IMPROVING GROUNDWATER RECHARGE ESTIMATES AND GROUNDWATER MANAGEMENT FOR THE CUVELAI-ETOSHA BASIN

A MINI THESIS SUBMITTED IN PARTIAL FULFILMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE (WATER RESOURCES MANAGEMENT)

OF

THE UNIVERSITY OF NAMIBIA

BY

SIMON AMUTENYA

201305482

April, 2020

SUPERVISOR: Dr Heike Wanke (University of the West of England)

CO-SUPERVISOR: Dr.-Ing. Joachim Lengricht (University of Namibia)

Abstract

Various studies have shown that the use of tracer techniques such as the chloride mass balance (CMB) and stable isotopes' methods are suitable and good practical approaches to estimate groundwater recharge. Estimating groundwater recharge improves the understanding of groundwater availability in making informed strategies for groundwater resources management. Using secondary data, this study estimated groundwater recharge within the Cuvelai-Etosha Basin (CEB) via the CMB and stable isotopes' methods along six flow paths. Chloride content in groundwater at the flow path's endpoint was treated as an integral value of what has been happening from the starting point up to that endpoint. The stable isotopes' method has used the hydro-calculator to compute fractional losses along transects which determined evaporation losses assuming the rest of water retained along flow paths forms part of groundwater recharge. From the CMB method, endpoint recharge rates range between 0.21% and 38.46% of mean annual precipitation. Based on stable isotopes' method, about 50% of the initial recharge reaches the discharge zones in comparison to only 11% that of the CMB method. From the obtained results, there is much significance between the two methods with the stable isotopes' method estimating much higher values whilst the CMB method seems to underestimate, however, the notion of using CMB method to calculate integral recharge instead of point recharge seems more usable. Groundwater recharge rates determined by both methods agree well with the range of values found in previous studies. Study outlined the protection of recharge zones such as the southern rim of the basin for great groundwater management strategies. The calculated recharge to aquifer systems has indicated that there is a need for sustainable groundwater use as demands may exceed the current potential in the near future.

Contents

List of Tables

List of Figures

List of Abbreviations and/or Acronyms

BGR Federal Institute for Geosciences and Natural Resources

CEB Cuvelai-Etosha Basin

CMB Chloride Mass Balance

DO Otavi Dolomite Aquifer

GMWL Global Meteoric Water Line

KEL Etosha Limestone Aquifer

KOH Ohangwena Aquifer

KOM Omusati Multi-zoned Aquifer

KOS Oshana Multi-layered Aquifer

KOV Oshivelo Multi-layered Aquifer

MAWF Ministry of Agriculture, Water and Forestry

NAMWATER Namibian water cooperation

SMOW Standard Mean Ocean Water

TDS Total Dissolved Solids

UNESCO United Nations Educational, Scientific and Cultural Organisation

V-SMOW Vienna Standard Mean Ocean Water

Acknowledgement

I am deeply indebted to Dr Heike Wanke, who supervised this research thesis, for her guidance and encouragement. She is my academic mother. I wish to thank Dr.-Ing. Joachim Lengricht for playing his role as the co-supervisor, for he really supported me and has been a good mentor. I would like to thank the Ministry of Agriculture Water and Forestry for initiating and funding this programme through UNESCO for it played a huge role and created a good platform for capacity building. A very special thank you to my colleagues and the University of Namibia's Department of Civil Engineering for making this an interesting and a memorable journey. My acknowledgement will be incomplete without mentioning my family. I am very grateful for the love and support they gave me during my study period. Thank you to my parents for always encouraging and motivating me to aim high while also being supportive through all my decisions.

Declaration

I declare that "Improving groundwater recharge estimates and groundwater management for the Cuvelai-Etosha Basin" is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references. This thesis is therefore my own work and effort.

Full name: Simon Amutenya Signed....................................

1. Introduction

1.1 Orientation of Study

Namibia relies heavily on groundwater and the predicted increase in both temperature and rainfall variability due to climate change may increase this reliance. Assuming 100% efficiency of water usage, the water share is approximately at 86 l/capita/day. This volume is small in comparison to the 150 l/capita /day as recommended by the World Health Organization. Decreasing aquifer recharge due to low rainfalls and high evaporation is likely to cause and exacerbate the quality and quantity situation. Namibia is one of the driest countries in Sub-Saharan Africa with an average rainfall of 350 mm/a, where precipitation is highly unequal distributed over the country [1]. Therefore, there is a need to estimate groundwater recharge for sustainable development. Groundwater moves through spaces and cracks between the soil particles from an area of high potential (high elevation) to an area of low potential (lower elevations) against a gradient and there is a constant movement of water above, on and below Earth's surface. Recharge is the ultimate input parameter for sustainable groundwater use and various methods can be used to estimