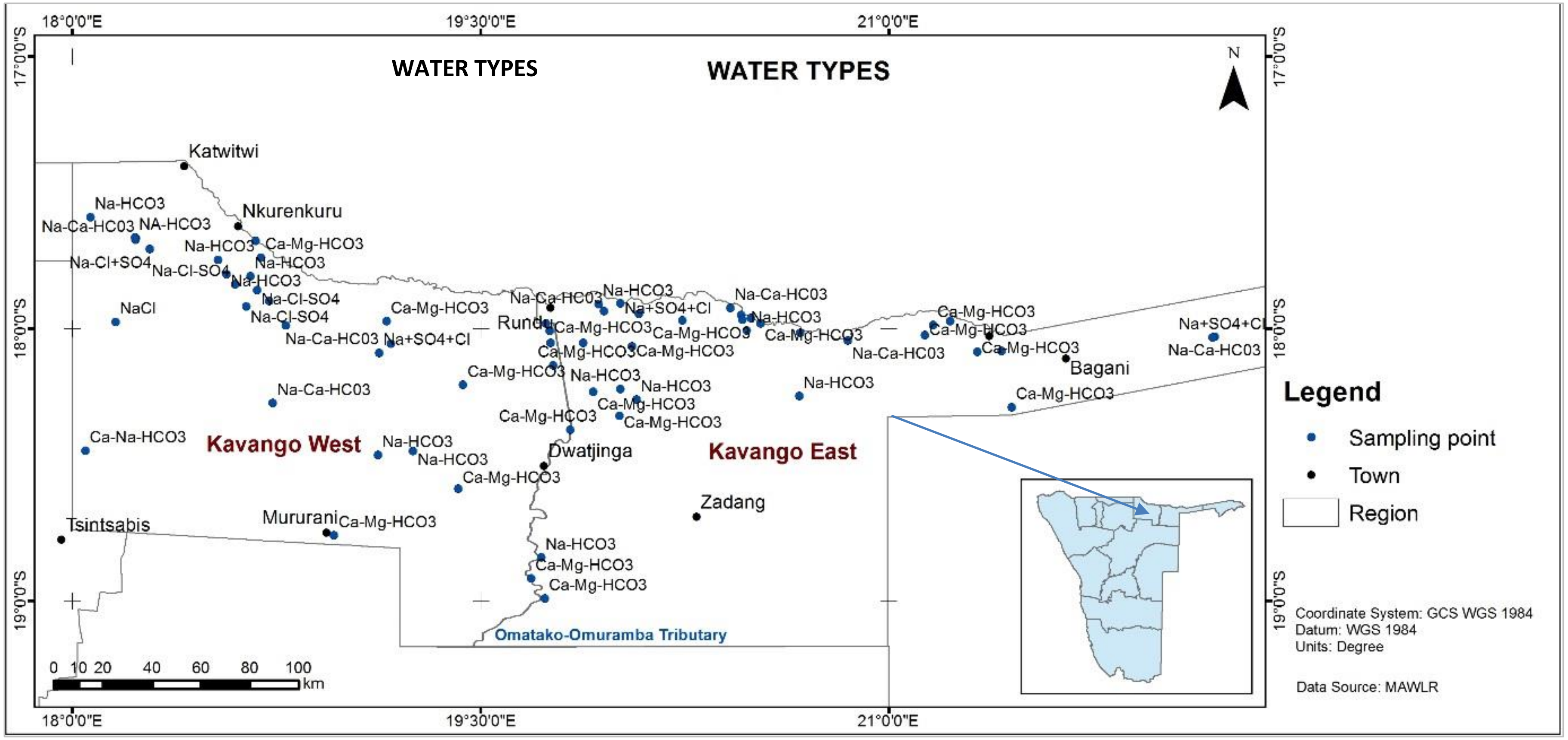


Figure 5-30: A map of the water types in the study area

Recently recharged groundwater of the type Ca^{2+}-Mg^{2+}-HCO_3^- was sampled in the boreholes WW39967, WW35534, WW7912 proximal to the Omuramba-Omatako tributary (Figure 5-30). Shallow water levels ranging from3.88 m b g l to 13.86 m b g l are recorded in these boreholes. It is hypothesized that when there are good rains and the ephemeral Omuramba-Omatako flows, recharge of the Kalahari aquifers occurs. Additional research to either qualify or disqualify this hypothesis is necessary.

Overall, the Piper Diagram shows the ionic supremacy of the ions Na^+ over Ca^{2+} and Mg^{2+}, and HCO_3^- and CO_3^{2-} over Cl^- and SO_4^{2-}. Furthermore, the geochemical facies in the Piper plot support the dominance of Alkalies over Alkaline Earth metals and weak acids over strong acids in the groundwater of the KE and KW regions.

Ionic Relationships

Figure 5-31 is a plot of Cl^- vs Na^+ for groundwater analyses. A majority of the analyses plot above the 1:1 line. Cl^- shows a positive correlation with Na^+ with R^2 = 86% based on the regression line.

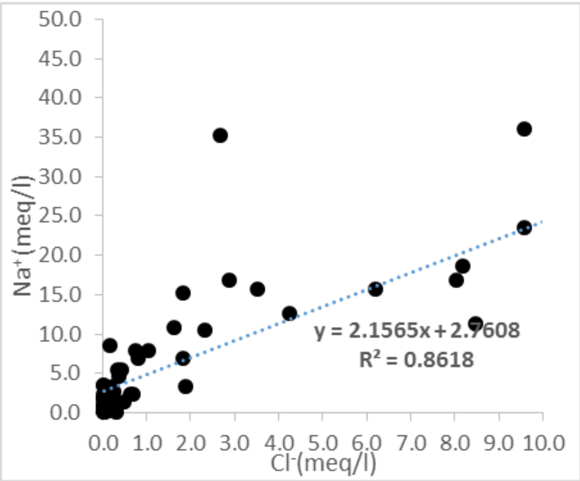


Figure 5-31: Temporal variation diagram of Na^+ vs Cl-

The ratio of Ca^{2+}/Mg^{2+} gives an indication of the source of calcium and magnesium. A ratio of Ca^{2+}/Mg^{2+} = 1 gives evidence that dissolution of dolomite occurs and that above 1, calcite dissolution is dominant (Mohamed & Zineb, 2015). A ratio that is greater than 2 indicates that the dissolution of silicate minerals largely contributes calcium and magnesium to the water. Therefore, a Ca^{2+}/Mg^{2+} ratio smaller than 2 indicates the dominance of carbonate weathering. The calculated ratio for the groundwater analyses averages 1.7 and falls in the range of 0.6 to 10.9. Therefore, calcium and magnesium are sourced primarily from calcite dissolution and less from dolomite dissolution. Silicate weathering is a very important source of calcium and magnesium in groundwater as well. The presence of calcite (calcrete) and silicates in Kalahari sands favour the above weathering processes.

By calculating the Chloro-Alkaline Indices (CAI), it can be determined whether ion exchange is occurring between aquifer material and groundwater during groundwater travel or residence process. The formulas for these according to Schoeller (1997) are seen below:

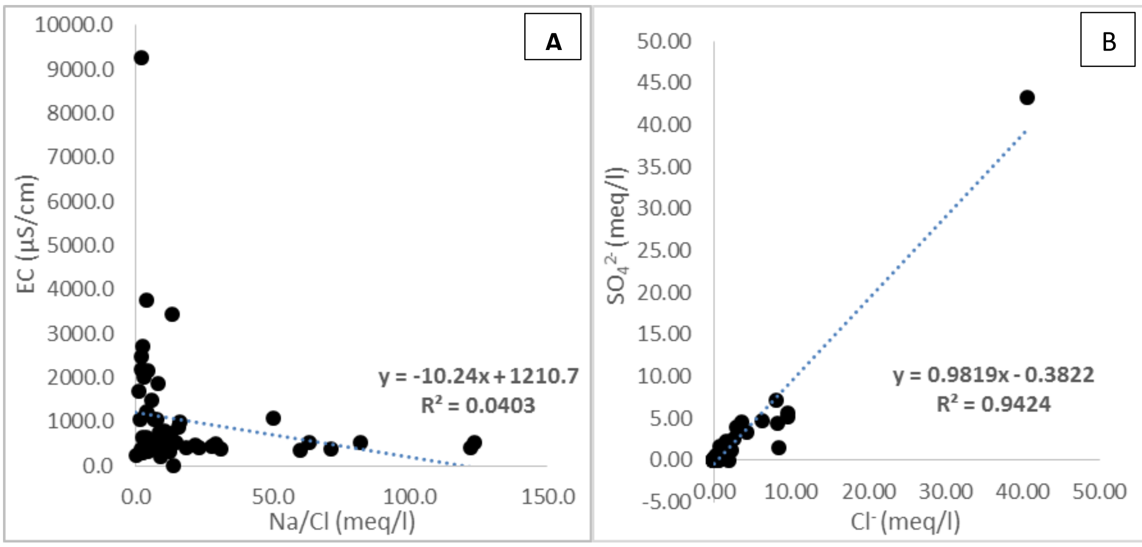
$$CAI - I = Cl^{-} - (Na^{+} + K^{+}) / Cl^{-}$$

$$CAI\text{-}II = Cl^{-} - (Na^{+} + K^{+}) / HCO_3^{-} + SO_4^{2-} + CO_3^{2-} + NO_3^{-} \qquad \textbf{eq. 8}$$

According to Schoeller (1977), when there is an exchange between calcium or magnesium in the groundwater with sodium and potassium in the aquifer material, negative CAI is obtained. If the indices are positive, then reverse ion exchange is occurring. A majority of the samples in the study area have negative values for CAI-I and CAI-II indicative of chloro-alkaline disequilibrium, also known as cation-anion exchange dominance (Schoeller, 1977; Srinivasamoorthy et al. 2013). This has resulted in the high concentration of sodium and chloride compared to Ca and Mg in groundwater of the PKA's. Sodium gets into solution by means of ion exchange in aquifers with clay minerals or organic material via equation 9 (Holting, 1996, as cited in Lohe & Hoeben, 2014).

$$2Na^{+}_{(clay)} + Ca^{2+}_{(aq)} \leftrightarrow Ca^{2+}_{(clay)} + 2Na_{(aq)} \qquad \textbf{eq. 9}$$

Other notable sources of sodium include Na-silicates including plagioclase feldspar (possibly sourced from Karoo basalt), dissolution of pre-existing evaporite minerals in the aquifer matrix, or exchange with aquitards (Marandi & Shand, 2018). Na/Cl vs EC has $R^2 = 0.04$ (4%) indicating a poor correlation between the ratio of Na/Cl and conductivity in groundwater analyses (Figure 5-32 A). This means, the higher the sodium concentration vs the chloride content, the larger the Na/Cl ratio. The higher the chloride content vs the sodium content, the lower the Na/Cl ratio. As observed in the figure, higher EC concentrations are related to a lower Na/Cl ratio, which indicates that conductivity in groundwater is controlled largely by the chloride content as opposed to the sodium content.



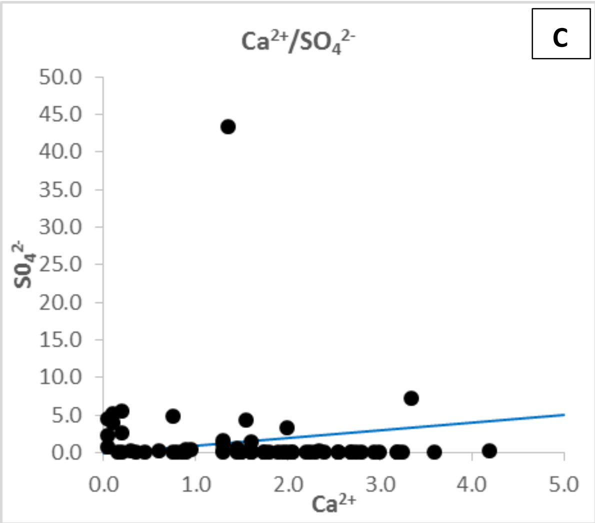


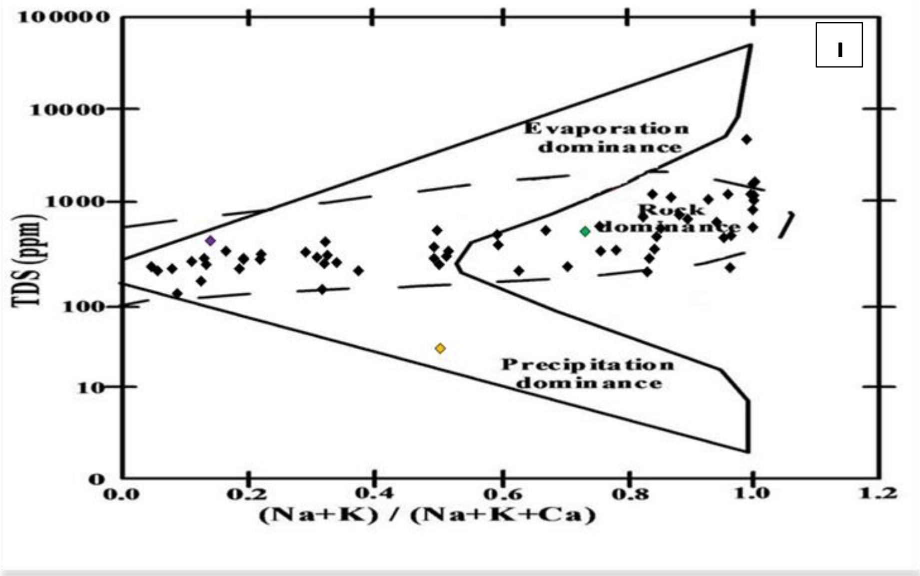
Figure 5-32: Variation diagrams displaying ionic relationships for groundwater samples

The Na/Cl ratio does not vary by much in groundwater analyses, ranging between 0 to 80 with an average of 11. Analyses with high EC up to 9000 mg/l have a low Na/Cl ratio. Those with a high Na/Cl ratio have EC lower than 600 µS/cm. Sulphate and chloride in groundwater show a positive correlation with R^2 = 0.94 or 94% (Figure 5-32 B).

The ratio of calcium vs sulphate (Figure 5-32 C) is used to determine the relationship between the two. A majority of the analyses plot below the equiline (blue line), indicating that the minerals of gypsum and anhydrite are not the primary source of calcium and sulphate. Calcium may be derived instead from ion exchange processes between clay minerals and groundwater. Sulphates may be derived from anthropogenic sources such as irrigation return from agricultural chemicals (Ebrahimi et al., 2015).

Mechanisms Controlling Groundwater Chemistry: Gibbs Ratio

Applying the Gibbs Plot (Figure 5-33) to this study, values for groundwater samples in the study area range from 0 to 1. 0 meq/l on the Gibbs ratio I plot, with an average of 0.7 meq/l. Gibbs ratio II values for the same samples also range from 0 to 1.0 meq/l, with an average of 0.1 meq/l. All the groundwater samples plot in the middle section of the Gibbs Plots, suggestive of rock dominance as the main control of the groundwater chemistry in the area of study. This is the same conclusion made by the use of the Piper Plot above.



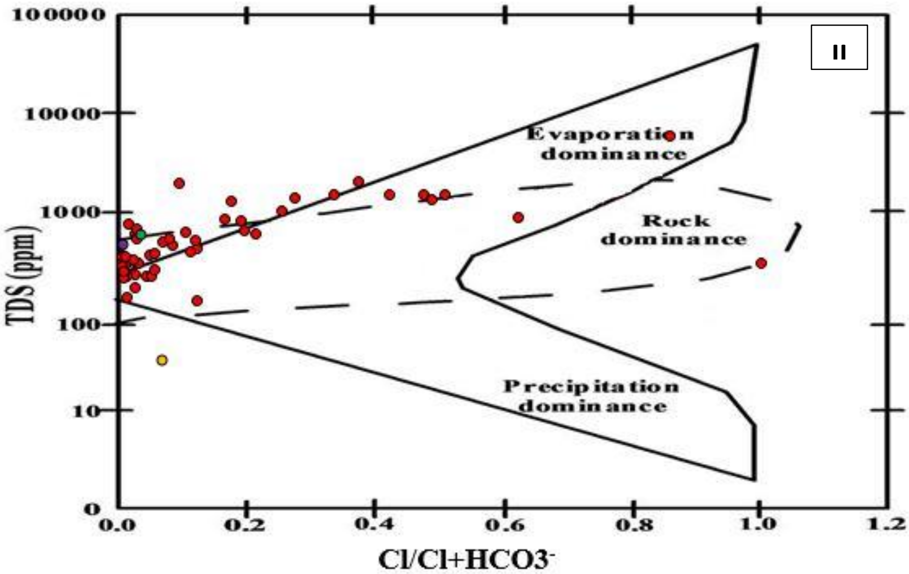


Figure 5-33: Gibbs plots showing the mechanisms involved in determining the major ion composition of surface water and groundwater in the study area. Plot I presents Gibbs ratio I and Plot II presents Gibbs ratio II.

Groundwater spans the entire range of (Na+K)/(Na+K+Ca) at mid-range TDS. The TDS levels are between 100 to 1000 ppm, with an outlier at 5828 ppm (mg/l). The latter is brackish water which according to the plot is a result of evaporation and crystallization processes. The Gibbs Plot II shows that samples cluster somewhat along the rock-dominance end member, with $Cl/Cl+HCO_3$ ratios well below 0.62. The outlier sample from the borehole at Namkupa indicates evaporation as the dominant process affecting the groundwater chemistry.

The river, pond and well samples values are 0.5 meq/l, 0.7 meq/l, and 0.1 meq/l in the Gibbs ratio I plot. In the Gibbs ratio II plot, the values are 0.1 meq/l, 0 meq/l, and 0 meq/l for the river, pond, and well samples, respectively. The river sample plots along the precipitation control end member (Gibbs ratio

I) and contains 30 mg/l TDS. Both the pond and well samples plot in the rock-dominance end member, with the pond displaying a much higher ratio of (Na+K)/(Na+K+Ca) than the well. On the Gibbs ratio II, the pond has a slightly higher ($Cl/Cl+HCO_3$) ratio than the well. Higher Na^+ and Cl^- ratios in the pond compared to the well are as a result of more evaporation-crystallization in the open pond as compared to the partially sealed well. In summary, both the cations and anions in the aquifer are principally sourced from rock-weathering rather than evaporation, crystallization, and precipitation mechanisms.

Summary

A compilation of the results analysed shows that groundwaters of the PKAs follow the evolutionary path as clearly described by Cheboratev (1955, as cited in Hiscock, 2005) from a Ca^{2+}-Mg^{2+}-HCO_3^- to Na^+-HCO_3^- water type, and eventually Na^+-Cl^--SO_4^-→Na^+-Cl^- type. Dissolution of calcite, calcrete; clays, calcareous sands, and carbonate cemented sandstone which makes up the mineralogy of the aquifers influence the overall groundwater chemistry by means of long-term water-rock interactions. In the southwest and southern KW, calcium and magnesium are potentially sourced from the carbonates (limestone and dolomite) of the OTM, which are identified as sources of recharge for this aquifer, thus influencing the initial groundwater composition. Calcrete soils and nodules are an important source of crypto-crystalline calcite and dolomite in the Kalahari sediments (Lohe & Hoeben, 2014). *Calcite dissolution* occurs via the equation below as described in Sidibe et al. (2019):

$$CaCO_3 + CO_{2\,(g)} + H_2O = Ca^{2+} + 2HCO_3^- \qquad \textbf{eq. 10}$$

Including the step: $CO_{2\,(g)} + H_2O = H^+ + HCO_3^-$,

whereby the presence of hydrogen ions produces acidic conditions that further dissolve calcite by this reaction:

$$CaCO_3 + H^+ = Ca^{2+} + HCO_3^-$$

An increase in calcite dissolution increases bicarbonate in solution which increases the pH of groundwater to more alkaline, as seen in many analyses.

Calcite dissolution is further evidenced by the calculation of the $Ca^{2+}/(Ca^{2+} + SO_4^{2-})$ ratio in groundwater across the two regions. The calculated ratio averages 0.78 for 44 out of 60 samples. Five samples from deep boreholes in the KE and one from a 60 m deep borehole in the KW (Yinsu Clinic) have ratios below 0.5. A ratio of less than 0.5 indicates that most of the Ca^{2+} in the groundwater is from gypsum and not calcite (Chapter 4: Water Quality Interpretation, n.d). Therefore, in the deeper sections of the aquifer in the KE gypsum is the likely source of calcium. Gypsum is also a likely source of sulphate in groundwater.

Disseminated clay minerals (e.g. montmorillonite) in the aquifer support the *ion exchange* of $Ca^{2+}$and Mg^{2+} in groundwater by Na^+ adsorbed on clay minerals, to form Na-HCO_3^- type water. More Ca^{2+} is exchanged compared to Mg^{2+} in this process. This conclusion is shown by the curved line (purple line in Figure 5-28) drawn parallel to the Mg^{2+} apex and then curving towards the Na^+ apex (Chapter 4: Water Quality Interpretation, n.d).

Na^+-HCO_3^- water types occurring in boreholes with deep water levels (averaging 70.5 m b g l) in the same locations above are likely a result of ion-exchange reactions by long term-water rock interactions, with the dissolution of Na-silicates (albite) in the presence of phyllosilicates (clays), silica phases (silcrete), calcite and calcrete. Enrichment in Na^+ is largely related to water-rock interactions. Other reported occurrences of Na^+-HCO_3^- water is when fresh groundwater occupies an area that had previously contained sea-water or sodium enriched brine derived from seawater, common in a palaeo-marine environment (Sidibe et al., 2019). Ion exchange processes are verified by the calculation of the Schoeller Index.

Silica in groundwater is primarily sourced from silicate rocks such as underlying Damara Sequence feldspathic quartzites, sandstone, sand and gravel grains, silcrete, and silt which make up the aquifer material.

5.2 Stable Isotope Results

Thirty samples (Table 5-6) were collected for stable isotope analyses, inclusive of 3 samples from the Okavango River, 4 rain samples, 1 sample each from a pond and hand-dug well, 19 groundwater samples, and 2 duplicate samples. The hand-dug well is approximately 20 m deep or more.

Table 5-6: Stable isotopes data for groundwater and surface water samples, inclusive of EC and Cl

BH ID	Sample ID	Location	Latitude	Longitude	Sampling Date	Analysis Date	$\delta^{18}O$	s.d.	$\delta^{2}H$	s.d.	Deuterium excess	Cl (mg/l)	EC (mS/m)	Date Sample Received at
WW28595	JINNAM1	Kahenge	18.673800	-17.676800	23/03/2020	24/06/2020	-8.2	0.10	-59.6	0.2	-59.3	1	33.6	22/06/2020
WW25540	JINNAM2	Sambiu	20.013900	-17.907100	23/03/3020	24/06/2020	-9.0	0.18	-65.3	1.1	-63.9	125	215	22/06/2020
WW31944	JINNAM3	Nyangana	20.675400	-18.015100	23/03/2020	24/06/2020	-8.7	0.20	-65.6	1.4	-62.1	1	52.3	22/06/2020
WW35053	JINBH1	Yinsu Clinic	18.567500	-17.800180	24/03/2020	24/06/2020	-9.3	0.22	-68.1	0.7	-65.5	65	187.4	22/06/2020
WW37339	JINBH2	Mukekete	18.067400	-17.589480	24/03/2020	24/06/2020	-9.3	0.06	-65.8	0.5	-65.3	6	107.9	22/06/2020
WW41274	JINBH3	Bravo	18.048667	-18.447967	24/03/2020	24/06/2020	-9.3	0.04	-67.6	0.9	-65.5	65	122.8	22/06/2020
WW3835	JINBH4	Mpungu	18.232250	-17.673260	24/03/2020	24/06/2020	-9.3	0.14	-67.0	1.0	-65.7	1	51.4	22/06/2020
WW205029	JINBH5	Sharukwe Clinic	19.757400	-18.051300	25/03/2020	24/06/2020	-9.0	0.12	-64.9	0.6	-63.7	1	38.3	22/06/2020
WW35054	JINBH6	Ncuncuni	19.766820	-18.134280	25/03/2020	24/06/2020	-9.3	0.07	-66.9	0.3	-65.7	1	36.9	22/06/2020
WW7912	JINBH7	Ncaute	19.830670	-18.370840	25/03/2020	24/06/2020	-8.9	0.08	-64.1	0.7	-63.0	1	42.4	22/06/2020
WW33868	JINBH8	Klein Karakuwisa	19.722790	-18.840350	25/03/2020	25/06/2020	-9.0	0.06	-64.4	0.3	-64.0	15	72.1	22/06/2020
WW35534	JINBH9	Satoka	19.686250	-18.917550	25/03/2020	25/06/2020	-9.1	0.21	-66.1	1.3	-64.3	1	44.5	22/06/2020
WW39967	JINBH10	Zadang	19.735800	-18.990967	25/03/2020	25/06/2020	-9.2	0.10	-65.0	0.3	-64.9	17	65.5	22/06/2020
Duplicate	JINBH11	MAWLR	17.014777	-22.553087	22/06/2020	25/06/2020	-6.7	0.08	-51.2	0.4	-51.0	0	ND	22/06/2020
Duplicate	JINBH12	MAWLR	17.014777	-22.553087	23/06/2020	25/06/2020	-6.7	0.14	-51.7	0.5	-50.8	0	ND	22/06/2020
Rain	JINR1	Ndonga Linena	20.475040	-17.952990	16/03/2020	25/06/2020	-4.5	0.12	-26.7	1.0	-38.5	0	ND	22/06/2020
Rain	JINR2	Mashare	20.213950	-17.897470	16/03/2020	25/06/2020	-4.6	0.16	-27.6	0.6	-39.1	0	ND	22/06/2020
Rain	JINR3	Rundu	17.912700	-19.768710	16/03/2020	25/06/2020	-3.4	0.09	-22.5	0.7	-32.3	0	ND	22/06/2020
Rain	JINR4	Rundu Guesthouse	17.919670	-19.748330	24/03/2020	25/06/2020	-13.4	0.07	-94.2	1.4	-88.5	0	ND	22/06/2020
Well	JINW1	Mavandje	19.753950	-18.007700	25/03/2020	25/06/2020	-6.7	0.31	-52.0	1.9	-51.1	67.9	1	22/06/2020
Pond	JINP1	Mavandje	19.740590	-17.980630	26/03/2020	26/06/2020	0.7	0.07	-19.9	0.2	-8.9	10	86.2	23/06/2020
WW34811	AKS8	Omega	22.199170	-18.028550	14/03/2020	26/06/2020	-8.5	0.23	-60.6	0.5	-60.8	150	202	22/06/2020
WW40567	AKS4	Tcalikawa	18.737620	-18.273200	11/03/2020	26/06/2020	-9.4	0.14	-66.4	0.98	-66.3	24	60.6	22/06/2020
WW40571	AKS2	Desi	18.784840	-17.987560	11/03/2020	26/06/2020	-9.5	0.12	-67.9	0.3	-66.5	7	87.3	22/06/2020
WW204140	AKS20	Shinunga Toring	19.128000	-18.088600	18/03/2020	26/06/2020	-9.6	0.1	-66.6	0.9	-67.2	220	217	22/06/2020
WW204253	AKS7	Rupetho	20.057000	-18.064400	13/03/2020	26/06/2020	-8.4	0.22	-60.6	0.8	-60.4	1	50.6	22/06/2020
WW204138	AKS21	Tcausha	18.230600	-17.664500	18/03/2020	26/06/2020	-9.2	0.21	-65.8	1.0	-64.7	8	53.5	22/06/2020
River	AKS30	Nkurenkuru River	18.615150	-17.621430	16/03/2020	26/06/2020	-9.0	0.35	-63.4	1.3	-64.1	0	ND	22/06/2020
River	AKS29	Kalai Bridge	19.802730	-17.872690	18/03/2020	26/06/2020	-6.8	0.08	-44.5	0.4	-51.3	0	ND	22/06/2020
River	JINRV1	Kandjimi Murangi	18.694664	-17.737801	23/03/2020	26/06/2020	-6.8	0.06	-43.0	0.4	-51.4	1	4.5	22/06/2020

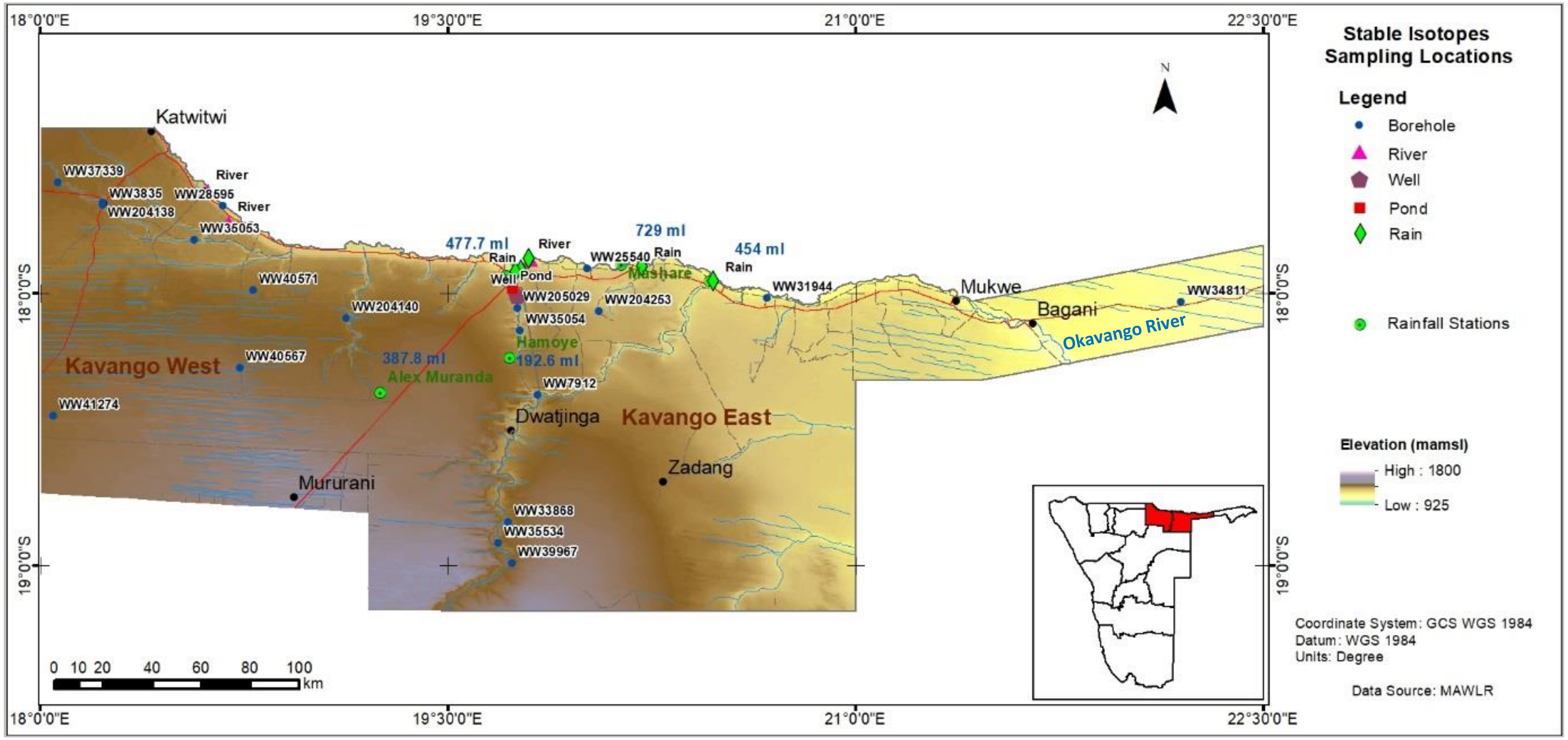


Figure 5-34: Location map for stable isotopes collected in KE & KW Regions

The two river samples were collected upstream at Nkurenkuru and Kandjimi Murangi, while the 1 sample was collected midstream at Kalai Bridge in Kaisosi village (Figure 5-34). Kandjimi Murangi is located 114.8 km west of Rundu and 17.09 km (Google, n.d) east of Nkurenkuru.

Samples were collected at varying altitudes ranging between 1200 m to <1000 m; the highest elevations occurring in central, north, and southern KW and the lower elevations occurring along the Okavango River, in the north-east and eastern parts of the KE (WW3481, Omega).

5.2.1 Spatial Variation of Stable Isotopes in KE and KW

$\delta^{18}O$ values become progressively depleted from the north-east of the KE towards the north-west and south-east KW along the Omuramba-Omatako (Figure 5-35). The distribution of deuterium in space over the two regions is not as varied, with the more depleted values occurring across the Kavango West, particularly in the northwest and north-central KW towards the south. In this case, both $\delta^{18}O$ and $\delta^{2}H$ become progressively depleted in groundwater as elevation increases (altitude effect) from north-east KE to south-west KW (Figure 5-35 & 5-36).

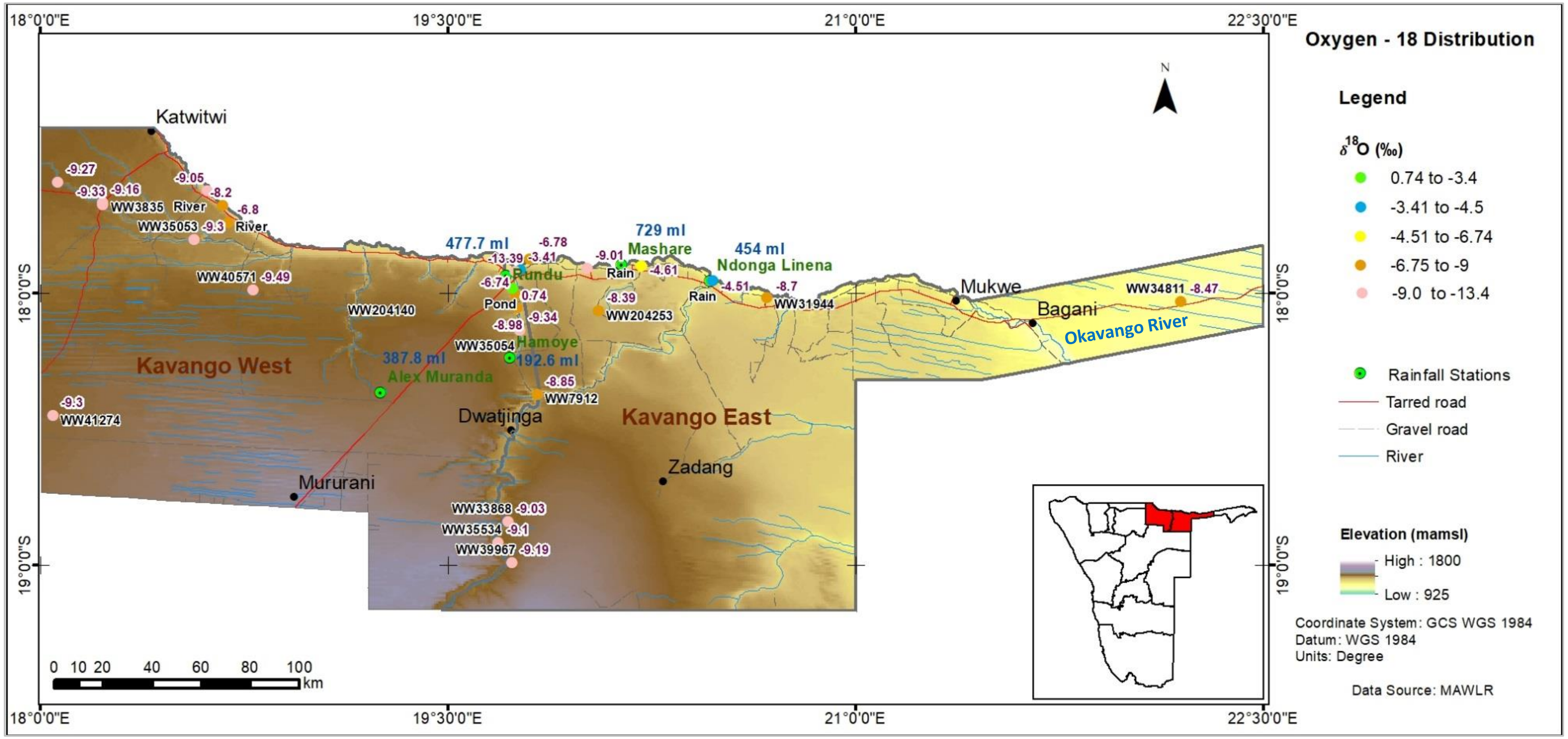


Figure 5-35: Spatial distribution of $\delta^{18}O$ in the KE & KW Regions

Elevations are lower along the Okavango River, where both parameters are less depleted but also more variable i.e. $\delta^{18}O$ = -6.8 to -9.0‰ and $\delta^{2}H$= -43.0 to -63.4‰. The article titled 'Kalahari Groundwater Isotope Synthesis' as part of the report to the Water Research Commission (Abiye, 2013) made the same conclusion that oxygen-18 and deuterium roughly decrease from east to west according to prevailing rain gradients. This report synthesized data on the Kalahari aquifers in Namibia, South Africa, and Botswana. The most depleted values in groundwater for $\delta^{18}O$ = -9.3‰ and $\delta^{2}H$ = -68.1‰ are recorded at Yinsu Clinic in the KW. The rain sample collected at the Rundu Guesthouse comprises $\delta^{18}O$ = -13.4‰ and $\delta^{2}H$ = -94.2‰.

Isotopic composition ranges for all analyses are as follow: rainfall: $\delta^{18}O$ (-3.4 ‰ to -4.6‰), $\delta^{2}H$ (-22.5‰ to -27.6‰); Okavango River: $\delta^{18}O$ (-6.8‰ to -9.0‰), $\delta^{2}H$ (-43‰ to -63.4‰); groundwater: $\delta^{18}O$ (-8.2‰ to -9.6‰), $\delta^{2}H$ (-59.6‰ to -68.1‰); well: $\delta^{18}O$ (-6.7‰), $\delta^{2}H$ (-52.0‰) and the pond $\delta^{18}O$ (0.7‰), $\delta^{2}H$ (-19.9‰). The mean isotopic composition in groundwater is $\delta^{18}O$ = -9.1 ± 0.14‰ and $\delta^{2}H$ = -57.8 ± 0.7‰. In rain, isotopic composition values average $\delta^{18}O$ = -6.5 ± 0.1‰; $\delta^{2}H$ = -42.7 ± 0.9‰ and in the collected river samples $\delta^{18}O$ = -7.5 ± 0.2‰ and $\delta^{2}H$ = -50.3 ± 0.7‰. D-excess ranges from -59.3‰ to -67.2‰ for groundwater, -38.5‰ to -88.5‰ for rain samples, -51.3‰ to 64.1‰ for the river, -51‰ for the well, and -8.9‰ for the pond. The depleted values of d-excess in the groundwater samples suggest that there is significant evaporation of rainwater, leaving the residual groundwater with lower values of d-excess.

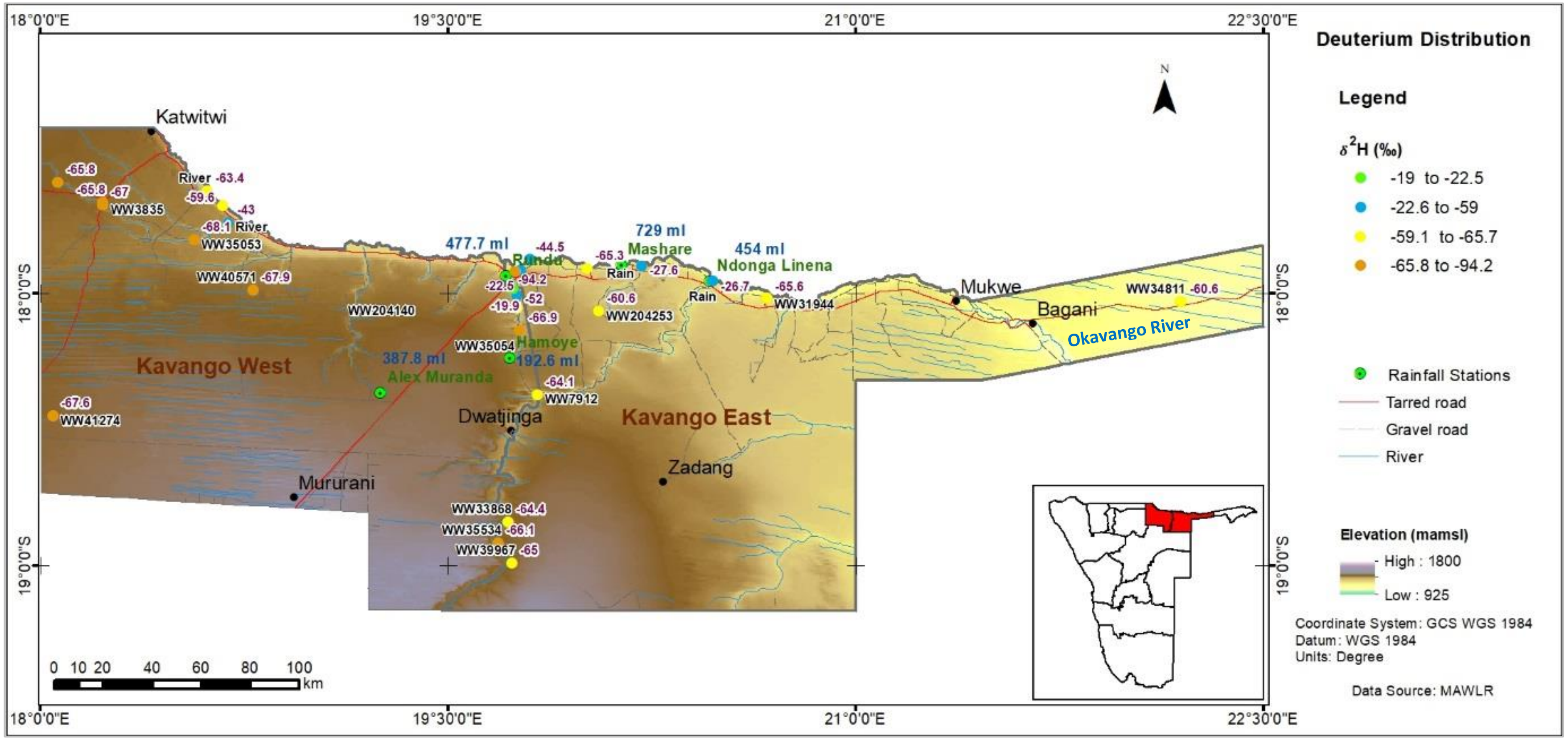


Figure 5-36: Spatial distribution of δ2H in the KE & KW Regions

All samples plot on the regression line $\delta^2H = 6.18\delta^{18}O - 8.26$; $R^2 = 0.91$ in Figure 5-37, where δ^2H vs $\delta^{18}O$ values for all water samples is plotted. Clark and Fritz (1997) report that the intersection of the regression line with the GMWL/LMWL gives the isotopic signature of the parent meteoric water.

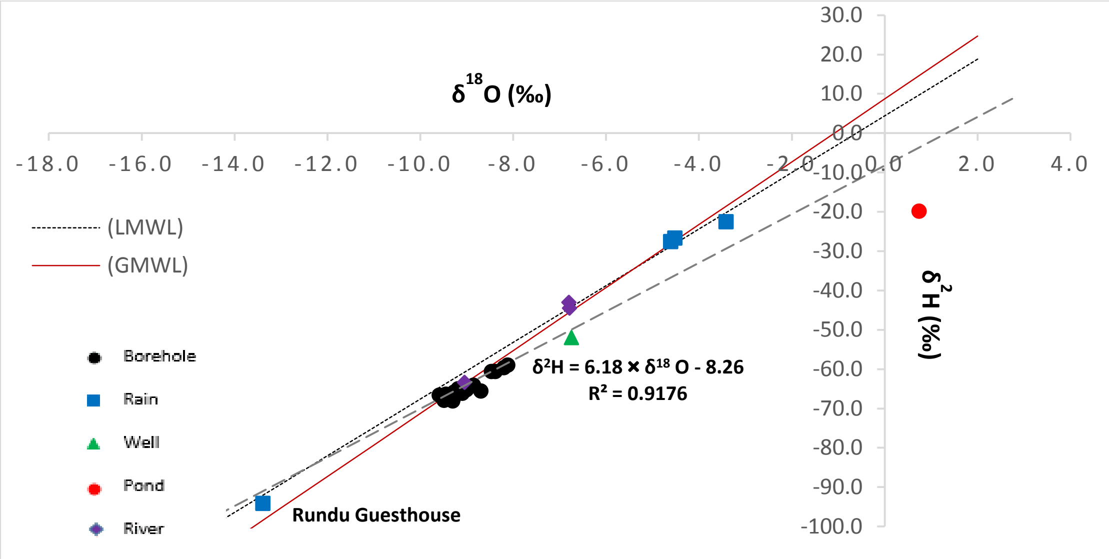


Figure 5-37: A. Graph of $\delta^{18}O$ values vs δ2H values

The regression line for the groundwater samples is computed as $\delta^2H = 5.79\ \delta^{18}O - 12.74$; $R^2 = 0.83$ and cuts the LMWL at -11.6‰ and -70.8‰, which is a more depleted signature indicative of a more depleted parent signature. This signature shows that the aquifers are recharged by higher rainfall amounts and intensive rainfall events which is common in many areas in semi-arid Namibia.

The computed regression line for the river analyses is $\delta^2H = 6.82\delta^{18}O + 0.84$; $R^2 = 0.99$. The LMWL used in the interpretation of these isotope results is the Cuvelai Etosha Basin (CEB) LMWL defined by $\delta^2H = 7.2\ \delta^{18}O + 4.4$, $R^2=0.99$ (Hamutoko et al., 2017). The GMWL is defined by $\delta^2H = 8*\delta^{18}O + 10$ based on a 60-year precipitation record (Abiye et al., 2021). A new GMWL defined as $\delta^2H = 8*\delta^{18}O + 8.72$ (Figure 5-37), has been developed based on a 49 (1960-2009) years precipitation data record (Terzer et al., 2013). The difference between the two lines is that the new GMWL has a lower d-excess of 8.72‰ compared to the 10‰ for the 1961 equation (Abiye et al., 2021).

Groundwater sample analyses reflect a more depleted signature indicative of enrichment of the heavier isotopes of $\delta^{18}O$ and δ^2H. The groundwater analyses plot on and just below the Global Meteoric Water Line (GMWL), and on and below the Local Meteoric Water Line (LMWL). This shows that modern precipitation infiltrates and recharges the aquifers, which is also shown by hydrochemistry results. Groundwater analyses plotting on the meteoric lines indicate that they have the same signature as the meteoric water that contributed to their recharge. There is a small evaporation signature shown by analyses plotting below the meteoric lines, indicating that evaporation processes affected infiltrating waters either before or during infiltration.

The precipitation samples plot on both the LMWL and GMWL. The local rainfall analyses are less depleted and isotopically distinct from groundwater isotope signatures. This may be due to differing air mass sources or local climatic factors. Two samples from the Okavango River plot on the GMWL and LMWL, and one analysis from a sample at Nkurenkuru plots just below the LMWL. The well and pond analyses plot below both the LMWL and GMWL signifying evaporation enrichment, as both these are open to the atmosphere.

The analyses have been clustered in Figure 5-38 below into 1) two groundwater clusters, wherein one, groundwater is clustered together with 1 river sample analysis, 2) a cluster of the rain analyses, 3) a cluster for the well and river analyses, the pond, and anomalous rainfall analysis at Rundu.

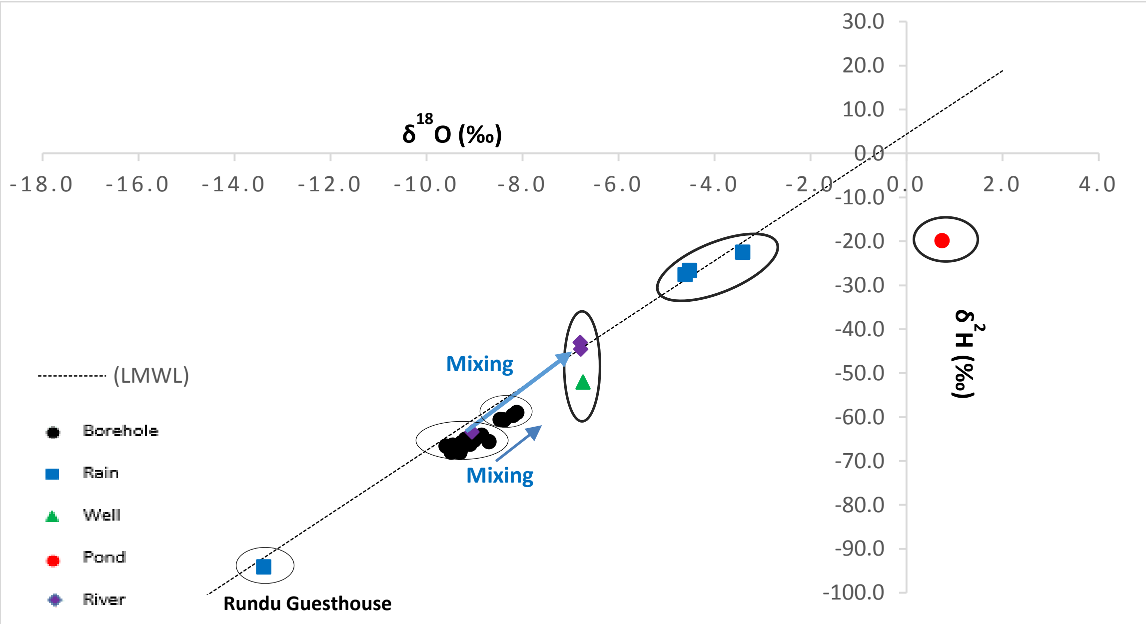


Figure 5-38: A clustering of analyses with similar isotope signatures

The latter was not collected on the same date as the rest of the rain samples. It plots as an anomaly, which the researcher interprets as due to a higher degree of rain-out process. The sample from the Okavango River at Nkurenkuru has a similar signature to that of the more depleted groundwater cluster. This gives evidence that there is a link between the Okavango River and the aquifers below as reported in the report to the Water Research Commission (Abiye, 2013). On the other hand, the study by Water Surveys Botswana (2011) states that based on the groundwater flow gradient, the Okavango River is likely not a recharge source to the underlying Kalahari aquifers. However, in Botswana where the gradient is similar towards the Okavango River, the river recharges the aquifer within the floodplain.

Tritium

Tritium analyses are seen in Table 5-7 below. In the KW, 4 locations were sampled, inclusive of the river (upstream) near Nkurenkuru. All 3 boreholes sampled in the KW are proximal to the river and exhibit groundwater with tritium averaging 0.3 TU. In the Kavango East Region, 8 locations were sampled inclusive of 3 river points i.e. Rundu (mid-stream), Andara, and Omega (downstream), the latter with an average of 1.3 TU.

Tritium in precipitation has been analysed since 1961-2001 at the Windhoek station (Figure 5-39) as recorded on the Global Network of Isotopes in Precipitation (GNIP). According to these records, tritium in precipitation has decreased from 63.73 TU (weighted average in the year 1963) to 6.65, 4.83, 6.24, 4.2 TU in 1983, 1984, 1985, and 1999, respectively (IAEA/WMO, 2021). No records are visible on the IAEA NUCLEUS site for the period 2000 to 2001 and up to date.

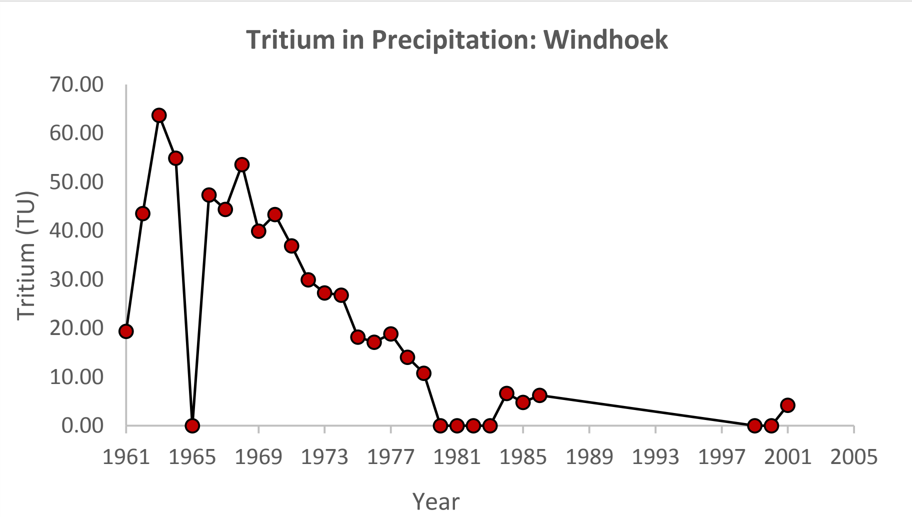


Figure 5-39: Tritium values in precipitation from 1961-2000 at the Windhoek GNIP Station (IAEA/WMO, 2021)

From 2001-2020, it is expected that Tritium in precipitation should have decreased significantly. The Okavango River analyses are a close representation of precipitation and average 1.7 TU ± 0.3.
If the original content of tritium ($^3H_0$) in infiltrating precipitation is known, it is possible to calculate the amount of tritium (^3H_t) after a known residence time (t). This is computed via the equation obtained from Mook (2001):

$$^3H_t = {}^3H_0^{-\lambda t} \qquad \textbf{eq.11}$$

where $\lambda = \ln(2)/T^{1/2}$ and $T^{1/2} = 12.32$ years (Lucas & Unterweger, 2000)
If tritium recorded in precipitation in 1999 was 4.2 TU (IAEA/WMO, 2021), t = 21 years from (2020 to 1999) computing the equation-based half life of 12.32 years equates:
λ = 0.05626
Therefore, ^3H_t = 0.183498, approx. 0.2 TU is expected to be present in groundwater in the study area today. The average tritium in groundwater based on the analyses in the two regions as presented in Table 5-7 is 0.5 TU ± 0.2. This would put the tritium levels in groundwater very close to the calculated 0.2 TU.

Table 5-7: Tritium results (David, 2021)

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

The average tritium in groundwater based on the analyses in the two regions as presented in Table 5-7 is 0.5 TU ± 0.2. This would put the tritium levels in groundwater very close to the calculated 0.2 TU. The average value of tritium in groundwater is similar to that in the river analyses which are assumed close to precipitation values. This would suggest that there is infiltration of current precipitation recharging the aquifer (Figure 5-40).

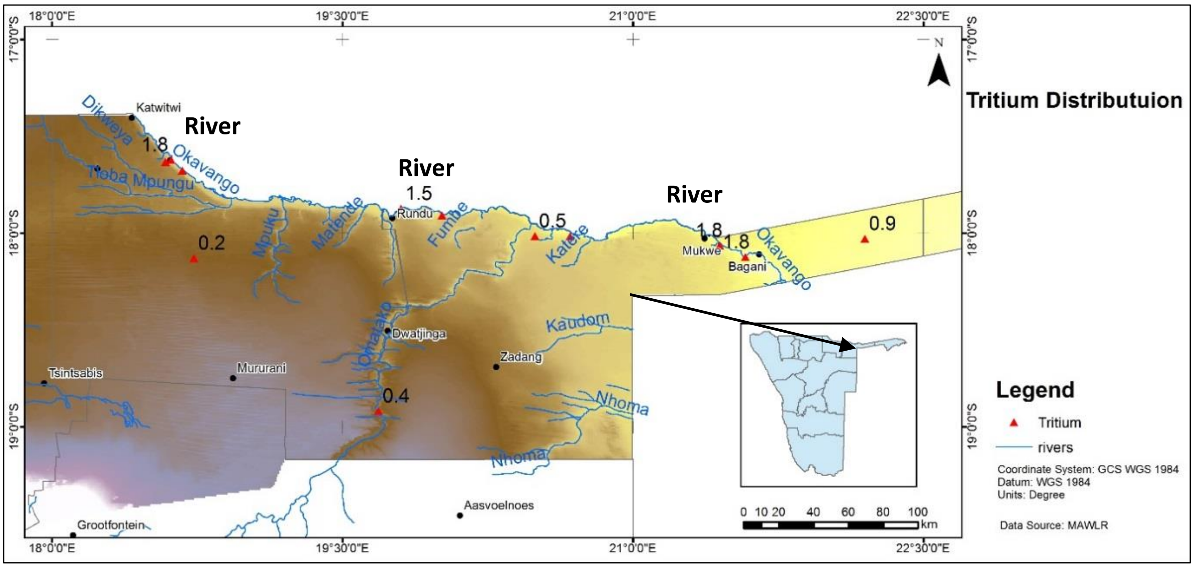


Figure 5-40: Spatial distribution map for tritium in the KE and KW Regions

The tritium content present now would be the natural background value from the upper atmosphere. This hypothesis also gives evidence that the use of tritium for age dating in these aquifers is not the best fit method

A plot of chloride vs $\delta^{18}O$ is illustrated in Figure 5-41 to further understand the mechanisms causing mineralization in groundwater. Across the KE and KW, it is observed that groundwater salinization is primarily due to the dissolution of soluble salts, where an increase in chloride concentration does not correspond to an increase in $\delta^{18}O$. Evaporation is marginally observed to lead to salinization in the groundwater except where it is defined for the well analysis (green triangle). Eight out of nineteen (8/19) groundwater analyses recorded 1 mg/l of chloride.

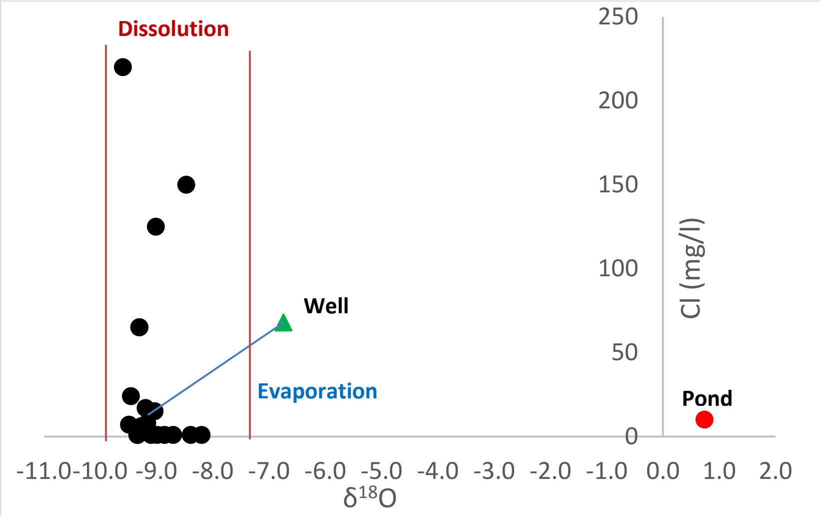


Figure 5-41: Stable isotope composition vs salinity for the identification of different salinization processes in groundwater

Important conclusions drawn from the isotope analyses are summarized below:

- The stable isotopes results based on Figures 5-37 and 5-38 show that there is a hydraulic connection between groundwater and water from the Okavango River. This connection is interpreted as the Okavango River recharging the underlying aquifer(s) where the river water level is higher than the aquifer level. This is seen at Nkurenkuru and Kahenge, where groundwater levels are very shallow at 5 to 10 m b g l. Where the Okavango River water level is shallower than the underlying aquifer (s), the aquifer(s) feeds the river by means of baseflow
- Tritium results coupled with Hydrogeochemistry results show that there is recent recharge to the Kalahari Aquifers. Accordingly, recharge rates vary as well as residence times (Abiye, 2013), the latter indicated by saline water types and natural background tritium content in groundwater. Recharge is seen to occur along the Omuramba-Omatako tributary. According to Water Surveys Botswana (2011), localized infiltration may occur in interdunal zones and in the omiramba where ponding occurs.
- There is a mixing of groundwater between the different Kalahari aquifers i.e. Upper, Middle, and Lower Kalahari. This is shown by the two groundwater clusters with different isotope signals, and it is also shown by Hydrogeochemistry results.

5.3 Design of a Groundwater Monitoring Network

In designing a monitoring network for the Primary Kalahari Aquifers System, it is recognizec that the possibility of the aquifer being transboundary in nature. Notably, transboundary groundwater monitoring is different from internal monitoring systems as a result of the nature of the aquifer, legal mandates, and institutional capacities/lack thereof in RBOs (AGW-Net, 2015). It is more complex and requires a unified and consistent approach across the catchment and riparian states.

Due to these complexities, the network is designed in the context of groundwater monitoring by the DWA of Namibia, which can be expanded to the other riparian states constituted in OKAKOM.

5.3.1 Management Questions/Information Needs

i. What is the extent of the Kalahari Aquifer System? Does the aquifer extend into Angola and Botswana, thus making it transboundary in nature?

ii. The hydraulic link between the Okavango River and groundwater is verified by this report. Due to this link, an increase in activities occurring in either of the three riparian states would affect groundwater resources' quantity and quality.

iii. Availability of data to support the characterization of the Kalahari Aquifers. Missing data include groundwater levels; recharge rates; abstraction data from all users; hydraulic parameters such as hydraulic conductivity, transmissivity, permeability, aquifer storativity, safe yield, aquifer porosities, and geological data.

iv. Consolidation of available groundwater quality data from previous studies and campaigns in the study area. Evaluation and analysis of data to support decision making the nation and regional scale.

v. Determining the relation between groundwater and socio-economic activities and environmental issues.

vi. A decision support tool to inform the decision-makers and relevant stakeholders on the availability of groundwater resources in the KE and KW Regions.

5.3.2 Monitoring Objectives

- **Resource monitoring:** to further characterise the Kalahari groundwater system and increase understanding of groundwater flows, recharge and discharge mechanisms, changes in groundwater levels and quality in the longer term, as well as investigate linkages between surface water and groundwater. To understand the response of the Kalahari aquifers to various pressures i.e. over-abstraction and climate change.
- **Pollution monitoring**: to provide early warning information on the impacts of potential pollution hazards from irrigation schemes, fish farms, and the tourism industry in the Kavango East and Kavango West Regions. To improve the protection and management of groundwater resources by reducing risks of groundwater pollution.

5.3.3 Management Tasks: Consolidation of Data and Preliminary Characterization of the Aquifer

The process of designing an effective and target-oriented monitoring system involves primarily, the preliminary characterization of the aquifer and an understanding of groundwater flow in the catchment. Characterization in this sense includes defining the geometry of the aquifer; determining hydraulic parameters; geology within the catchment, understanding groundwater flow, and establishing surface-water and groundwater interactions (Mediterranean Groundwater Working Group, 2007). Consolidation of available data is the first step to be considered in the design of an effective monitoring network in the study area. The data to be consolidated is outlined in Appendix F.

The following should be sufficiently understood after an inventory of data in Appendix F is completed:

- Groundwater assessment: Understand groundwater flow systems within the Kalahari groundwater system. The OKAKOM has commenced with groundwater assessment in the CORB.
- Development of a conceptual model based on the available hydrogeological and hydrological data
- Scope and limitations of the institutional setup centering groundwater management in the study area

NB: If the data is not sufficient to deduce a conceptual model, the monitoring network designed allows for the collection of data to assist in developing this model.

5.3.4 Type of Monitoring Network Designed: Regional Monitoring Network

A primary regional/basic network provides general information about the quality and quantity of a groundwater system on a permanent basis. It is designed to produce continuous long-term series data that would be useful in evaluating groundwater quantity and quality trends, as well as form the basis for hydrogeological investigations in the study area and on a national scale. This network would form part of the already existing DWA National Groundwater Monitoring Network, and it is important that it aligns closely with its objectives.

5.3.5 Technical Objectives

i. Groundwater Level Monitoring

- To understand groundwater level fluctuations and associated trends in the catchment
- To quantify groundwater response to inflow (recharge) and outflow (abstraction and natural leakage), by means of physically measuring the changes in water levels in a selected number of representative boreholes distributed over the aquifer/catchment (Mediterranean Groundwater Working Group, 2007). By monitoring abstraction and water level changes, the effects of pumping from the aquifer can be assessed, and this would provide valuable information for effective groundwater resource management (AGW_Net, 2015). Abstraction is mainly along the Okavango River from NamWater scheme boreholes as well as the community boreholes drilled by the Rural Water Supply, the latter across the entire two regions. Porosity

data combined with water level data yields volumetric recharge and discharge parameters of the aquifer.

- To calculate the Water Balance for the groundwater system by groundwater modeling (coupled with groundwater abstraction data, rainfall & evapotranspiration figures).
- To update the aquifer groundwater flow regime and rate of flow which is controlled by the gradient.
- To determine the aquifers' storage capacity (coupled with pumping test data and data on the extent/geometry of the aquifer) and safe yields.
- To provide early warning information regarding over-abstraction in order to take timely action to prevent aquifer exploitation (AGW_Net, 2015).
- To increase awareness among water users on groundwater issues and introduce them to participatory groundwater management and monitoring of the resource
- To provide essential information for the sustainable management of the groundwater resources and facilitate improved optimal use of the resources to avoid overdevelopment or water quality deterioration.

ii. Groundwater Quality Monitoring

- To understand the chemical status of groundwater and determine the processes controlling its chemistry through the collection and analysis of groundwater quality data.
- To identify trends in pollutant concentrations and reversal of these trends over short or long-term periods. An example would be the potential salinization of groundwater by the use of inappropriate irrigation practices.
- To identify sources of pollution/potential sources of pollution and establish mitigation procedures, particularly the salinization of groundwater by inappropriate irrigation techniques. Potential hazards that will negatively influence groundwater quality in the study area include an increase in agricultural land use (i.e. inception of the CRAVE Project) and use of agrochemicals, the potential transition from subsistence farming to commercial farming for local farmers, and recent drilling for oil and finding a reserve (oil spills).
- To ascertain local populations have access to safe drinking water

Specific impact stations for groundwater quality monitoring should be set up along the Okavango River and in the north and north-central Kavango West areas, where high levels of ionic composition in groundwater are observed. These elevated levels have resulted in groundwater being unsuitable for human consumption. There is no need to establish other specific monitoring boreholes as there currently is no evidence for any point source pollution resulting from anthropogenic activities. Any such evidence will be detected in the network designed herein and it would form the basis to develop a specific impact network.

The development of a Monitoring Strategy is key in the monitoring design. The Geohydrology Division has developed a Draft Groundwater Monitoring Strategy (Geohydrology Division, 2010).

Data Collection

According to the AGW_Net (2015), groundwater monitoring networks must be designed with a special focus on monitoring in the recharge and discharge areas. Determining the extent of the recharge area is notably complex, however, discharge areas are generally localized, often marked by wetlands, springs, baseflow, or seepage zones. This is the case in the study area, where the discharge areas are indeed localized and observed as outcrops near Rundu and Andara in the KE.

i. Parameters to be measured: Groundwater Level Monitoring

- Temperature, conductivity, water level, and piezometric pressure:
  Install water-level data loggers (e.g. Insitu Level Troll) in monitoring boreholes to measure these parameters daily. The advantage of using data loggers is that data is stored and downloaded at any time. Currently, the Geohydrology Division at DWA has installed UMWELTLEISTUNGEN (UIT) multi-sensor loggers with remote data transmission technology and standalone power supply in selected master stations across major groundwater aquifers. The use of telemetry stations has significantly improved the response time for data capture for the Geohydrology Division.
- The static water level in the borehole (to be taken during each field visit)
- Borehole collar height (initial static data)
- Borehole depth (initial static data)
- Time series of irrigation images for monitoring crops, mapping irrigated areas and irrigation water requirements estimates in the study area[these can be sourced from NASA: Landsat 8, Google Earth, Earth Explorer by USGS, Digital Globe through the Namibia Statics Agency].
- **Frequency:** Collection of groundwater level data should be conducted annually during an annual monitoring field visit. This field visit should be conducted at the end of each hydrological year, ending on 30th September.

ii. Parameters to be measured: Groundwater Quality Monitoring

- Determinants with aesthetic/physical implications according to the Water Resources Management Act (2013): colour, conductivity, total hardness, TDS, total alkalinity, turbidity, pH, redox potential
  major ions: calcium, magnesium, sodium, bicarbonate, chloride, sulphate, silica
  minor ions: potassium, carbonate, fluoride, iron, ammonium, bromide, fluoride, nitrate/nitrite, boron, strontium, carbon dioxide, DO
  metals: manganese& iron [copper, zinc, cadmium, lead, and arsenic]
  nutrients: total phosphate [and chlorophyll]
- Stable isotopes: oxygen-18, deuterium, tritium, and carbon-14

Frequency:

Groundwater sampling for geochemical analysis should be conducted annually, in conjunction with water level data collection. Sampling should be conducted procedurally by a Hydrogeologist during the annual monitoring field visit.

- Precipitation samples for stable isotope analyses are to be collected by trained personnel at the MAWLR ADC's in the study area on a bi-annual basis i.e. wet and dry season.
- Groundwater samples for stable isotope analysis should be collected in conjunction with hydrogeochemistry samples annually. The two samples should be separate for every borehole sampled. Collection of river samples from upstream, midstream, and downstream the Okavango River should be conducted in parallel.
- Groundwater samples for carbon-14 and tritium samples should be collected during a once-off isotope sampling campaign in the study area. Carbon-14 would yield important information on the age of groundwater, supported by tritium results. This sampling campaign should account for spatial distribution across the study area.

iii. Data to be collected from Users

- Abstraction data (NAMWATER and government-owned Irrigation Schemes). Since the groundwater system is not classified as a Water Protected Area, it is not possible to enforce private users to provide abstraction use data.
- Borehole Drilling Completion reports and pumping test reports for all new boreholes drilled [Division of Rural Water Supply, private farmers]

Locations and Depths for Parameter Measurements

- A hydrocensus of boreholes drilled by DWSSC and private boreholes should be carried out across the KE and KW regions. The spatial information for the boreholes can be extracted from the GROWAS II database. The hydrocensus would yield information on the working conditions of the boreholes, and would further support the decision to 1) rehabilitate old existing boreholes or 2) drill new boreholes for the purpose of monitoring. Production boreholes are generally not ideal for groundwater quantity monitoring, nor are they presently designed for ease of access for groundwater sampling.
- In the case new boreholes are drilled, the map below (Figure 5-42) outlines the locations requiring monitoring and at the same time are representative of the groundwater system. The criteria used for the selection of groundwater level monitoring sites are similar to those already set up by the Division Geohydrology for the monitoring in master stations: 1) stations are not directly influenced by production boreholes, 2) they are a representative of water levels in the Kalahari Sequence groundwater system, 3) they are free from human vandalism and are accessible all year long and 4) stations are spatially distributed over the porous aquifer extent (MAWLR, 2021).

- The researcher recommends that new boreholes that are to be drilled in future for rural water supply should have an outlet to measure the rest water level.

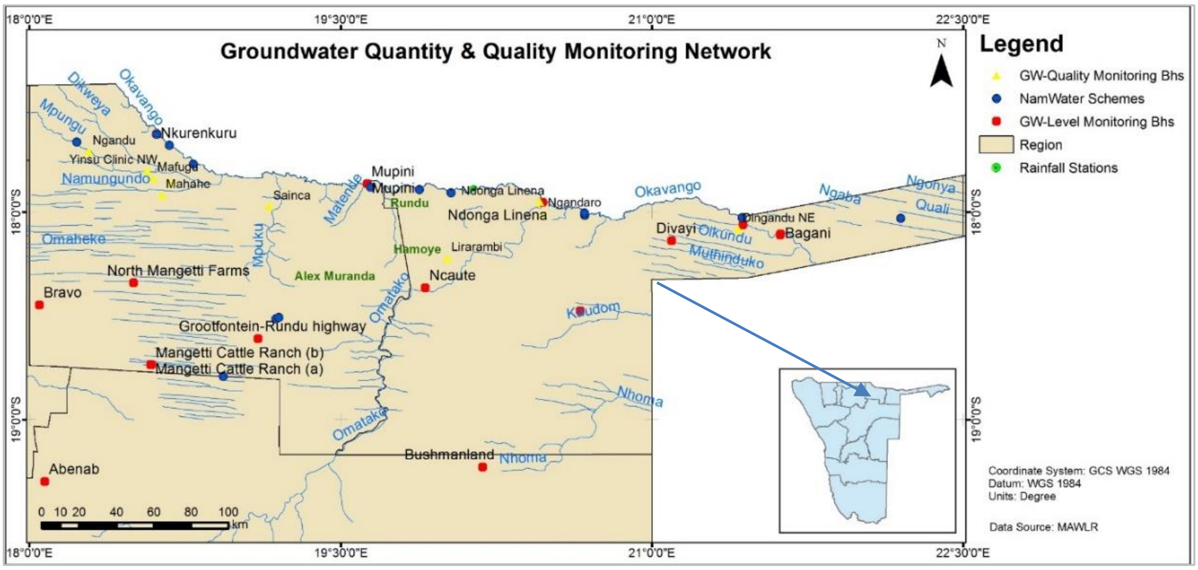


Figure 5-42: Proposed groundwater level (and quality) monitoring sites in the Kavango East and West Regions

Locations and depths for groundwater quality monitoring

- In groundwater sampling, it is important to consider borehole design, to ascertain the depth of sampling. Many boreholes drilled in the two Kavango Regions are drilled in such a way that they intersect either all or two of the Kalahari Sequence aquifers. In some cases, only the Lower Kalahari aquifer is intersected. This is because the boreholes are drilled primarily for water supply. By sampling such a borehole, a mixed sample from all the aquifer strata is collected. In the latter case, a depth-specific sample is collected. This type of sampling is used to determine water quality (and head) in a selected unit of a multi-layered aquifer system. The groundwater quality monitoring network should coincide with rehabilitated/newly drilled boreholes specified for the groundwater quantity monitoring network above and additionally those in table 5-8.
- Other locations are listed in Appendix F and include:
    - Boreholes drilled at or in close proximity to Government Irrigation Schemes/Projects. These are located in the areas namely, Ndonga Linena, Shadikongoro, Shitemo, Mashare, Musese, Uvhungu Vhungu Farm, Sikondo, and Andara
    - Rural Water Supply boreholes with inferior groundwater quality

Table 5-8: Additional boreholes selected for the groundwater quality monitoring network in the KE and KW

Borehole No.	Location	Latitude	Longitude	Water Quality Classification	Remarks
WW35053	Yinsu Clinic NW	-17.80018	18.56750	C	High fluoride (2.1 mg/l)
WW205492	Dingandu NE	-18.08193	21.41687	C	Turbidity
WW205486	Ngandaro	-18.00684	20.47869	D	Turbidity
WW205479	Lirarambi	-18.22144	20.01406	D	Turbidity
WW205483	Ndonga Linena	-17.94988	20.45857	C	Nitrate
WW205509	Namkupa	-17.85778	18.68000	D	Elevated sulphate, sodium chloride, TDS
WW205504	Ngandu	-17.70759	18.28489	D	Elevated fluoride
WW205510	Mafugu	-17.83656	18.59810	D	High sodium and Mn (1.2 mg/l)
WW205508	Mahahe	-17.91756	18.64023	B	Elevated Mn (19.7)
WW205512	Saìnca	-17.9725	19.15484	A	Elevated Mn (1.4 mg/l)
River Samples: Nkurenkuru, Rundu, Poppa Falls, Omega, Divundu					

All locations earmarked for groundwater sampling are highlighted in the map below (Figure 5-43).

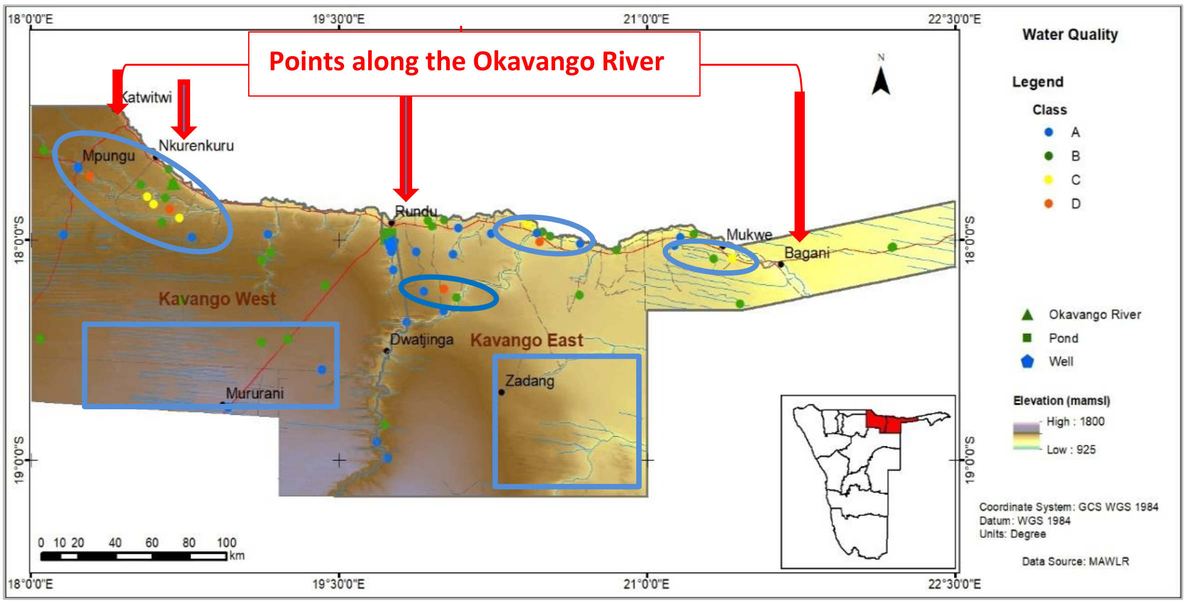


Figure 5-43: Locations selected for groundwater quality monitoring

Data storage, management, and Dissemination to Stakeholders

All the data collected is to be stored on the national database GROWAS II. Quantitative and qualitative groundwater data analysis and evaluation are to be carried out by Area Hydrogeologists at the

Geohydrology Division of the DWA. The Division submits an Annual Groundwater Status Report which would capture the information from groundwater monitoring. This report is made available to all relevant stakeholders. Additionally, through the recent Hydrogeological Map of Namibia Project, the public is able to access real-time groundwater level and water quality data via the newly developed NA-MIS Web-based Application (MAWLR, 2021).

The monitoring network is designed to be permanent in order to provide long-term data and increase the availability of data. An integrated groundwater data assessment approach that incorporates groundwater data, climatic data, surface water data, and essentially socio-economic aspects is encouraged. Data sharing on regional platforms such as the SADC-GMI Groundwater Information Portal (GIP) would ensure informed decision-making at the highest level.

A comprehensive approach to groundwater data collection and monitoring in this way would ensure effective management and protection of both groundwater and surface water and their dependent ecosystems (Mediterranean Groundwater Working Group, 2007). As information needs to change over time, the monitoring system should be agile enough to be adjusted to new data collection methodologies.

Other Important Factors to Consider (IGRAC, 2008):

- Long-term planning and the commitment of staff (capacity) and budget by MAWLR. Calculation of investments and annual costs involved in the monitoring programme should be set up. These are not covered in this study.
- Ascertain secure access to observation points in the long term and the functionality of data loggers to prevent data gaps.
- Analyse the feasibility of the designed network for long term implementation (IGRAC, 2008).

6 CONCLUSION & RECOMMENDATIONS

6.1 CONCLUSION

Groundwater quality studies offer significant benefits to the sustainable management of groundwater resources. Groundwater in the Primary Kalahari Aquifers is classified as suitable for human consumption with mainly excellent quality groundwater (Group A), except in a few discrete localities where it is classified as Group D. The D parameters are turbidity, fluoride, sodium, sulphate, and conductivity. Groundwater in the larger parts of the KE and KW is suitable for irrigation purposes, with the exception of groundwater in the areas of Namkupa, Ndombe za Matala and Mafugu in the KW where irrigation would be restricted-unsuitable.

The study found that the major hydrochemical facies for the Primary Kalahari Aquifers are predominantly Ca-Mg-HCO_3 water type > Na-HCO_3 > Ca-Na-HCO_3 > Na-SO_4-Cl > Na-Cl. Na-HCO_3^- water type is demonstrative of dynamic coordinated flow in the aquifers. Ca-Mg-HCO_3^- water type is indicative but not limited to recently recharged groundwaters occurring across the study area as well as along the Omuramba Omatako. Groundwater-rock interactions mainly control the study areas' groundwater composition via processes of ion exchange and dissolution of carbonates, principally.

Groundwater isotope analyses in the KE and KW plot on and just below the LMWL, indicating minor evaporation signature. Both $\delta^{18}O$ and $\delta^{2}H$ become progressively depleted in groundwater as elevation increases from north-east KE to south-west KW. Along the Okavango River, both parameters are less depleted due to lower elevations but also highly variable from east to west. The local rainfall is isotopically distinct from groundwater. Isotope analyses of groundwater at Kandjimi Murangi just east of Nkurenkuru has a similar signature to the Okavango River, demonstrating an interaction between the aquifers and the river. Tritium results show that there is a hydraulic link between groundwater and the Okavango River. A primary groundwater monitoring network for quantity and quality was designed, highlighting clearly the objectives for monitoring, preliminary data required, locations for monitoring, and data required within the study area. The network is aimed to provide information about the quality and quantity of the Kalahari aquifer groundwater system on a permanent basis. This study has added to geochemistry knowledge and is one of the very first few isotope studies conducted in the two regions.

6.2 RECOMMENDATIONS

Groundwater in the Kavango East and West Regions and the rest of Namibia is a vital livelihood resource for both social and economic development. It is so essential, that the rural communities making up the vast majority of these regions are supplied with groundwater from the Kalahari aquifers. There is no evidence of degradation in groundwater quality. However, with the envisaged upsurge of irrigation/horticulture including the CRAVE Project with an estimated land use of 302.25 hectares, and approximately 4.9 Mm^3/a of surface water and groundwater; it may affect groundwater and surface water quality. The effects of climate change resulting in erratic precipitation and prolonged drought periods have negative impacts on groundwater recharge. Additionally, with a future increase in groundwater abstraction, the complete reconstitution of groundwater abstracted by human activities may not take place. For this reason, more studies should be undertaken to understand 1) the impact of climate change and variability on the resources, 2) the origin of groundwater by means of widespread isotopic studies, 3) lithology logging of the boreholes drilled in the past 5-10 years to a ascertain the geology of the area, 4) recharge estimates and hydraulic parameters of the aquifer and 5) anthropogenic factors. To achieve number 3 above, core drilling one or two boreholes that can be analysed in a laboratory can yield accurate data on the stratigraphy of aquifers and aquitards in the area. A similar study was conducted for the Ohangwena Aquifer System in the Cuvelai Etosha Basin.

Further recommendations include:

- To conduct a detailed tritium sampling campaign over the study area in order to distinguish the various age zones within the modern water segments of groundwater flow systems in the Kalahari groundwater system. Precipitation sampling of tritium is recommended.
- To conduct more isotopic studies and geochemical sampling (by monitoring) along the Okavango River in order to find the link/not between the schemes and associated high TDS levels.
- To conduct a sampling campaign for the analyses of ^{14}C and $^{13}C/^{12}C$, which is useful in determining carbonate solution in groundwater and its effect on carbon-14 in groundwater.
- To conduct a precipitation sampling campaign that is representative of the catchment, and take into consideration elevations and temperature values.
- Assess groundwater flow directions based on land survey and analyse hydrochemical data along groundwater pathways.

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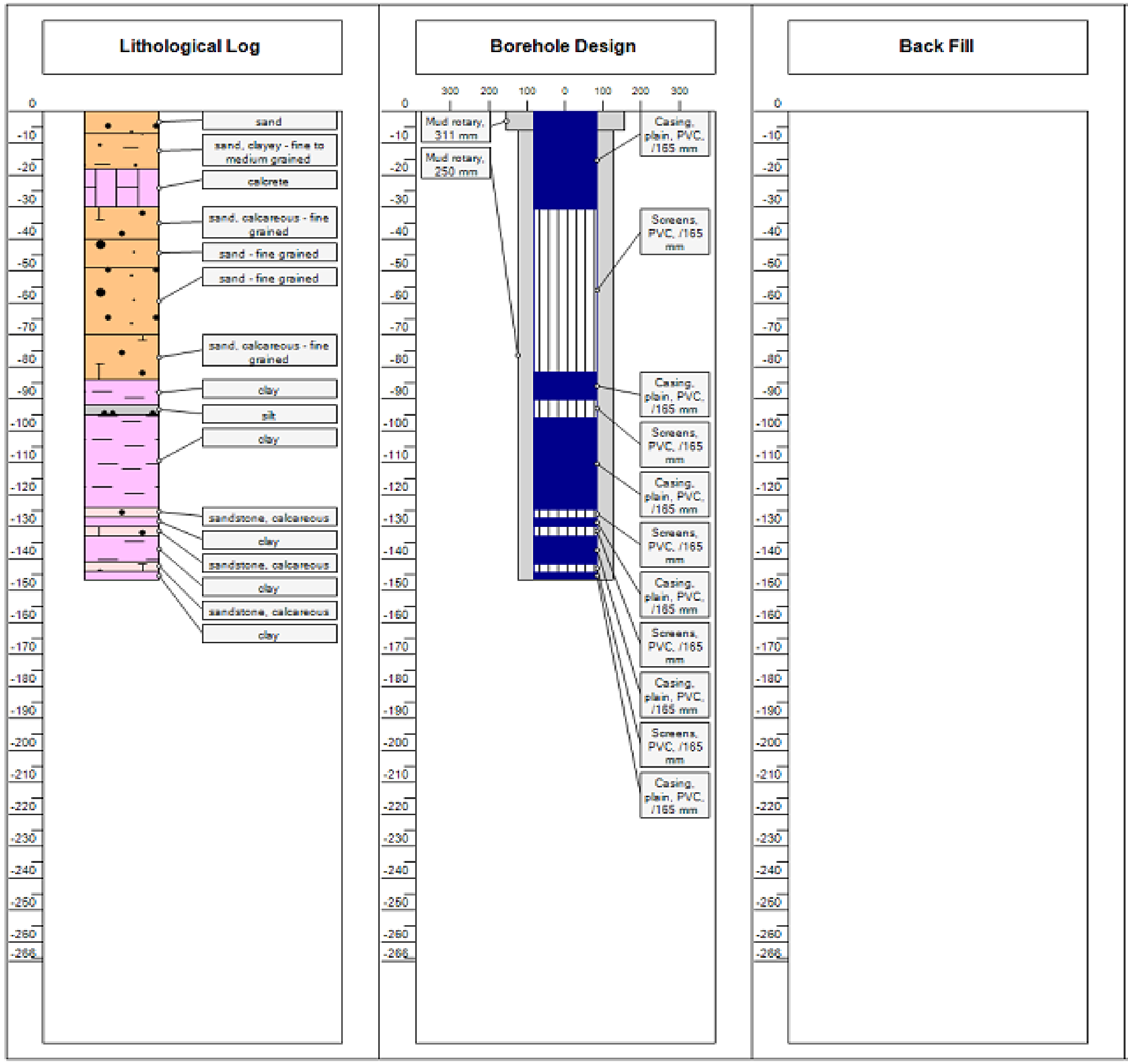
BOREHOLE LITHOLOGY AND CONSTRUCTION LOG

APPENDIX A



Database Information

Id	WW205029
Old name	
Old well number	
Local name	Sharukwe
Longitude	19.7574
Latitude	-18.0513
Coordinate method	Handheld GPS
Elevation	
Elevation method	
Data reliability	checked in field
Region	Kavango
Constituency	
Location	Sharukwe
Basin	KAVANGO-OMATAKO BASIN
Hydrogeological region	Okavango-Epukiro
Catchment area	Okavango - Omatako
Water management area	
Toposheet50	1819BB
Toposheet250	1819
Project	Drought Relief Management p
Administrated by	DWAF
Waterpoint number	
Point usage	
Drilling company	Super Drilling CC
Drilling start date	26.01.2018 11:41:00 AM
Drilling end date	29.01.2018 11:42:00 AM
Total depth	146
Installation depth	110
Artesian condition	
Geological group	
Initial rest water level	4.5
Initial yield	12
Yield accuracy	Estimated by pumping
Initial ec	
Initial ph	
Initial temperature	
Initial redox potential	
Initial oxygen	
Initial alkalinity	
Apparent water quality	Fresh
Specific capacity	
Water source	Borehole
Collar height msl	
Collar height	0.5
Borehole status	drilled
Project supervisor	DWA - Department of Water A
Owner	
Aquifer	
Supply scheme	

SAMPLING SHEET

Sample Number					
WW no. 28595	Kahenge	**Topo-sheet Well no**		**Sample no**	JINNAM1
Description of sampling point (e.g. well/reservoir, pump installed)	Kahenge NamWater Water Supply Scheme, installed borehole	**Latitude**	-17.6768	**Longitude**	18.6738

Time/weather conditions of sampling			
Date Sampled	**Time sampled**	**Weather at day of sampling**	**Remarks**
23/03/2020	12.30	Partly cloudy and sunny	Sampled successfully

Conditions of water level/pumps				
Rest water level (m.b.c)	**Depth pump/airlift (m.b.c)**	**Depth packer (m.b.c)**	**Pumping time (h)**	**Yield (m^3/h)**
11.21	N/A	N/A	N/A	N/A

Sampling				
Sample carrier	**Sampling procedure**	**Sample preparation**	**Sample storage**	**Analysis for samples**
1 litre polyethelene bottle 1 50 ml glass bottle	Pumped from borehole and sampled from a tap directly at the borehole	standard	In cooler box with cooling packs	Hydrochemistry Stable isotopes(oxygen-18 and deuterium)

Onsite parameters					
Smell	**Colour**	**Temp. (°C)**	**pH**	**TDS (mg/l)**	**DO**
None	Clear	26.6	8.16		6.29

EC (µS/cm)		**Remarks on the onsite determinants**
5 min after pump start	**10 min. after pump start**	EC probe error in stabilizing; we could not determine TDS and EC. DO determined although the probe stated ‘zero days remaining’ on meter screen. To compare DO with the lab result.
N/A	N/A	

C1: HYDROCHEMISTRY RESULTS IN MEQ/L AND CBE FOR: JINNAM1-DWSSC9

APPENDIX C

BH ID	Sample ID	Sample ID NamWater	Location	Longitude	Latitude	TDS calculated mg/l	Total hardness as $CaCO_3$	Anions							Cations						Sum anions (meq/l)	Sum cations (meq/l)	Ionic Balance (%)
								SO_4^{2-} (meq/l)	NO^-_3 (meq/l)	NO^-_2 (meq/l)	F^- (meq/l)	Cl^- (meq/l)	CO_3^{2-} (meq/l)	HCO_3^- (meq/l)	Na^+ (meq/l)	K^+ (Meq/l)	Ca^{2+} (meq/l)	Mg^{2+} (meq/l)	Fe^{2+} (meq/l)	Mn^{2+} (meq/l)			
WW28595	JINNAM1	DS56071	Kahenge	18.67380	-17.67680	225	142.00	0.04	0.01	0.00	0.01	0.03	0.00	3.28	0.39	0.05	2.00	0.82	0.00	0.01	3.36	3.27	-1.35
WW25540	JINNAM2	DS56072	Sambiu	20.01390	-17.90710	1441	7.00	4.58	0.01	0.00	0.10	3.53	0.52	7.00	15.66	0.08	0.05	0.08	0.00	0.00	15.74	15.87	0.42
WW31944	JINNAM3	DS56073	Nyangana	20.67540	-18.01510	350	157.00	0.08	0.01	0.00	0.02	0.03	0.00	5.04	1.78	0.10	1.80	1.32	0.00	0.00	5.18	5.00	-1.71
WW35053	JINBH1	DS56074	Yinsu Clinic	18.56750	-17.80018	1256	7.00	0.73	0.01	0.00	0.11	1.83	2.01	8.55	15.22	0.08	0.05	0.08	0.00	0.00	13.24	15.43	7.65
WW37339	JINBH2	DS56075	Mukekete	18.06740	-17.58948	723	68.00	0.21	0.01	0.00	0.03	0.17	0.00	10.20	8.48	0.38	0.60	0.74	0.00	0.00	10.61	10.21	-1.95
WW41274	JINBH3	DS56076	Bravo	18.04867	-18.44797	823	193.00	0.33	0.04	0.00	0.07	1.83	0.00	9.24	6.96	0.33	1.60	2.22	0.00	0.00	11.52	11.11	-1.79
WW3835	JINBH4	DS56077	Mpungu	18.23225	-17.67326	344	97.00	0.04	0.01	0.00	0.03	0.03	0.00	4.60	2.31	0.28	0.85	1.07	0.00	0.00	4.71	4.51	-2.22
WW205029	JINBH5	DS56078	Sharukwe Clinic	19.75740	-18.05130	257	128.00	0.12	0.01	0.00	0.02	0.03	0.00	3.44	0.87	0.08	2.05	0.49	0.00	0.00	3.62	3.49	-1.84
WW35054	JINBH6	DS56079	Ncuncuni	19.76682	-18.13428	247	148.00	0.02	0.01	0.00	0.01	0.03	0.00	3.40	0.35	0.05	2.69	0.25	0.00	0.00	3.47	3.34	-1.85
WW7912	JINBH7	DS56080	Ncaute	19.83067	-18.37084	284	157.00	0.02	0.01	0.00	0.01	0.03	0.00	3.84	0.52	0.10	2.30	0.82	0.00	0.00	3.90	3.74	-2.10
WW33868	JINBH8	DS56081	Klein Karakuwisa	19.72279	-18.84035	483	32.00	0.23	0.03	0.00	0.04	0.42	0.00	5.68	5.48	0.13	0.30	0.33	0.00	0.00	6.40	6.24	-1.30
WW35534	JINBH9	DS56082	Satoka	19.68625	-18.91755	298	152.00	0.02	0.01	0.00	0.01	0.03	0.00	4.08	0.78	0.18	2.20	0.82	0.00	0.00	4.14	3.98	-2.00
WW39967	JINBH10	DS56083	Zadang	19.73580	-18.99097	439	206.00	0.04	0.01	0.00	0.01	0.48	0.00	5.20	1.30	0.18	3.19	0.91	0.00	0.00	5.74	5.58	-1.34
WW34811	AK8	DS56087	Omega	22.19917	-18.02855	1353	258.00	3.33	0.02	0.00	0.03	4.23	0.00	11.12	12.61	0.23	2.00	3.13	0.00	0.00	18.74	17.97	-2.09
WW40567	AK4	DS56088	Tcalikawa	18.73762	-18.27320	406	146.00	0.02	0.01	0.00	0.01	0.68	0.09	4.87	2.35	0.18	1.75	1.15	0.00	0.00	5.67	5.43	-2.20
WW40571	AK2	DS56089	Desi	18.78484	-17.98756	585	204.00	0.06	0.01	0.00	0.02	0.20	0.00	7.64	3.04	0.46	1.75	2.30	0.00	0.00	7.93	7.56	-2.41
WW204140	AK20	DS56090	Shinunga Toring	19.12800	-18.08860	1454	67.00	4.79	0.05	0.00	0.03	6.21	0.00	6.88	15.66	0.23	0.75	0.58	0.00	0.00	17.96	17.21	-2.11
WW204253	AK7	DS56091	Rupetho	20.05700	-18.06440	339	192.00	0.04	0.01	0.00	0.01	0.03	0.00	4.80	0.83	0.08	2.25	1.56	0.00	0.00	4.89	4.71	-1.84
WW204138	AK21	DS56092	Tcausha	18.23060	-17.66450	358	85.00	0.52	0.01	0.00	0.03	0.23	0.00	4.40	3.26	0.05	0.95	0.74	0.00	0.00	5.18	5.00	-1.75
Okavango Ri	JINRV1	DS56084	Kandjimi Murangi	18.69466	-17.73780	30	14.00	0.02	0.01	0.00	0.01	0.03	0.00	0.40	0.17	0.03	0.20	0.08	0.01	0.00	0.46	0.49	2.79
Pond	JINP1	DS56085	Mavandje	19.74059	-17.98063	578	213.00	0.04	0.01	0.00	0.08	0.28	0.00	8.24	3.48	0.56	1.50	2.72	0.00	0.00	8.66	8.26	-2.37
Well	JINW1	DS56086	Mavandje	19.75395	-18.00770	455	239.00	0.29	0.15	0.00	0.04	0.03	0.00	4.64	0.35	0.31	4.19	0.58	0.00	0.00	5.15	5.42	2.59
WW205492	DWSSC1	AnaLab	Dingando	21.41687	-18.08193	292	264.00	0.04	0.01	0.00	0.01	0.06	0.00	5.88	0.40	0.14	3.79	1.48	0.00	0.00	5.99	5.82	-1.43
WW205493	DWSSC2	AnaLab	Shamagumbo	21.45333	-18.28850	225	216.00	0.06	0.02	0.00	0.02	0.11	0.00	4.30	0.24	0.03	3.24	1.07	0.01	0.00	4.51	4.59	0.92
WW205491	DWSSC3	AnaLab	Muthindiko	21.32676	-18.08403	163	153.00	0.02	0.01	0.00	0.01	0.08	0.00	3.26	0.22	0.04	1.90	1.15	0.00	0.00	3.38	3.31	-1.05
WW205490	DWSSC4	AnaLab	Nayara	21.22730	-17.97158	293	254.00	0.06	0.01	0.00	0.01	0.17	0.00	5.98	0.61	0.07	2.94	2.14	0.00	0.00	6.23	5.77	-3.77
WW205489	DWSSC5	AnaLab	Sharuhenga	21.13369	-18.02338	213	206.00	0.02	0.01	0.00	0.01	0.06	0.00	4.42	0.11	0.05	2.79	1.32	0.00	0.00	4.51	4.27	-2.77
WW205488	DWSSC6	AnaLab	Makena	20.85101	-18.04393	214	93.00	0.25	0.01	0.00	0.01	0.17	0.00	3.68	2.09	0.07	1.30	0.57	0.01	0.00	4.12	4.03	-1.02
WW205487	DWSSC7	AnaLab	Gcorodani	20.67258	-18.24781	364	103.00	0.44	0.01	0.00	0.06	0.37	0.00	6.20	4.57	0.09	0.90	1.15	0.00	0.00	7.07	6.71	-2.57
WW205486	DWSSC8	AnaLab	Ngandaro	20.47869	-18.00684	629	4.00	2.29	0.02	0.00	0.04	1.61	0.24	6.55	10.83	0.04	0.05	0.03	0.02	0.00	10.75	10.98	1.04
WW205485	DWSSC9	AnaLab	Shitemo	20.52944	-17.97998	119	103.00	0.02	0.01	0.00	0.01	0.31	0.00	2.20	0.20	0.06	1.30	0.77	0.09	0.01	2.55	2.42	-2.55

C2: DWSSC10-DWSSC41

BH ID	Sample ID	Sample ID NamWater	Location	Longitude	Latitude	TDS calculated mg/l	Total hardness as CaCO3	Anions							Cations						Sum anions (meq/l)	Sum cations (meq/l)	Ionic Balance (%)
								SO_4^{2-} (meq/l)	NO^-_3 (meq/l)	NO^-_2 (meq/l)	F^- (meq/l)	Cl^- (meq/l)	CO_3^{2-} (meq/l)	HCO_3^- (meq/l)	Na^+ (meq/l)	K^+ (meq/l)	Ca^{2+} (meq/l)	Mg^{2+} (meq/l)	Fe^{2+} (meq/l)	Mn^{2+} (meq/l)			
WW205484	DWSSC10	AnaLab	Mbarena	20.49414	-17.96048	384	230.00	0.12	0.27	0.00	0.02	0.62	0.00	4.90	2.39	0.05	2.54	2.06	**0.00**	0.0004	5.93	7.05	8.58
WW205477	DWSSC11	AnaLab	Dausima	20.24166	-17.96892	212	146.00	0.04	0.01	0.00	0.01	0.20	0.00	3.64	0.87	0.07	1.60	1.32	**0.00**	**0.00**	3.89	3.85	-0.53
WW205474	DWSSC12	AnaLab	Draai ya Kamuncaya	19.93398	-17.90869	994	10.00	4.00	0.01	0.00	0.08	2.88	0.00	8.48	16.83	0.06	0.10	0.10	0.00	0.00	15.45	17.10	5.08
WW205476	DWSSC13	AnaLab	Tyeye Teya	20.08186	-17.94499	250	150.00	0.21	0.01	0.00	0.02	0.23	0.00	3.74	1.52	0.06	1.60	1.40	0.00	0.00	4.20	4.58	4.40
WW205479	DWSSC14	AnaLab	Lirarambi	20.01406	-18.22144	659	247.00	0.02	0.01	0.00	0.03	0.34	0.00	11.44	5.44	0.74	2.05	2.88	0.01	0.00	11.84	11.11	-3.15
WW205480	DWSSC15	AnaLab	Mutwekombahe	20.01080	-18.32051	320	249.00	0.02	0.01	0.00	0.04	0.08	0.00	5.40	0.37	0.38	2.74	2.22	0.00	0.00	5.55	5.72	1.56
WW205481	DWSSC16	AnaLab	Shakamba 2	20.07414	-18.26012	782	139.00	1.19	0.05	0.00	0.06	2.31	0.00	9.80	10.48	0.21	1.30	1.48	0.00	0.00	13.41	13.48	0.27
WW205478	DWSSC17	AnaLab	Shimpanda no.2	19.87722	-18.05190	306	176.00	0.02	0.01	0.00	0.01	0.08	0.00	5.18	1.83	0.19	1.95	1.56	0.00	0.00	5.31	5.53	2.05
WW205453	DWSSC18	AnaLab	Shighuru	20.41931	-17.92347	616	155.00	0.65	0.14	0.00	0.04	1.04	0.00	9.00	7.96	0.14	1.45	1.65	0.01	0.01	10.87	11.20	1.47
WW205483	DWSSC19	AnaLab	Ndonga Linena	20.45857	-17.94988	591	373.00	0.02	0.40	0.00	0.01	1.89	0.00	7.00	3.39	0.12	3.59	3.87	0.00	0.00	9.32	10.98	8.14
WW205475	DWSSC20	AnaLab	Kambowo Teya	19.95461	-17.93542	502	93.00	1.60	0.01	0.00	0.05	0.82	0.00	6.06	6.87	0.08	1.30	0.55	0.00	0.00	8.54	8.80	1.54
WW205598	DWSSC21	AnaLab	Omega	22.19100	-18.03194	1471	460.00	7.20	0.03	0.01	0.03	8.04	0.00	11.00	16.79	0.28	3.34	5.84	0.00	0.00	26.30	26.26	-0.09
WW205502	DWSSC22	DS55941	Heha	18.15953	-17.97457	291.8	38.00	0.02	0.01	0.00	0.01	0.03	0.00	5.10	3.48	0.18	0.75	0.58	0.00	0.00	5.16	4.98	-1.78
WW205503	DWSSC23	DS55942	Kavango village	18.12988	17.89947	1905.6	14.00	2.60	0.01	0.00	0.53	2.68	2.37	25.38	35.23	0.13	0.20	0.08	0.02	0.00	33.58	35.66	3.01
WW205504	DWSSC24	DS55943	Ngandu	18.28489	-17.70759	1995.9	9.00	5.21	0.01	0.00	0.27	9.59	1.89	16.03	36.10	0.20	0.10	0.08	0.00	0.00	32.99	36.49	5.04
WW205505	DWSSC25	DS55944	Dikweya	18.53584	-17.74687	234.6	83.00	0.08	0.01	0.00	0.01	0.03	0.00	3.68	2.00	0.10	0.90	0.74	0.03	0.00	3.81	3.78	-0.48
WW205506	DWSSC26	DS55945	Nsivi	18.65596	-17.80690	229	12.00	0.10	0.01	0.00	0.02	0.03	0.07	3.61	3.44	0.08	0.15	0.08	0.01	0.00	3.84	3.75	-1.12
WW205507	DWSSC27	DS55946	Ndombe Za Matala	18.72405	-17.89786	1289.7	165.00	4.37	0.01	0.00	0.03	8.18	0.00	8.60	18.70	0.26	1.55	1.73	0.00	0.00	21.19	22.24	2.42
WW205508	DWSSC28	DS55947	Mahahe	18.64023	-17.91756	871	80.00	1.46	0.01	0.00	0.01	8.46	0.00	5.12	11.31	0.23	1.60	1.40	0.00	0.00	15.06	14.54	-1.77
WW205509	DWSSC29	DS55948	Namkupa	18.68000	-17.85778	5828	151.00	43.31	0.08	0.00	0.09	40.62	0.00	6.72	87.00	0.41	1.35	1.65	0.00	0.00	90.82	90.40	-0.23
WW205510	DWSSC30	DS55949	Mafugu	18.59810	-17.83656	1472.1	10.00	5.62	0.01	0.00	0.11	9.59	0.34	9.24	23.49	0.15	0.20	0.08	0.00	0.00	24.92	23.92	-2.03
WW205511	DWSSC31	DS55950	Gcana	19.16955	-18.05451	286.9	173.00	0.08	0.01	0.00	0.01	0.14	0.00	4.32	1.26	0.13	1.45	1.97	0.00	0.00	4.56	4.82	2.74
WW205512	DWSSC32	DS55951	Sainca	19.15484	-17.97250	263.3	80.00	0.02	0.01	0.00	0.03	0.03	0.00	3.92	0.65	0.15	1.60	1.73	0.00	0.05	4.00	4.18	2.19
WW205513	DWSSC33	DS55952	Masiro	19.26802	17.88131	279	208.00	0.02	0.01	0.00	0.01	0.06	0.00	4.76	0.57	0.13	2.99	1.15	0.00	0.00	4.85	4.84	-0.12
WW205514	DWSSC34	DS56178	Gcigcau	19.43606	-18.20585	132.3	90.00	0.02	0.01	0.00	0.01	0.03	0.00	2.00	0.26	0.10	0.80	0.99	0.01	0.00	2.07	2.15	2.06
WW205515	DWSSC35	DS56179	Mauguva	19.25213	-18.44941	205	60.00	0.02	0.01	0.00	0.02	0.03	0.09	3.11	1.70	0.46	0.45	0.74	0.01	0.00	3.28	3.35	1.14
WW205516	DWSSC36	DS56180	Eharo	19.12310	-18.46381	519.4	63.00	0.10	0.01	0.00	0.02	0.73	0.00	8.60	7.83	0.51	0.35	0.91	0.00	0.00	9.47	9.60	0.67
WW205470	DWSSC37	DS55846	Likorera	19.41779	-18.58831	314	178.00	0.10	0.02	0.00	0.03	0.11	0.00	4.56	1.00	0.13	2.40	1.15	0.00	0.00	4.83	4.68	-1.60
WW205469	DWSSC38	DS55845	Mururani	18.96216	-18.75947	525	268.00	0.21	0.03	0.00	0.03	0.25	0.00	8.48	2.65	0.72	2.35	2.96	0.00	0.00	9.00	8.68	-1.80
WW205468	DWSSC39	DS55844	Mpuma	18.23167	-19.91961	269	202.00	0.02	0.02	0.00	0.01	0.03	0.00	4.12	0.30	0.08	3.19	0.82	0.00	0.00	4.20	4.40	2.35
WW205466	DWSSC40	DS55843	Kangono Teya	21.09847	-17.59208	237	178.00	0.08	0.02	0.00	0.01	0.03	0.00	3.44	0.09	0.03	2.54	0.99	0.00	0.00	3.58	3.65	0.88
WW205465	DWSSC41	DS55842	Ndonga Linena	20.46317	-17.96621	347	243.00	0.08	0.05	0.00	0.02	0.06	0.00	4.88	0.43	0.08	2.69	2.14	0.00	0.00	5.09	5.35	2.43

STABLE ISOTOPES RESULTS **APPENDIX D**

BH ID	Sample ID	Location	s.d	$\delta^{18}O$ (‰)	s.d	$\delta^{2}H$‰	$\delta^{18}O$ (‰) (GMWL)	Water Type	Sampling Date	Date Sample Received at Lab	Date Sample Analysed
WW28595	JINNAM1	Kahenge	0.06	-8.2	0.28	-59.6	-1	Ca-Mg-HCO3	23/03/2020	22/06/2020	24/06/2020
WW25540	JINNAM2	Sambiu	0.15	-9.0	1.29	-65.3	-2	Na+SO4+Cl	23/03/3020	22/06/2020	24/06/2020
WW31944	JINNAM3	Nyangana	0.10	-8.7	0.30	-65.6	-3	Ca-Mg-HCO3	23/03/2020	22/06/2020	24/06/2020
WW35053	JINBH1	Yinsu Clinic	0.10	-9.3	0.15	-68.1	-4	Na-HCO3	24/03/2020	22/06/2020	24/06/2020
WW37339	JINBH2	Mukekete	0.18	-9.3	1.14	-65.8	-5	Na-HCO3	24/03/2020	22/06/2020	24/06/2020
WW41274	JINBH3	Bravo	0.39	-9.3	1.43	-67.6	-6	Ca-Na-HCO3	24/03/2020	22/06/2020	24/06/2020
WW3835	JINBH4	Mpungu	0.17	-9.3	0.72	-67.0	-7	Na-Ca-HC03	24/03/2020	22/06/2020	24/06/2020
WW205029	JINBH5	Sharukwe Clinic	0.06	-9.0	0.51	-64.9	-8	Ca-Mg-HCO3	25/03/2020	22/06/2020	24/06/2020
WW35054	JINBH6	Ncuncuni	0.04	-9.3	0.87	-66.9	-9	Ca-Mg-HCO3	25/03/2020	22/06/2020	24/06/2020
WW7912	JINBH7	Ncaute	0.14	-8.9	0.99	-64.1	-10	Ca-Mg-HCO3	25/03/2020	22/06/2020	24/06/2020
WW33868	JINBH8	Klein Karakuwisa	0.12	-9.0	0.61	-64.4	-11	Na-HCO3	25/03/2020	22/06/2020	25/06/2020
WW35534	JINBH9	Satoka	0.07	-9.1	0.33	-66.1	-12	Ca-Mg-HCO3	25/03/2020	22/06/2020	25/06/2020
WW39967	JINBH10	Zadang	0.08	-9.2	0.65	-65.0	-13	Ca-Mg-HCO3	25/03/2020	22/06/2020	25/06/2020
Duplicate	JINBH11	MAWLR	0.08	-6.7	0.40	-51.2	-14	Duplicate	22/06/2020	22/06/2020	25/06/2020
Duplicate	JINBH12	MAWLR	0.14	-6.7	0.51	-51.7	-15	Duplicate	23/06/2020	22/06/2020	25/06/2020
Rain	JINR1	Ndonga Linena	0.12	-4.5	1.02	-26.7	-16	Rain	16/03/2020	22/06/2020	25/06/2020
Rain	JINR2	Mashare	0.16	-4.6	0.64	-27.6	-17	Rain	16/03/2020	22/06/2020	25/06/2020
Rain	JINR3	Rundu	0.09	-3.4	0.70	-22.5	-18	Rain	16/03/2020	22/06/2020	25/06/2020
Rain	JINR4	Rundu Guesthouse	0.07	-13.4	1.38	-94.2	-19	Rain	24/03/2020	22/06/2020	25/06/2020
Well	JINW1	Mavandje	0.17	-6.7	0.50	-52.0	-20	Well	25/03/2020	22/06/2020	25/06/2020
Pond	JINP1	Mavandje	0.07	0.7	0.20	-19.9	-21	Pond	26/03/2020	23/06/2020	26/06/2020
WW34811	AKS8	Omega	0.12	-8.5	1.30	-60.6	-22	Na-Ca-HC03	14/03/2020	22/06/2020	26/06/2020
WW40567	AKS4	Tcalikawa	0.14	-9.4	1.00	-66.4	-23	Na-Ca-HC03	11/03/2020	22/06/2020	26/06/2020
WW40571	AKS2	Desi	0.12	-9.5	0.30	-67.9	-24	Na-Ca-HC03	11/03/2020	22/06/2020	26/06/2020
WW204140	AKS20	Shinunga Toring	0.10	-9.6	0.90	-66.6	-25	Na+SO4+Cl	18/03/2020	22/06/2020	26/06/2020
WW204253	AKS7	Rupetho	0.16	-8.4	0.90	-60.6	-26	Ca-Mg-HCO3	13/03/2020	22/06/2020	26/06/2020
WW204138	AKS21	Tcausha	0.13	-9.2	1.70	-65.8	-27	NA-HCO3	18/03/2020	22/06/2020	26/06/2020
River	AKS30	Nkurenkuru River	0.10	-9.0	0.40	-63.4	-28	River	16/03/2020	22/06/2020	26/06/2020
River	AKS29	Kalai Bridge (Kaisosi)	0.08	-6.8	0.40	-44.5	-29	River	18/03/2020	22/06/2020	26/06/2020
River	JINRV1	Kandjimi Murangi	0.06	-6.8	0.40	-43.0	-30	River	23/03/2020	22/06/2020	26/06/2020

SCHOELLER INDICES **APPENDIX E**

BH ID	Sample ID	Sample ID NamWater	Location	Na^+ (meq/l)	K^+ (Meq/l)	Cl^- (meq/l)	SO_4^{2-} (Meq/l)	NO^-_3 (meq/l)	HCO_3^- (meq/l)	CO^{2-}_3 (meq/l)	CAI-I	CAI-II
WW28595	JINNAM1	DS56071	Kahenge	0.39	0.05	0.03	0.04	0.01	3.28	0.00	-15.66	-0.10
WW25540	JINNAM2	DS56072	Sambiu	15.66	0.08	3.53	4.58	0.01	7.00	0.52	-0.94	2.23
WW31944	JINNAM3	DS56073	Nyangana	1.78	0.10	0.03	0.08	0.01	5.04	0.00	-66.82	-0.34
WW35053	JINBH1	DS56074	Yinsu Clinic	15.22	0.08	1.83	0.73	0.01	8.55	2.01	-6.51	0.48
WW37339	JINBH2	DS56075	Mukekete	8.48	0.38	0.17	0.21	0.01	10.20	0.00	-52.21	-0.68
WW41274	JINBH3	DS56076	Bravo	6.96	0.33	1.83	0.33	0.04	9.24	0.00	-2.14	1.07
WW3835	JINBH4	DS56077	Mpungu	2.31	0.28	0.03	0.04	0.01	4.60	0.00	-91.67	-0.53
WW205029	JINBH5	DS56078	Sharukwe Clinic	0.87	0.08	0.03	0.12	0.01	3.44	0.00	-33.53	-0.24
WW35054	JINBH6	DS56079	Ncuncuni	0.35	0.05	0.03	0.02	0.01	3.40	0.00	-14.12	-0.09
WW7912	JINBH7	DS56080	Ncaute	0.52	0.10	0.03	0.02	0.01	3.84	0.00	-22.10	-0.13
WW33868	JINBH8	DS56081	Klein Karakuwisa	5.48	0.13	0.42	0.23	0.03	5.68	0.00	-12.83	-0.52
WW35534	JINBH9	DS56082	Satoka	0.78	0.18	0.03	0.02	0.01	4.08	0.00	-34.07	-0.21
WW39967	JINBH10	DS56083	Zadang	1.30	0.18	0.48	0.04	0.01	5.20	0.00	-2.61	0.20
WW34811	AK8	DS56087	Omega	12.61	0.23	4.23	3.33	0.02	11.12	0.00	1.20	3.34
WW40567	AK4	DS56088	Tcalikawa	2.35	0.18	0.68	0.02	0.01	4.87	0.09	-3.06	0.17
WW40571	AK2	DS56089	Desi	3.04	0.46	0.20	0.06	0.01	7.64	0.00	-17.55	-0.26
WW204140	AK20	DS56090	Shinunga Toring	15.66	0.23	6.21	4.79	0.05	6.88	0.00	3.65	4.85
WW204253	AK7	DS56091	Rupetho	0.83	0.08	0.03	0.04	0.01	4.80	0.00	-31.99	-0.16
WW204138	AK21	DS56092	Tcausha	3.26	0.05	0.23	0.52	0.01	4.40	0.00	-14.46	-0.45
Okavango River	JINRV1	DS56084	Kandjimi Murangi	0.17	0.03	0.03	0.02	0.01	0.40	0.00	-7.05	-0.44
Pond	JINP1	DS56085	Mavandje	3.48	0.56	0.28	0.04	0.01	8.24	0.00	-14.05	-0.21
Well	JINW1	DS56086	Mavandje	0.35	0.31	0.03	0.29	0.15	4.64	0.00	-23.19	-0.10
WW205492	DWSSC1	AnaLab	Dingandu	0.40	0.14	0.06	0.04	0.01	5.88	0.00	-9.58	-0.04
WW205493	DWSSC2	AnaLab	Shamagumbo	0.24	0.03	0.11	0.06	0.02	4.30	0.00	-2.23	0.05
WW205491	DWSSC3	AnaLab	Muthindiko	0.22	0.04	0.08	0.02	0.01	3.26	0.00	-3.02	0.00
WW205490	DWSSC4	AnaLab	Nayara	0.61	0.07	0.17	0.06	0.01	5.98	0.00	-3.87	0.06
WW205489	DWSSC5	AnaLab	Sharuhenga	0.11	0.05	0.06	0.02	0.01	4.42	0.00	-2.69	0.02
WW205488	DWSSC6	AnaLab	Makena	2.09	0.07	0.17	0.25	0.01	3.68	0.00	-12.56	-0.38
WW205487	DWSSC7	AnaLab	Gcorodani	4.57	0.09	0.37	0.44	0.01	6.20	0.00	-12.35	-0.33
WW205486	DWSSC8	AnaLab	Ngandaro	10.83	0.04	1.61	2.29	0.02	6.55	0.24	-5.15	0.41
WW205485	DWSSC9	AnaLab	Shitemo	0.20	0.06	0.31	0.02	0.01	2.20	0.00	-0.52	0.20

WW205484	DWSSC10	AnaLab	Mbarena	2.39	0.05	0.62	0.12	0.27	4.90	0.00	-3.32	0.16
WW205477	DWSSC11	AnaLab	Dausima	0.87	0.07	0.20	0.04	0.01	3.64	0.00	-4.54	-0.06
WW205474	DWSSC12	AnaLab	Draai ya Kamuncaya	16.83	0.06	2.88	4.00	0.01	8.48	0.00	-3.00	1.52
WW205476	DWSSC13	AnaLab	Tyeye Teya	1.52	0.06	0.23	0.21	0.01	3.74	0.00	-6.80	-0.18
WW205479	DWSSC14	AnaLab	Lirarambi	5.44	0.74	0.34	0.02	0.01	11.44	0.00	-17.91	-0.20
WW205480	DWSSC15	AnaLab	Mutwekombahe	0.37	0.38	0.08	0.02	0.01	5.40	0.00	-8.87	-0.05
WW205481	DWSSC16	AnaLab	Shakamba 2	10.48	0.21	2.31	1.19	0.05	9.80	0.00	-2.31	1.34
WW205478	DWSSC17	AnaLab	Shimpanda no.2	1.83	0.19	0.08	0.02	0.01	5.18	0.00	-23.74	-0.30
WW205453	DWSSC18	AnaLab	Shighuru	7.96	0.14	1.04	0.65	0.14	9.00	0.00	-6.71	0.22
WW205483	DWSSC19	AnaLab	Ndonga Linena	3.39	0.12	1.89	0.02	0.40	7.00	0.00	0.03	1.42
WW205475	DWSSC20	AnaLab	Kambowo Teya	6.87	0.08	0.82	1.60	0.01	6.06	0.00	-7.68	-0.09
WW205598	DWSSC21	AnaLab	Omega	16.79	0.28	8.04	7.20	0.03	11.00	0.00	5.92	7.10
WW205502	DWSSC22	DS55941	Heha	3.48	0.18	0.03	0.02	0.01	5.12	0.00	-129.67	-0.68
WW205503	DWSSC23	DS55942	Kavango village	35.23	0.13	2.68	2.60	0.01	25.38	2.37	-10.51	1.52
WW205504	DWSSC24	DS55943	Ngandu	36.10	0.20	9.59	5.21	0.01	16.03	1.89	5.81	8.02
WW205505	DWSSC25	DS55944	Dikweya	2.00	0.10	0.03	0.08	0.01	3.68	0.00	-74.53	-0.53
WW205506	DWSSC26	DS55945	Nsivi	3.44	0.08	0.03	0.10	0.01	3.61	0.07	-124.50	-0.90
WW205507	DWSSC27	DS55946	Ndombe Za Matala	18.70	0.26	8.18	4.37	0.01	8.60	0.00	5.86	6.72
WW205508	DWSSC28	DS55947	Mahahe	11.31	0.23	8.46	1.46	0.01	5.12	0.00	7.10	6.71
WW205509	DWSSC29	DS55948	Namkupa	87.00	0.41	40.62	43.31	0.08	6.72	0.00	38.47	38.88
WW205510	DWSSC30	DS55949	Mafugu	23.49	0.15	9.59	5.62	0.01	9.24	0.34	7.13	8.04
WW205511	DWSSC31	DS55950	Gcana	1.26	0.13	0.14	0.08	0.01	4.32	0.00	-9.71	-0.17
WW205512	DWSSC32	DS55951	Sainca	0.65	0.15	0.03	0.02	0.01	3.92	0.00	-28.54	-0.18
WW205513	DWSSC33	DS55952	Masiro	0.57	0.13	0.06	0.02	0.01	4.76	0.00	-12.23	-0.09
WW205514	DWSSC34	DS56178	Gcigcau	0.26	0.10	0.03	0.02	0.01	2.00	0.00	-12.85	-0.15
WW205515	DWSSC35	DS56179	Mauguva	1.70	0.46	0.03	0.02	0.01	3.11	0.09	-76.43	-0.64
WW205516	DWSSC36	DS56180	Eharo	7.83	0.51	0.73	0.10	0.01	8.60	0.00	-10.64	-0.22
WW205470	DWSSC37	DS55846	Likorera	1.00	0.13	0.11	0.10	0.02	4.56	0.00	-9.89	-0.13
WW205469	DWSSC38	DS55845	Mururani	2.65	0.72	0.25	0.21	0.03	8.48	0.00	-13.02	-0.13
WW205468	DWSSC39	DS55844	Mpuma	0.30	0.08	0.03	0.02	0.02	4.12	0.00	-13.49	-0.06
WW205466	DWSSC40	DS55843	Kangono Teya	0.09	0.03	0.03	0.08	0.02	3.44	0.00	-3.96	0.00
WW205465	DWSSC41	DS55842	Ndonga Linena	0.43	0.08	0.06	0.08	0.05	4.88	0.00	-9.01	-0.05

DATA TO BE CONSOLIDATED AS A FIRST STEP IN SETTING UP A MONITORING NETWORK FOR THE STUDY AREA **APPENDIX F**

Data Category	Static Data	Institution	Task
Geology	▪ Lithology logs ▪ Geological maps (define the geology and groundwater bodies) ▪ Geological controls on groundwater occurrence ▪ Soil types	▪ MAWLR Geohydrology Division and Rural Water Supply ▪ MME	▪ Log the recently drilled boreholes in the KE and KW as part of the Rural Water Supply Drought Campaign. Log chips are stored at MAWLR and MME ▪ Populate GROWAS II with the lithology data ▪ Analyse geological data in order to ***clearly document*** thicknesses of the aquifers, aquitard and aquiclude layers within the study area
Groundwater occurrence and aquifer properties	▪ Groundwater levels & quality data ▪ Pumping test data ▪ Depth to water table ▪ Depths to the top of aquifer, vertical thickness of aquifers ▪ Degree of aquifer confinement ▪ Aquifer cross sections ▪ Porosity, transmissivity, total ▪ Groundwater volume ▪ Documented natural discharge mechanisms ▪ Elevations	▪ MAWLR,GROWASII ▪ Private Consultants ▪ Gravity Recovery and Climate Experiment (GRACE) by National Aeronautics and Space Administration (NASA)	▪ Personnel at the Geohydrology Division to engage consultants to submit available groundwater data from KE and KW ▪ Update GROWAS II with data collected ▪ Access GRACE to obtain groundwater storage data https://grace.jpl.nasa.gov/mission/grace/ ▪ Conduct a topographic survey of the area to determine precisely hydraulic gradient ▪ Determine whether the groundwater system us transboundary in nature vi cross sections

Groundwater use data	▪ Pump installation data ▪ Borehole yields ▪ Total groundwater abstraction volumes/water use inventories ▪ Population registers and forecasts	▪ MAWLR: Department of Rural Water Supply ▪ NAMWATER, Rundu ▪ Namibia Statistics Agency (NSA)	▪ Capture borehole installation data for the newly drilled boreholes on GROWAS II: MAWLR personnel ▪ Obtain groundwater use data from NAMWATER ▪ Obtain population statistics from Namibia Statistics Agency (NSA)
Climate and surface water Data	▪ Climate data (precipitation, temperature, evapotranspiration) ▪ Land use inventories, topography data ▪ River flow gauging data (available at MAWLR & OKAKOM), swamps ▪ Surface water use Baseflow	▪ MAWLR: Hydrology Division ▪ SASSCAL WeatherNet ▪ Bulk water supply surface water use: NAMWATER, Local authorities	▪ Consolidate climatic data from ADC's in the KE and KW and data from the Meteorological Services of Namibia ▪ Obtain recent land use data for the KE and KW from NSA ▪ Contact NAMWATER to submit surface water use data
TEM geophysical investigation and logging	▪ Geophysical logs	▪ MME	▪ Assess availability of geophysical data from MME ▪ Obtain layout of traverses of geophysical surveys
Environmental Data	▪ Solid waste and waste water control	▪ MAWLR: Rundu Office ▪ Nkurenkuru and Rundu Town Councils	▪ Assess how wastewater is collected, treated and solid waste is stored; it may have an effect on shallow groundwater in proximity to the Okavango River.
Socio-economic data	▪ Population data (total & density)	▪ Namibia Statistics Agency	▪ Obtain population data from NSA

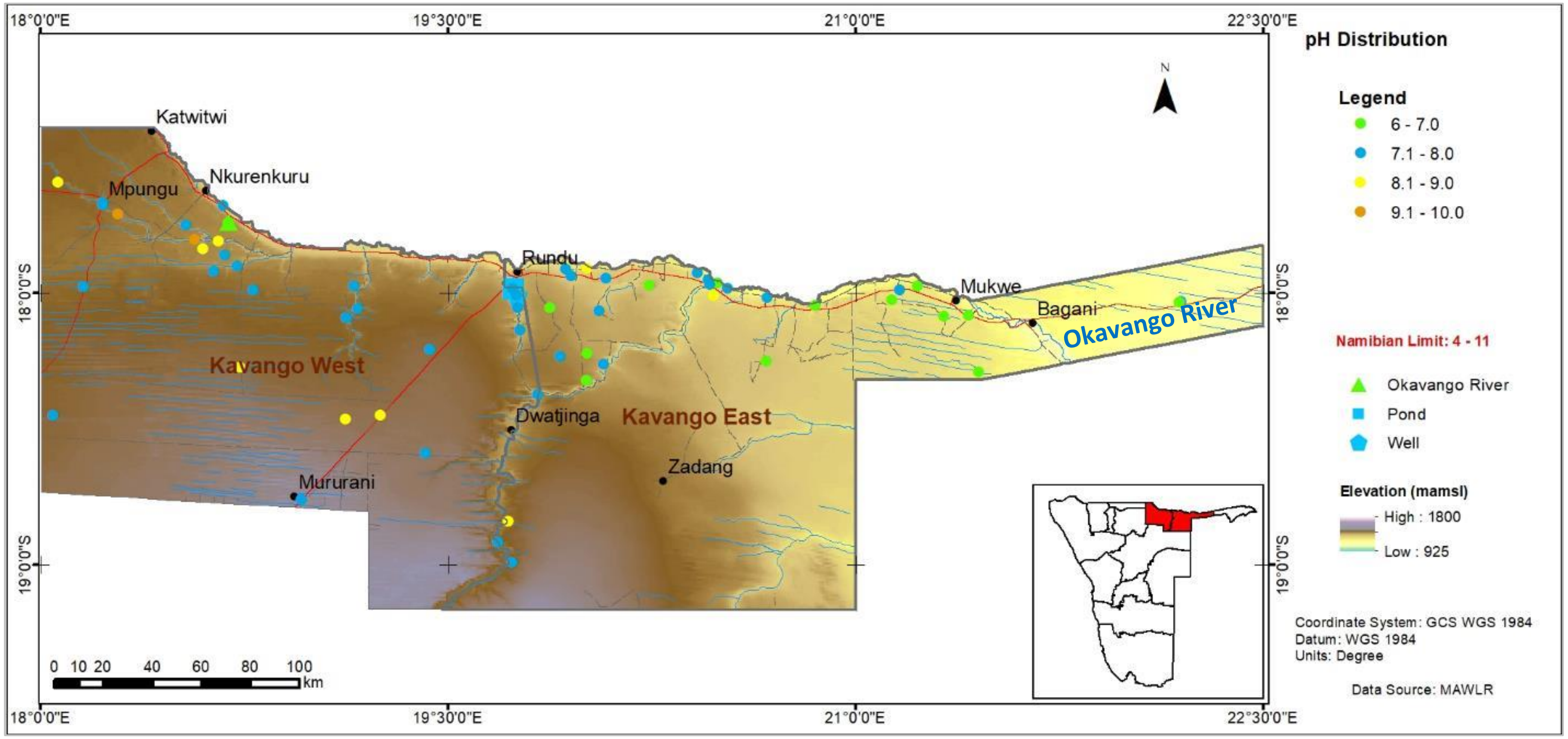
Legal and Institutional Framework	▪ Transboundary legal and institutional framework ▪ Domestic legal and institutional framework	▪ OKAKOM ▪ MAWLR ▪ Local authorities ▪ Angola, Botswana Water Departments	▪ Consolidate information from existing reports, particularly by OKAKOM

Constituency	Location	Aquifer	Latitude	Longitude	Remarks
All operational NAMWATER borehole schemes	Bagani, Buinja, Bukalo, **Kahenge**, **Kandjimi Murangi**, **Katji-na-Katji**, Kavango, **Kayengona**, **Mpungu Vlei**, Mupini, Nkurenkuru, **Mururani**, **Nyangana**, Rupara, **Sambiu**, **Tondoro**, Omega ***bolded schemes are known to be operational**				NAMWATER to provide ***groundwater abstraction volumes, water level data (production & monitoring boreholes) and pump test data.*** Most of the supply schemes are drilled along the Okavango River, except for the schemes at Mururani and Katji-na-Katji (located 40 km north-east of Mururani). Where NAMWATER boreholes are no longer in use, rehabilitate these for the purpose of monitoring.
NAMWATER River Abstraction Schemes:	Ndonga Linena, Ndiyona, Andara, Rundu, Divundu				These are the identified permit holders in the study area, abstracting a total of 60.83 Mm^3 per annum from the Okavango River (DWRM, 2018). Users submit abstraction returns to DWA. Abstraction should be measured by water meters.
Private Projects:	Mupapama village, Sikondo,Uvhungu-vhungu, Shipapo Wambangandu Investment CC, Ndiyona Mills CC, Tunguva Village				
Rainfall Stations	**ADC's**: Mashare, Ndonga Linena, Divundu, Nkurenkuru, Mukwe, Ndiyona, Rundu, Omega, Kaudom Game Reserve, Mpungu Mururani gate **SASSCAL Weather Stations:** Alex Muranda, Hamoye, Dudukabbe				Rain gauges should be placed at locations with adjacent monitoring borehole so that water level-rainfall relationships can be established. Collect samples of discrete rain events for stable isotope analyses [ADC's currently collect daily rainfall figures only]
Mukwe	Andara	Damara Fractured Aquifer	-18.06159	21.43929	Discharge zone (Damara Sequence meta-sedimentary outcrop). Rehabilitate NAMWATER borehole(s) (WW34342/WW9141) that are no longer in use.
Tsumkwe	Bushmanland	Deeper Kalahari	-19.2073 -19.4336	19.3469 20.1114	Drill a borehole northwest of Tsumkwe in the area previously known as north-central Bushmanland. Possible recharge zone. Existing boreholes: WW24755, WW24756
Grootfontein	Abenab	Calcareous Kalahari (Middle Kalahari)	-19.2986 -19.3027	18.0745 18.0745	Potential source of recharge area. Existing boreholes: WW39970, WW27333
Mukwe	Bagani	Shallow Kalahari	-18.11100	21.61900	Drill new borehole, located near the school, drill up to 50m
Mukwe	Bagani	Deeper Kalahari	-18.10586	21.62052	Use the existing borehole (WW10142). Located next to the clinic, It is recommended to open the borehole and measure the depth and RWL.
		Middle			Drill new borehole. Located in the middle of two roads branching from each

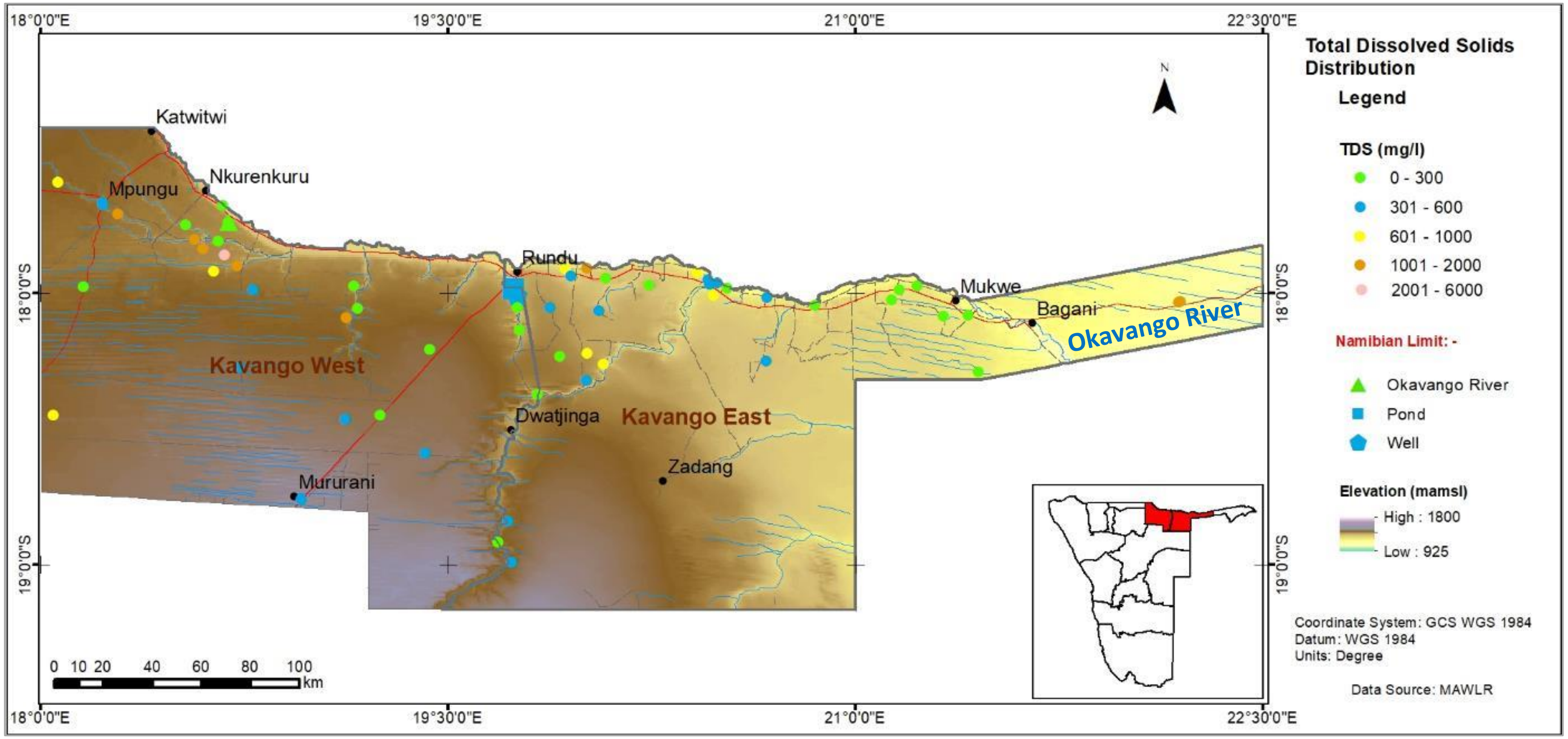
Mukwe	Divayi	Kalahari	-18.13848	21.09656	other. Drill up to 120m
Ndiyona	Kaudom	Middle Kalahari	-18.47685	20.65457	Drill new borehole, drill up to 120m, when reach Ndiyona drive to the southern direction rot.
Ndiyona	Ndonga Linena	Shallow Kalahari	-17.95366	20.47327	Located on the edge of the Omatako River bank just upstream of the tar road crossing, approximately depth 50m. The site is located west of the village next to the power line.
Rundu Rural East	Ncaute	Middle Kalahari	-18.36520	19.90664	Drill new borehole, drilling depth 120m
Rundu Urban	Mupini	Shallow Kalahari	-17.86376	19.62831	Located adjacent to track near Rural Water Supply boreholes, closest to the river floodplain edge, drilling depth 50m.
Rundu Urban	Mupini	Palaeo Okavango Channel	-17.86433	19.62725	Located adjacent to track near Rural Water Supply boreholes, drilling depth 100m
Mpungu	Bravo	Deeper Kalahari	-18.44797	18.04867	Rehabilitate non-functional existing boreholes; groundwater flow regime.
Mpungu	Nkurenkuru	Shallow Kalahari	-17.62469	18.61304	Drill new borehole, drill depth up to 50m
Mpungu	Nkurenkuru	Deeper Kalahari	-17.62469	18.61304	Drill new borehole, drill depth 150m
Kahenge	North Mangetti Farms	Deep Kalahari	-18.34145	18.50203	Located between farm Hompa Daniel Mpasi and Kouwa Kanjimi Pius's farm. Driiling depth 150m. it is 83km distance, west direction from Alex Muranda gravel road and 53km, east direction from Mpungu-Ntisebis tar road.
Kahenge	Grootfontein-Rundu highway	Middle Kalahari	-18.61059	19.10252	Located next to the Grootfontein-Rundu highway 101km from Rundu (2km before the 150km sign for Grootfontein). Drill new borehole to depth of 150m.
Kahenge	Mangetti Cattle Ranch	Shallow Kalahari	-18.73684	18.58490	Located next to the main gravel road before entering the veterinary compound. Drilling depth 50m.
Kahenge	Mangetti Cattle Ranch	Deep Kalahari	-18.73644	18.58833	Located in the school compound, near the sports field. Drilling depth 150m.
	Central regime 3	Middle			Siting should be carried out during drilling.

***Shaded grey: Monitoring localities identified in this study in addition to those already pre-selected by Beukes & Masule (2014) and Water Surveys Botswana (2011) studies.

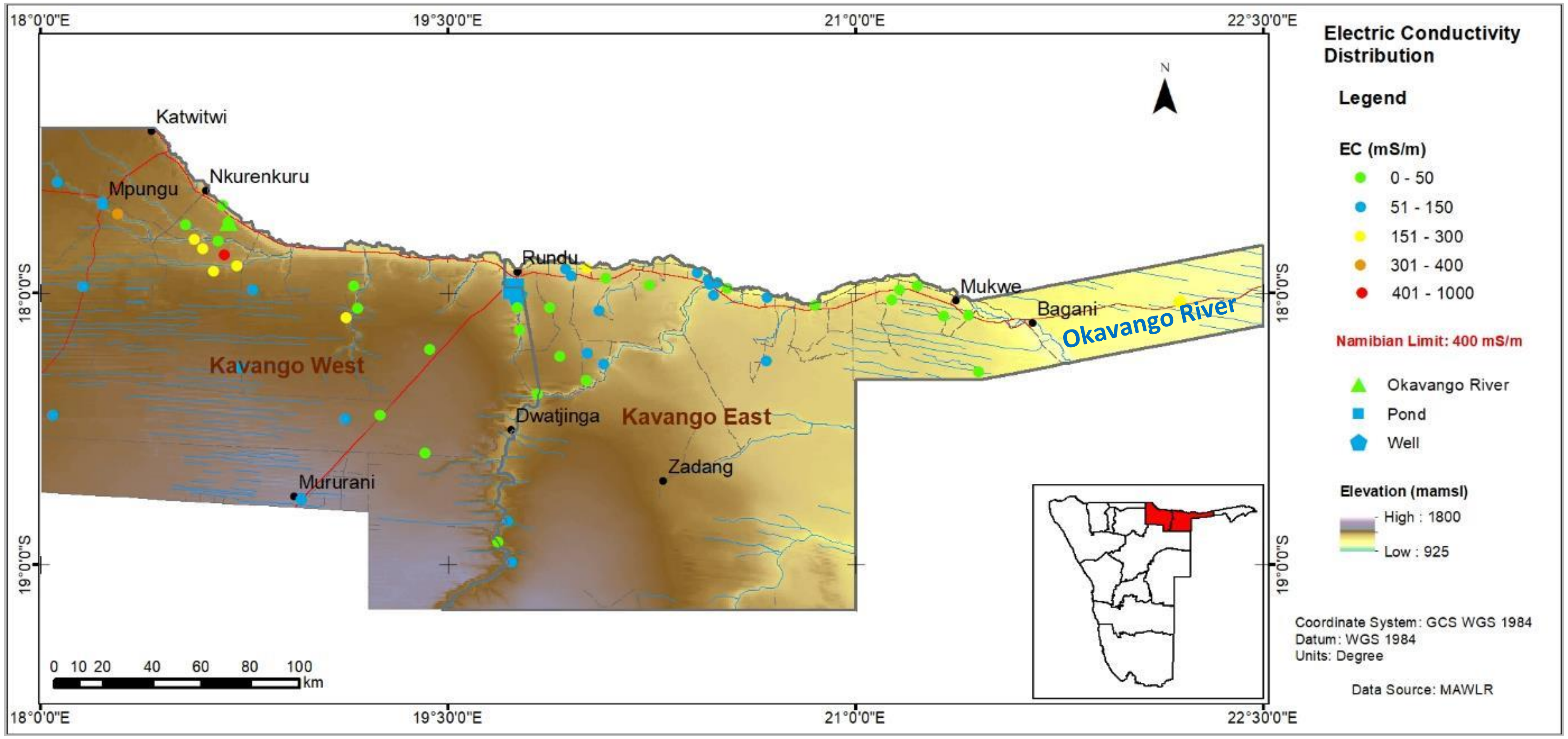
pH Distribution Map



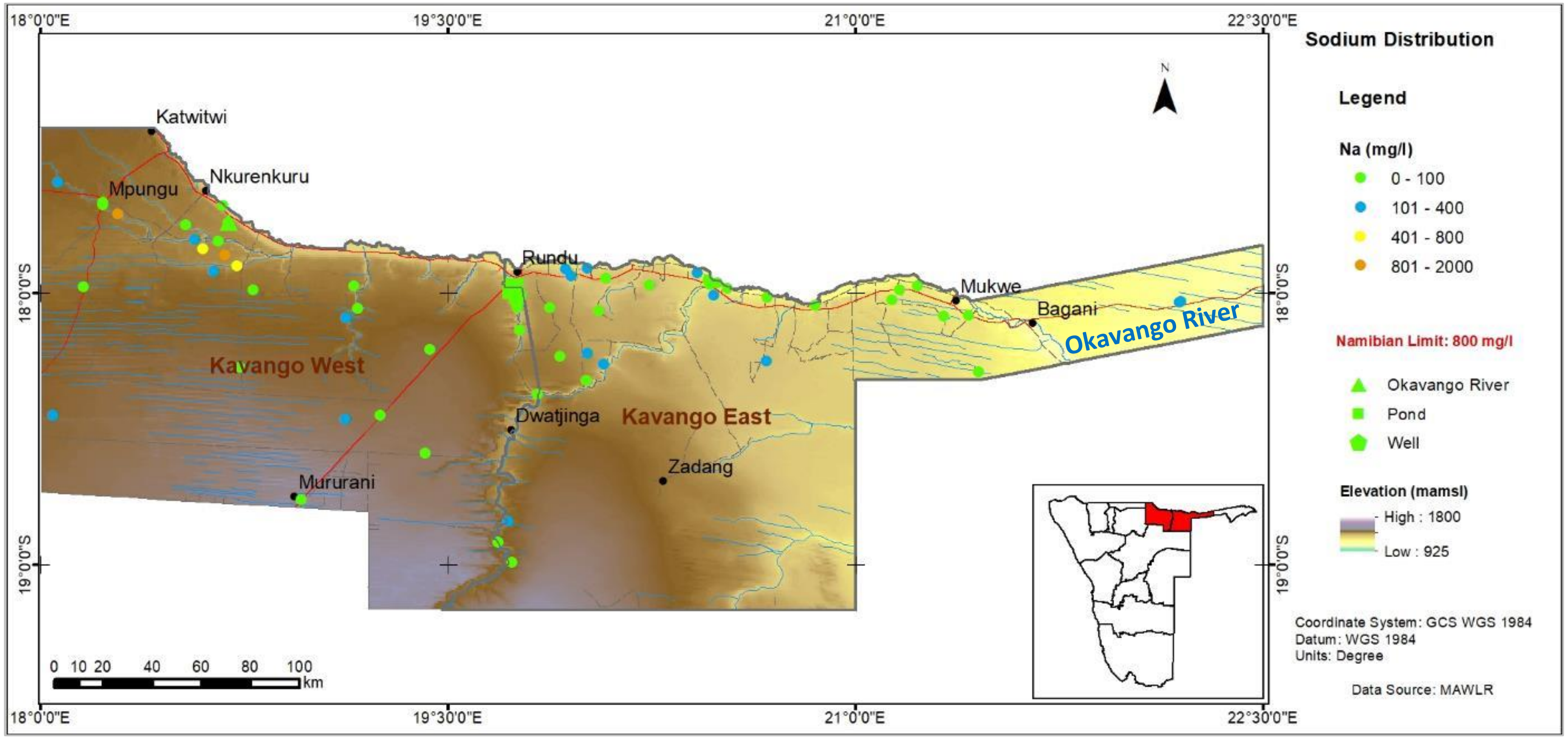
Total Dissolved Solids Distribution



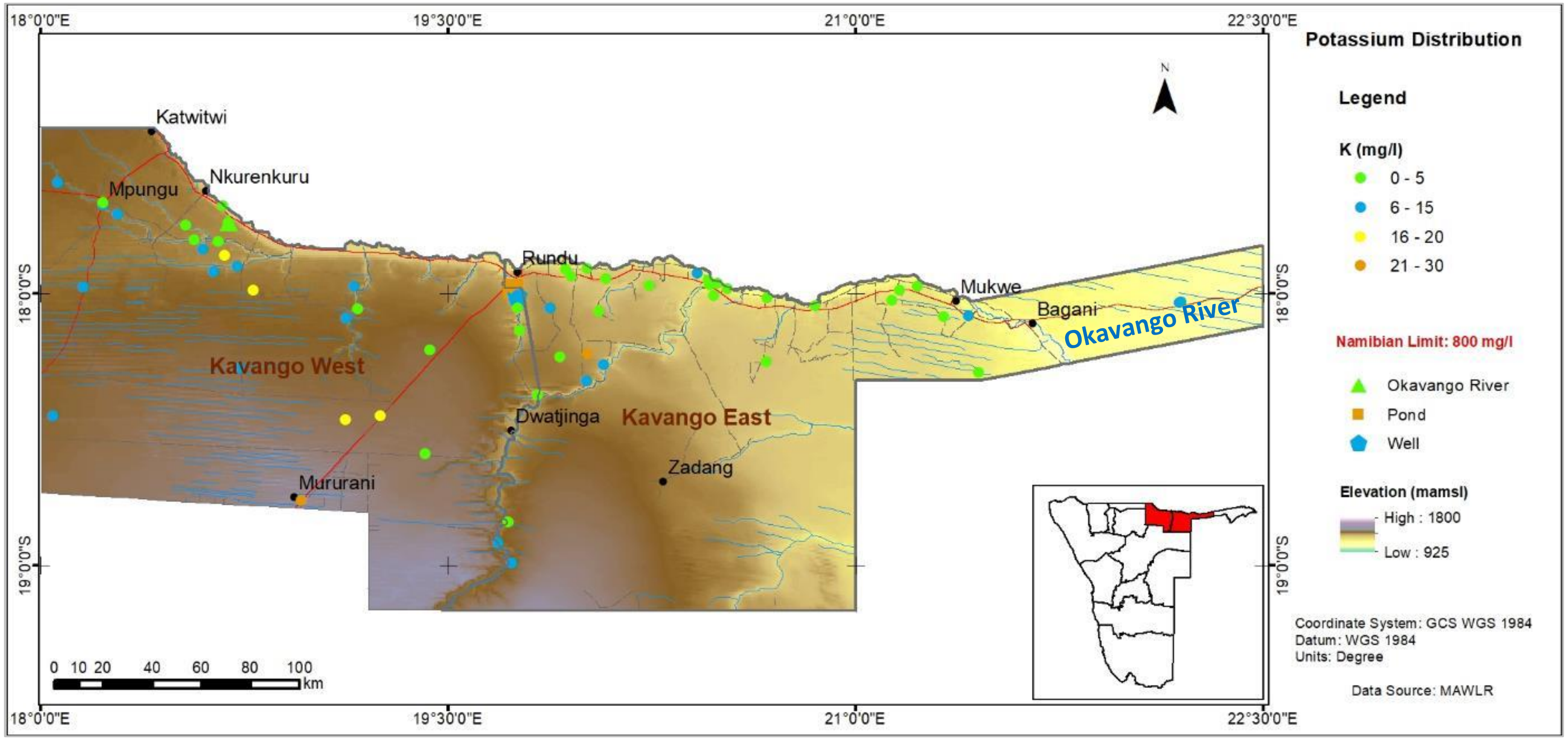
Electric Conductivity Distribution



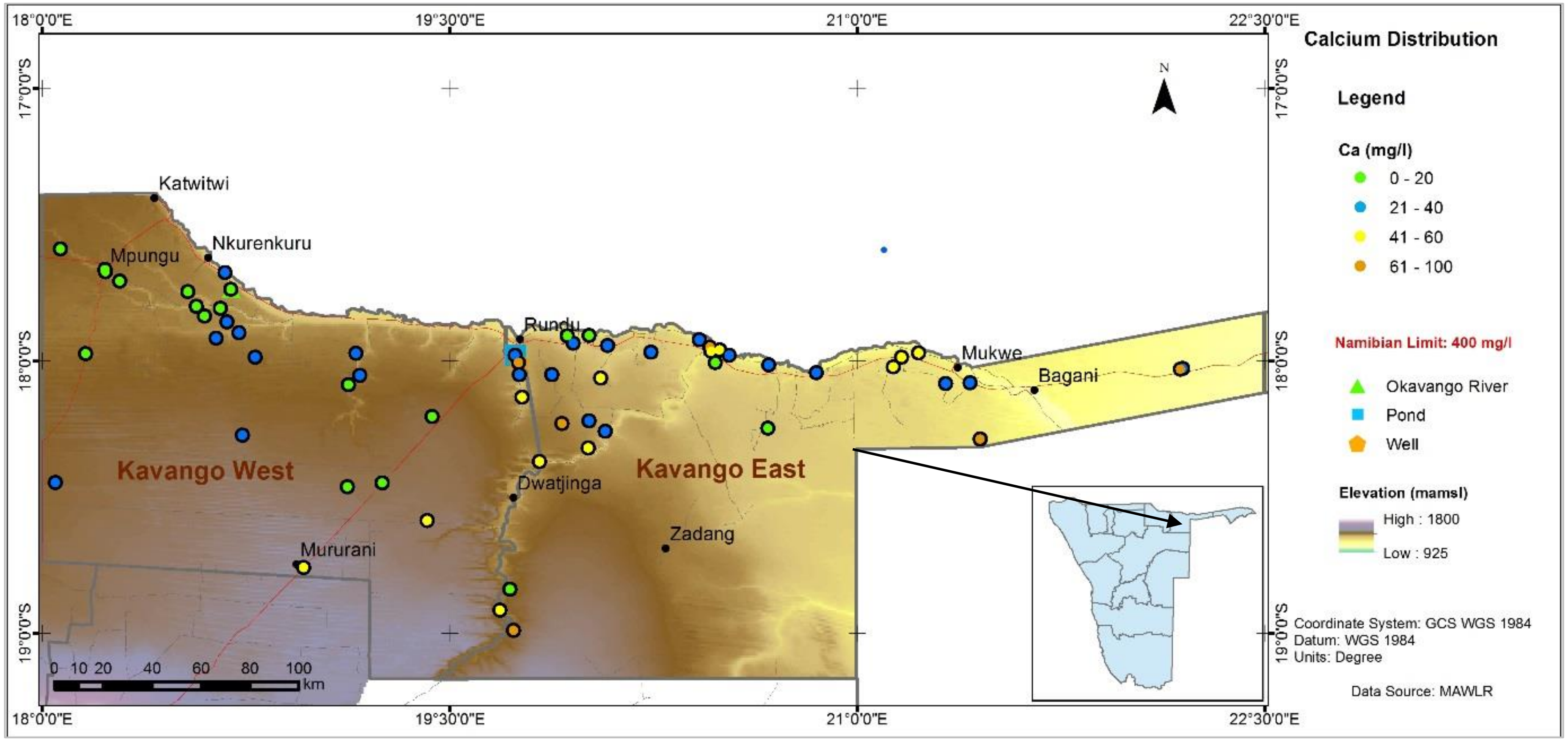
Sodium Distribution



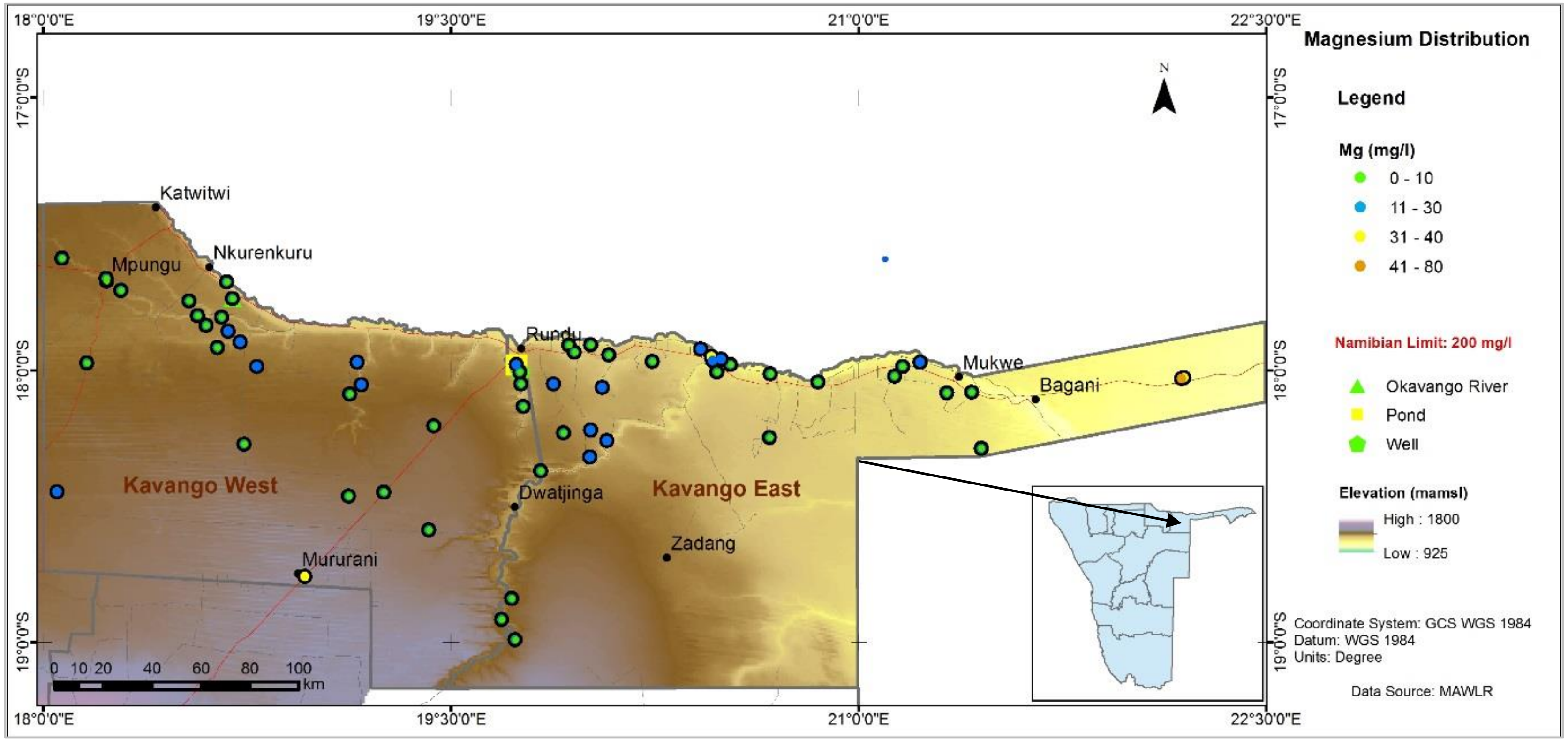
Potassium Distribution



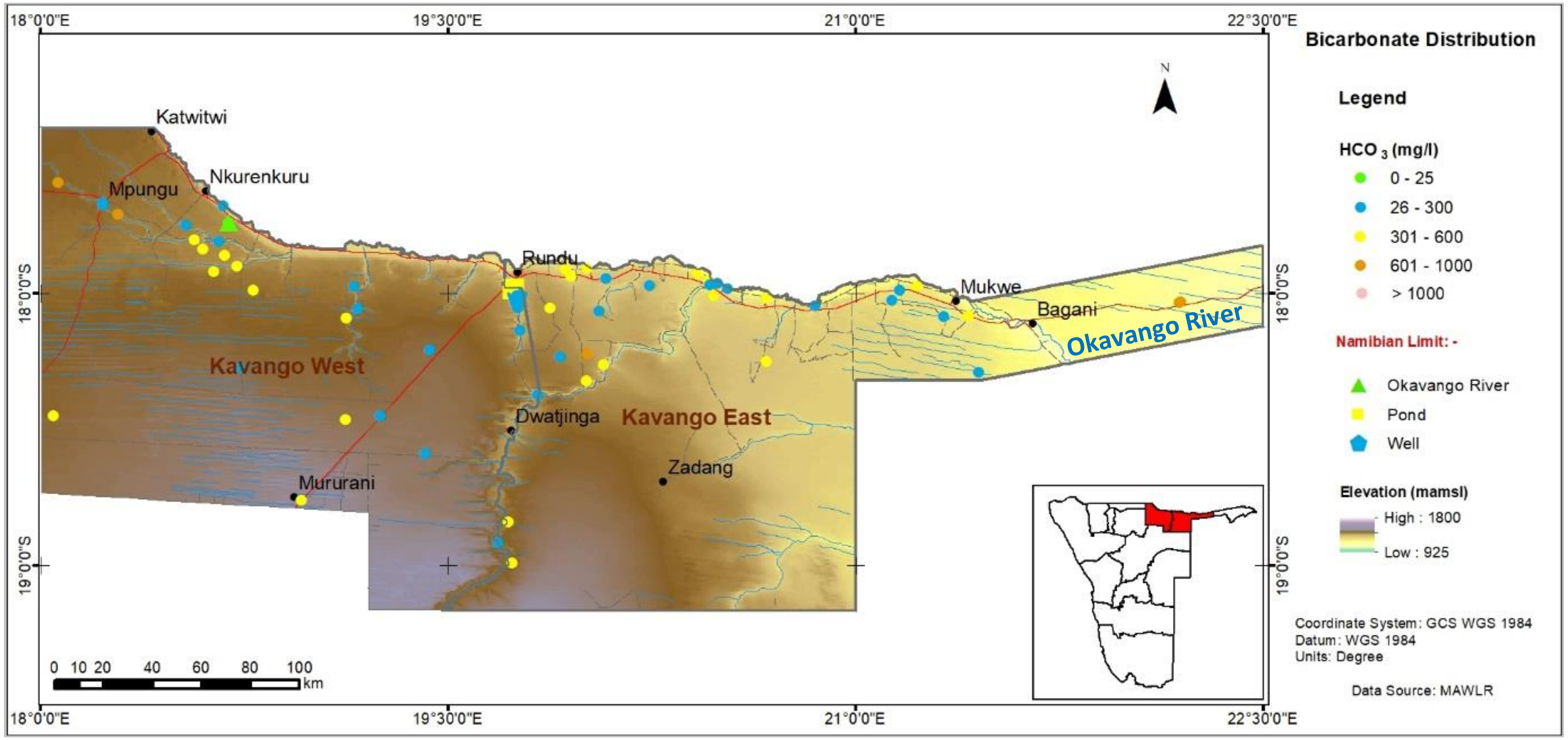
Calcium Distribution



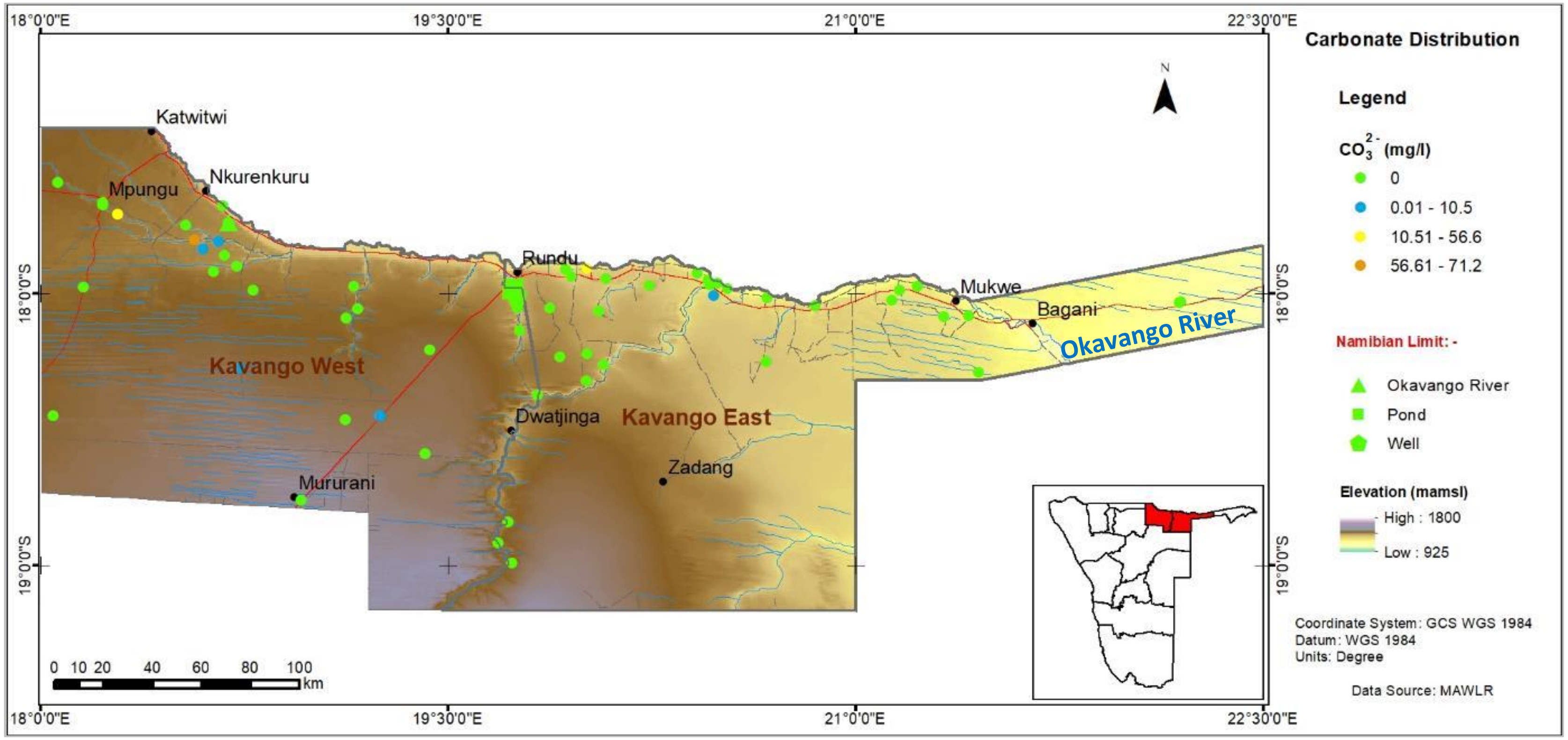
Magnesium Distribution



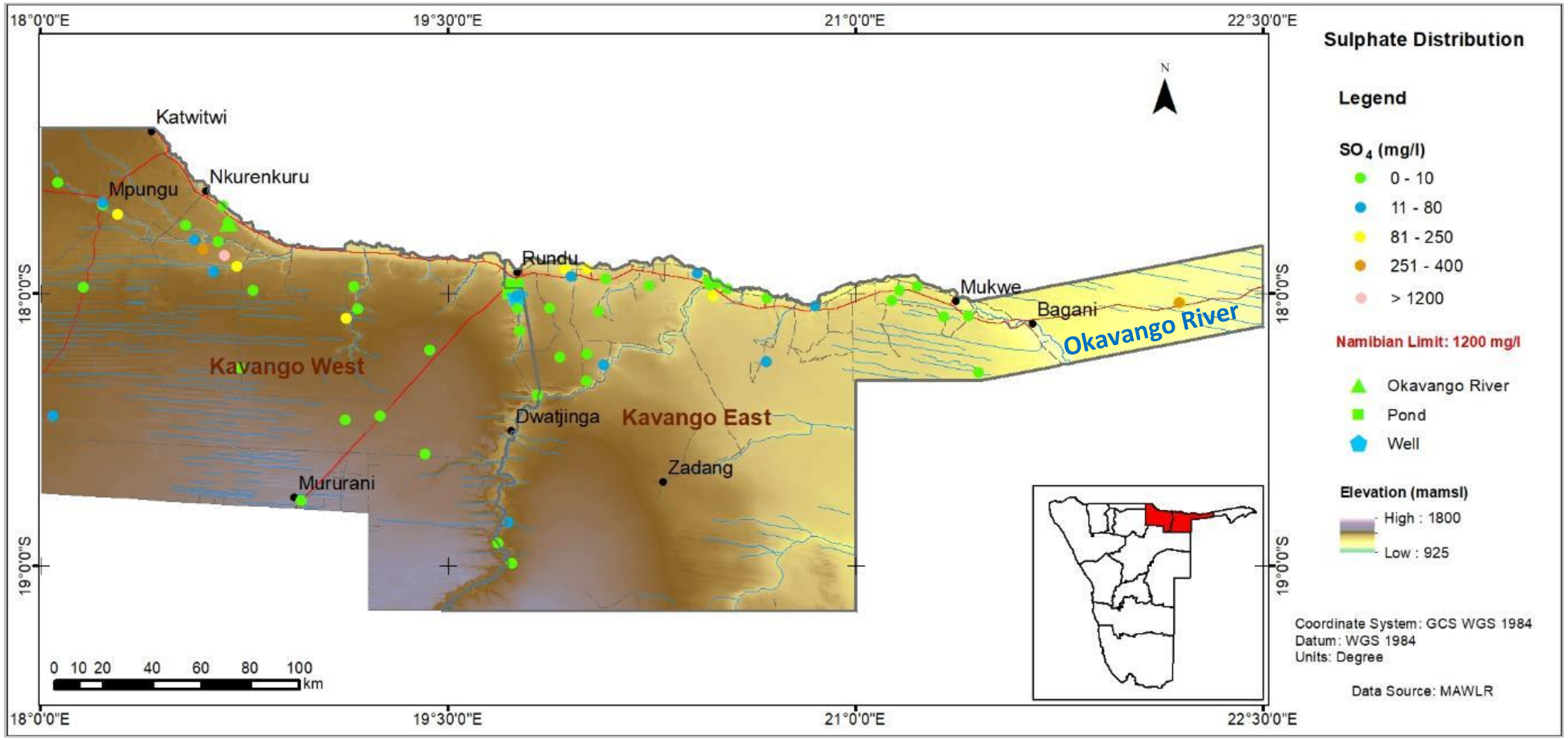
Bicarbonate Distribution



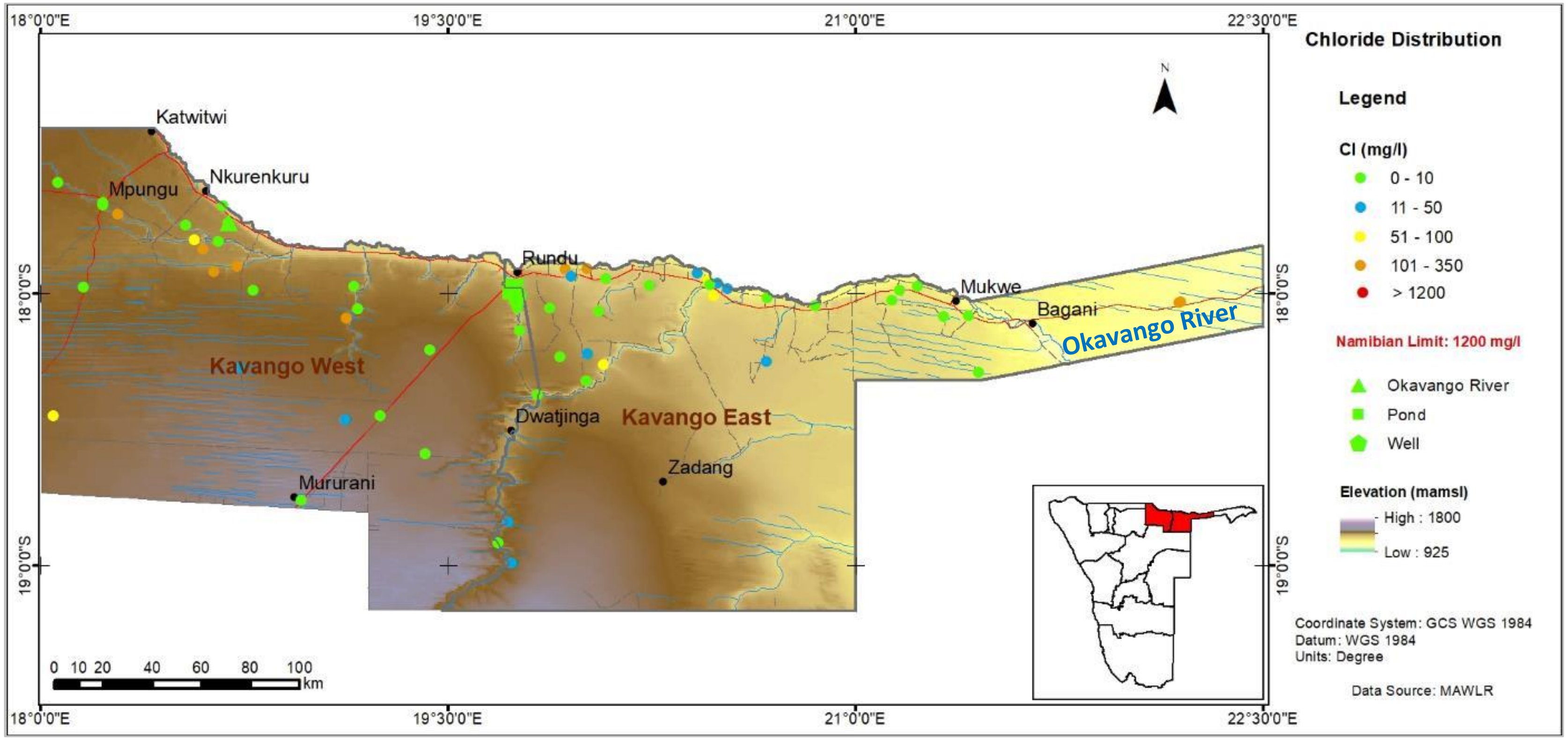
Carbonate Distribution



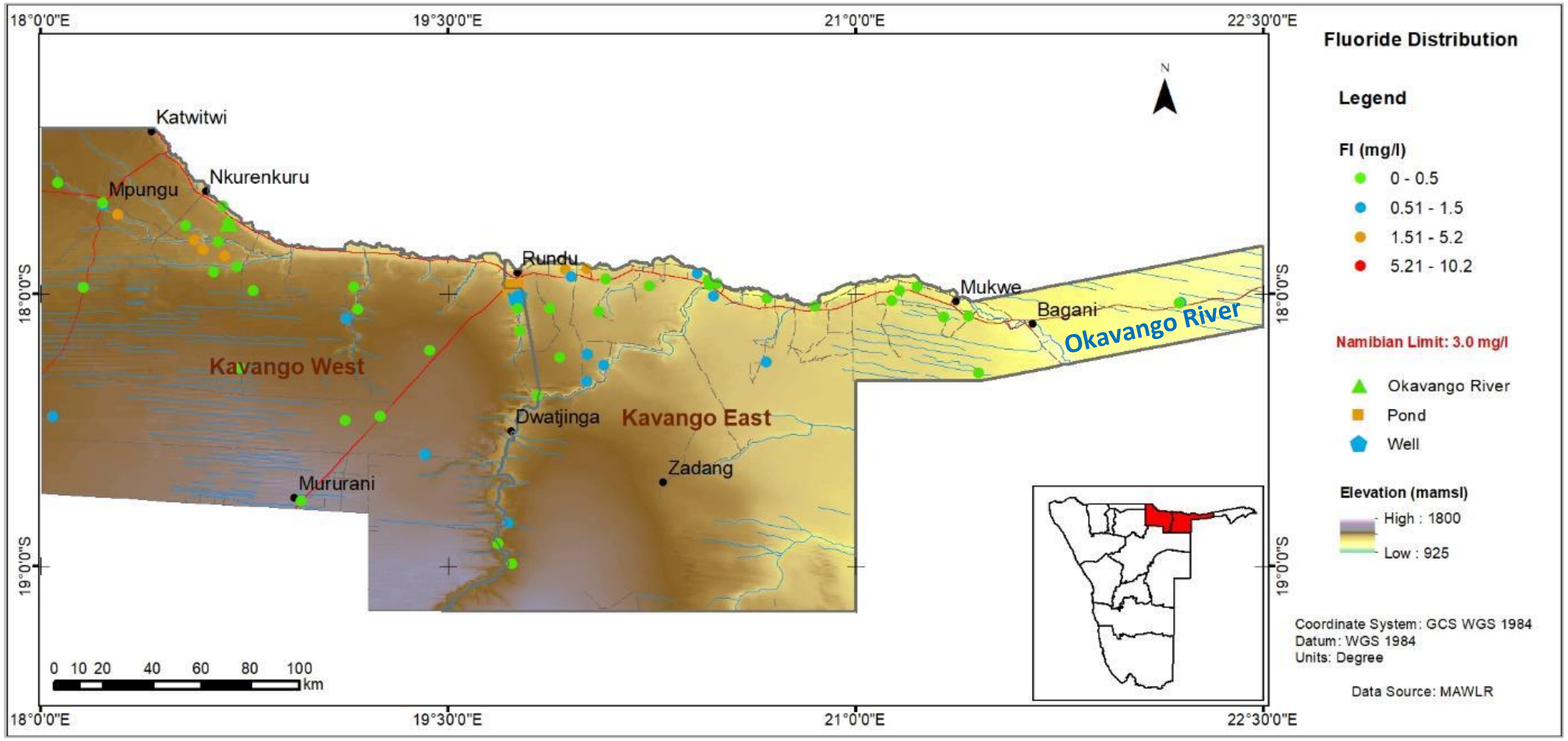
Sulphate Distribution



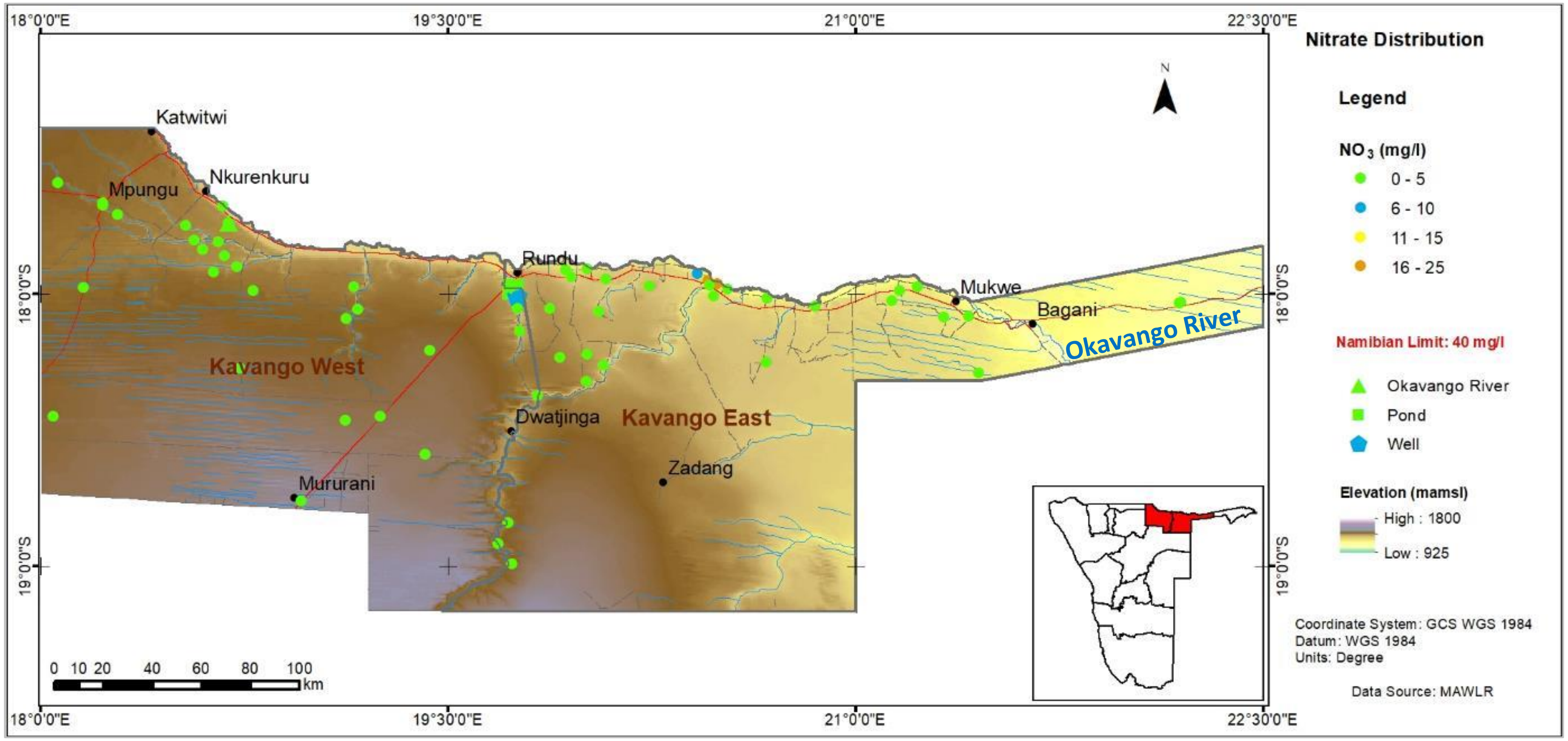
Chloride Distribution



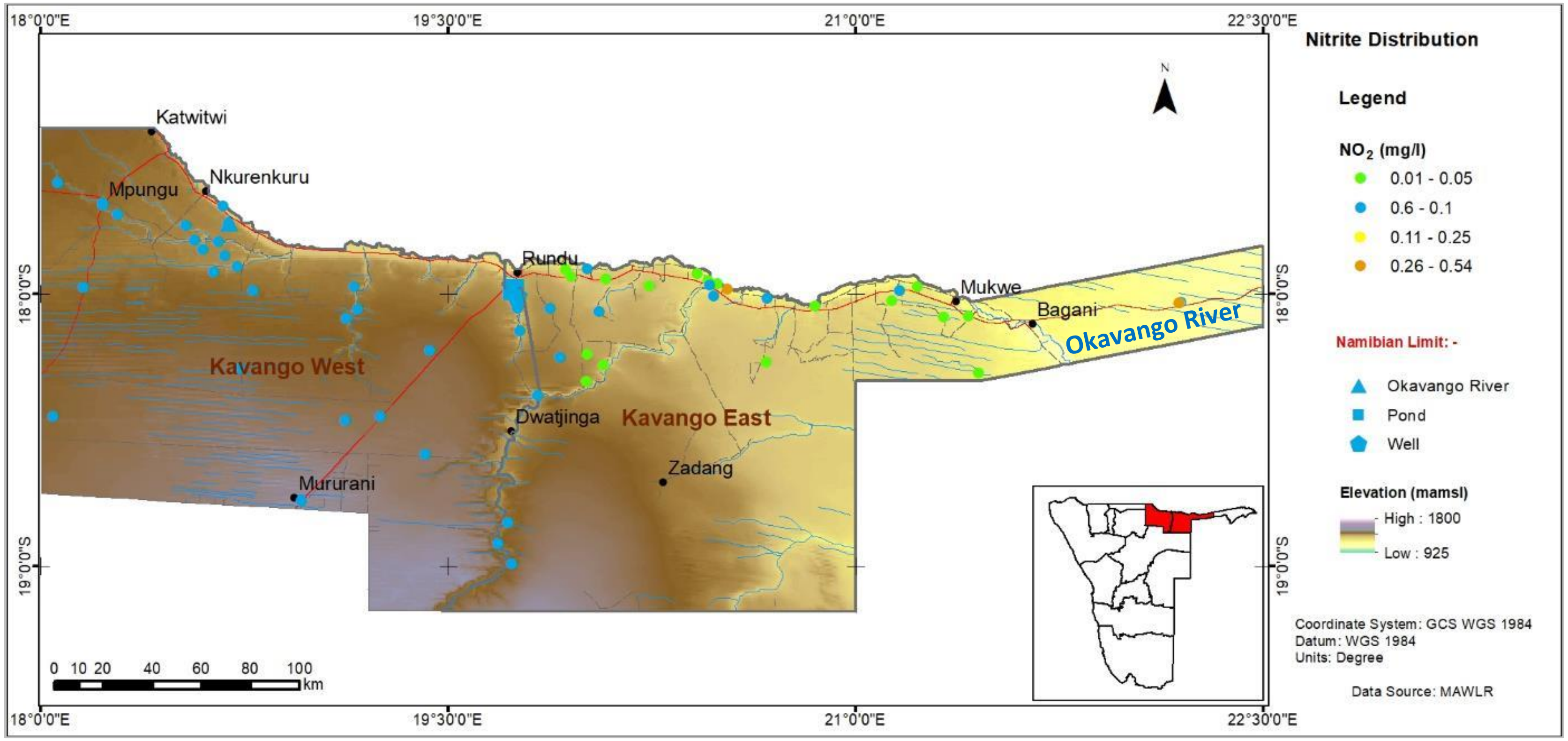
Fluoride Distribution



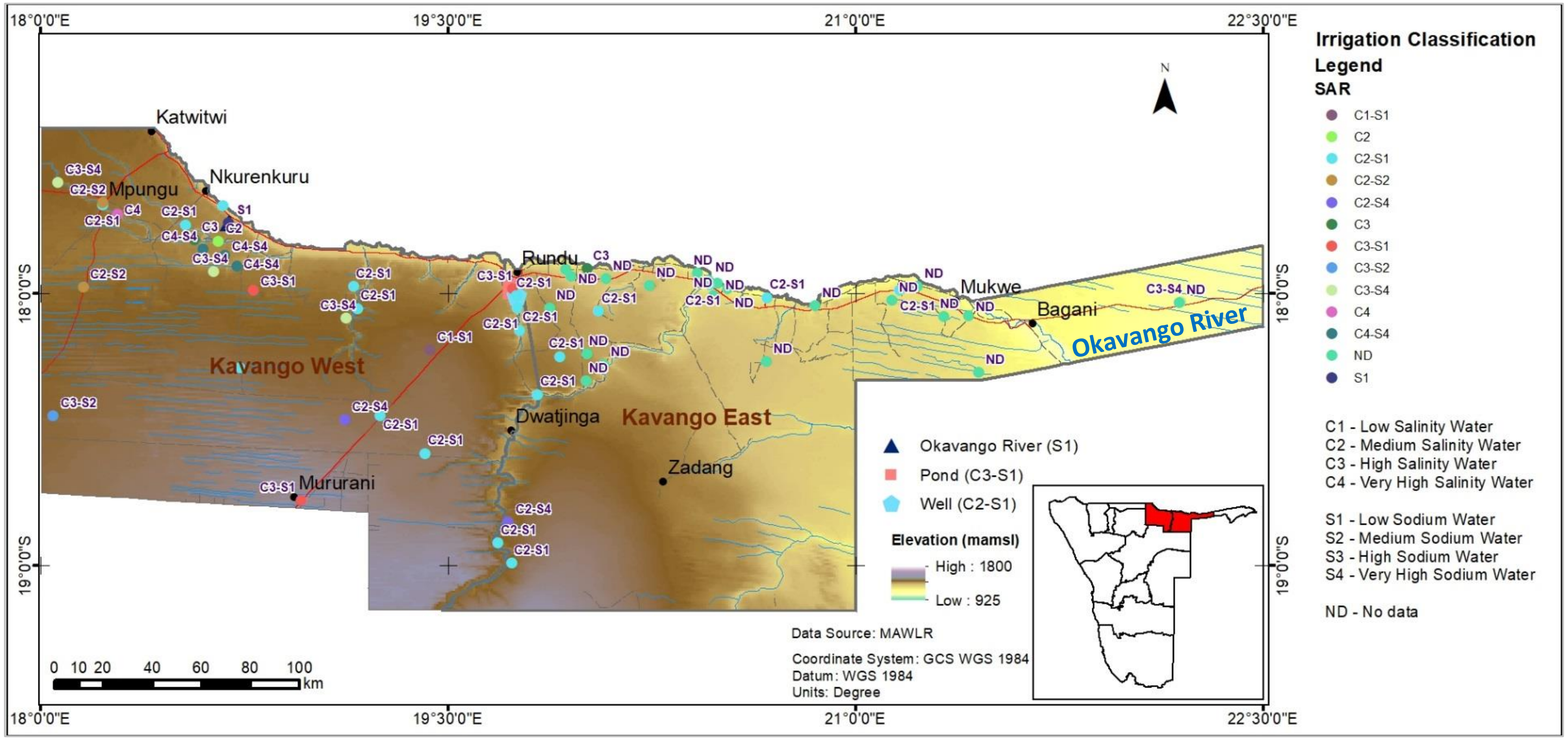
Nitrate Distribution



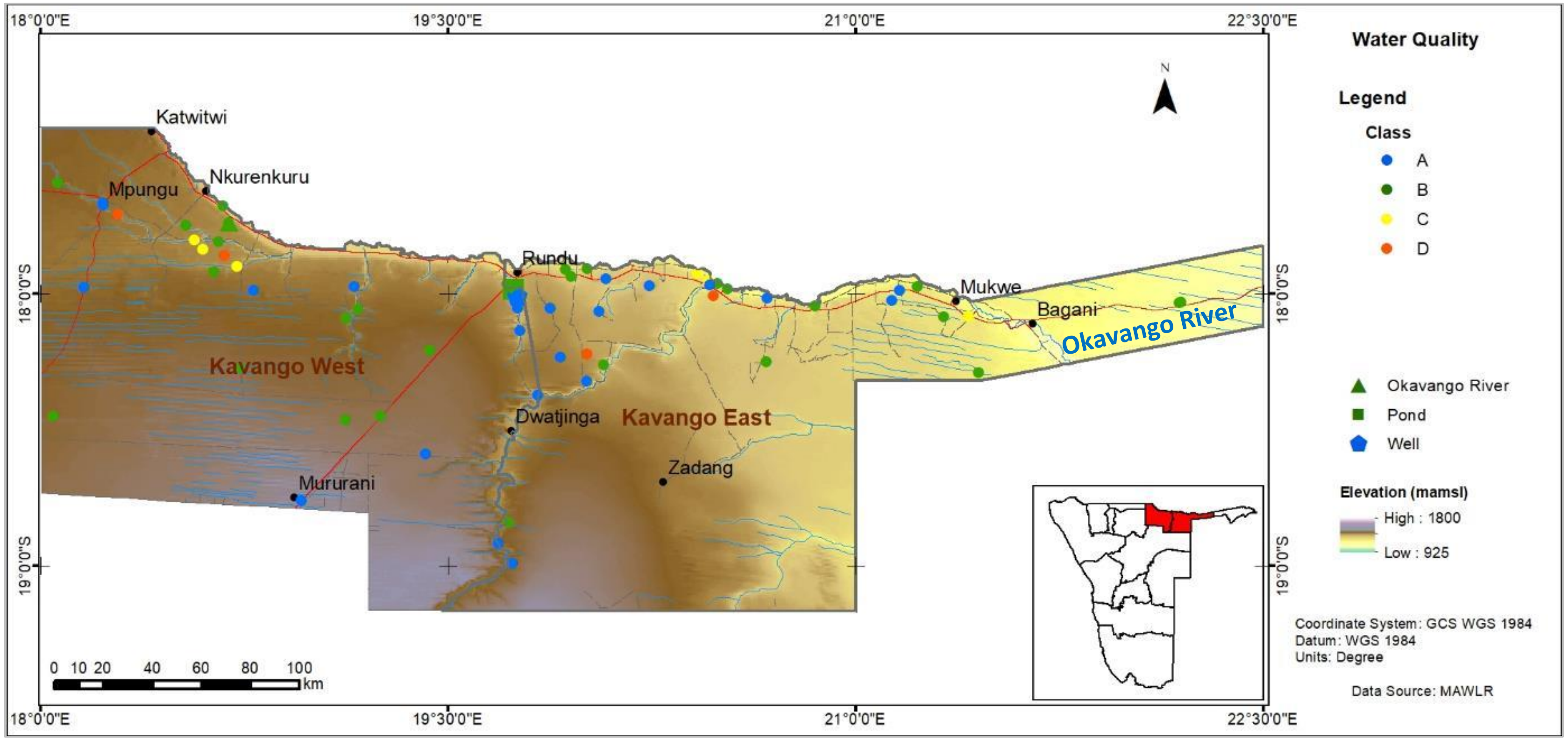
Nitrite Distribution



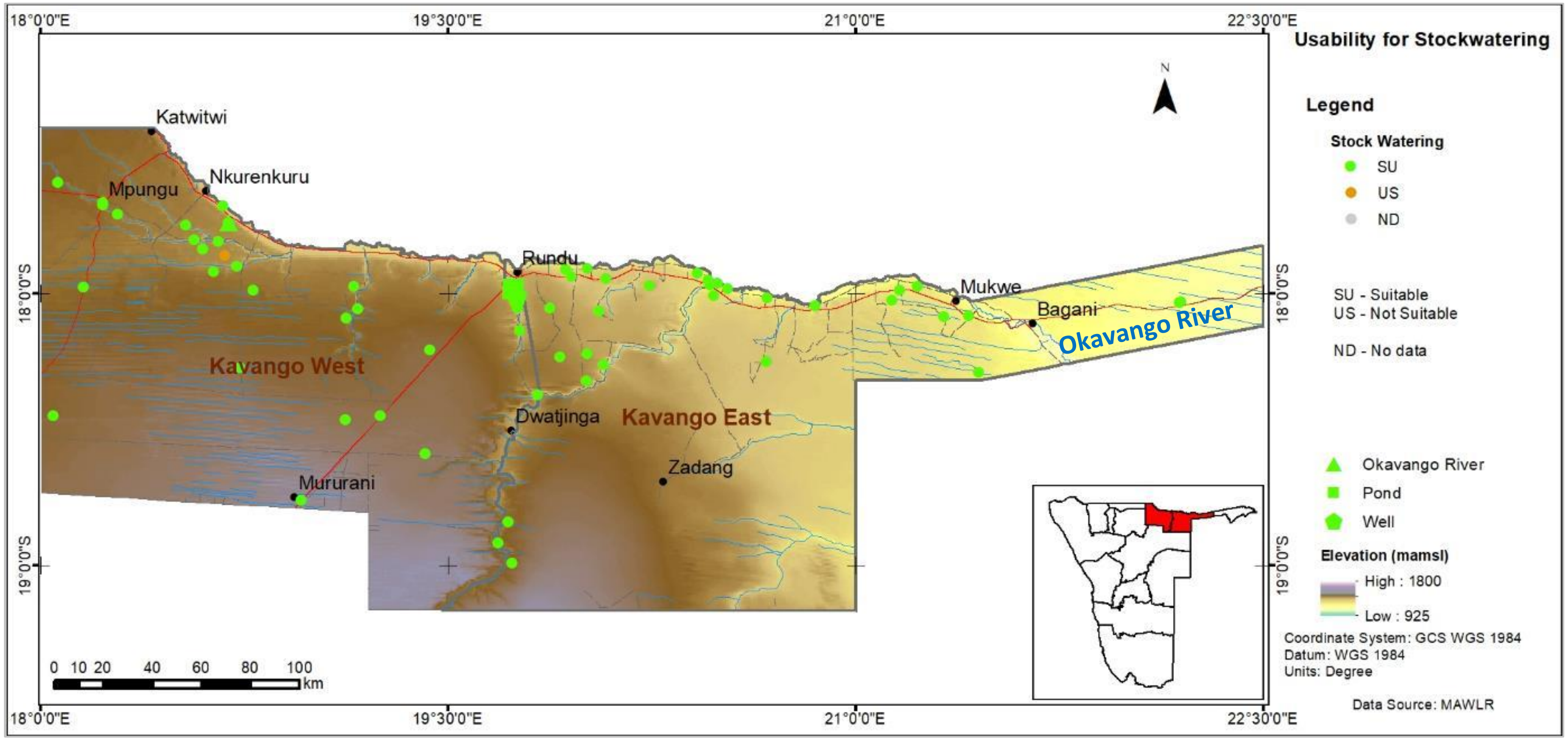
Sodium Adsorption Ratio Distribution

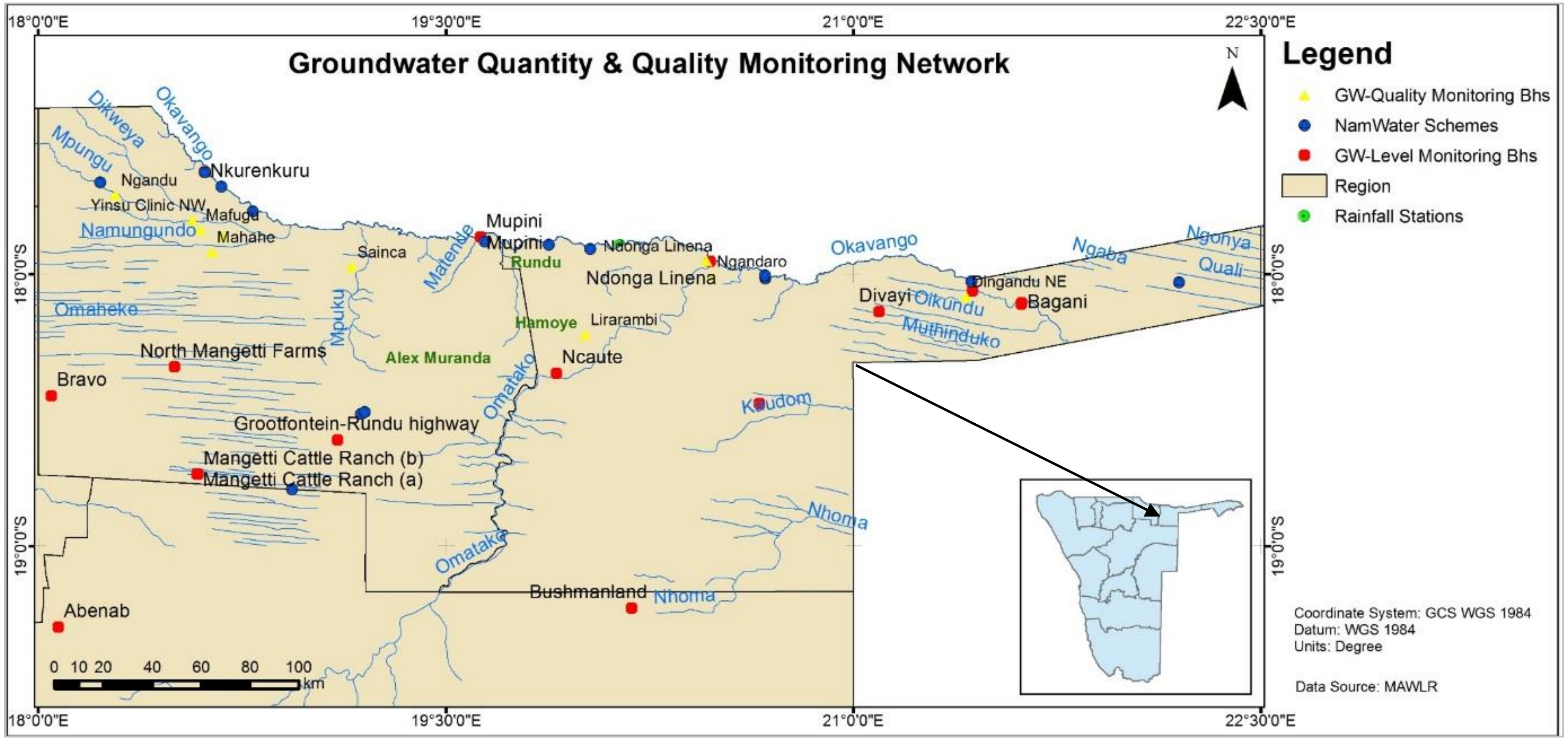


Usability of Groundwater for Human Consumption



Usability for Stockwatering




Groundwater Quantity & Quality Monitoring Network
Legend
GW-Quality Monitoring Bhs
NamWater Schemes
GW-Level Monitoring Bhs
Region
Rainfall Stations
N
18°0'0"E
19°30'0"E
21°0'0"E
22°30'0"E
18°0'0"S
19°0'0"S
Dikweya
Okavango
Mpungu
Ngandu
Nkurenkuru
Yinsu Clinic NW
Mafugu
Namungundo
Mahahe
Sainca
Matende
Mupini
Mupini
Rundu
Ndonga Linena
Ngandaro
Ndonga Linena
Okavango
Ngaba
Ngonya
Quali
Dingandu NE
Divayi
Okundu
Bagani
Muthinduko
Omaheke
Mpuku
Hamoye
Lirarambi
North Mangetti Farms
Alex Muranda
Ncaute
Bravo
Omatako
Kaudom
Grootfontein-Rundu highway
Mangetti Cattle Ranch (b)
Mangetti Cattle Ranch (a)
Nhoma
Omatako
Bushmanland
Nhoma
Abenab
0 10 20 40 60 80 100
km
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
Data Source: MAWLR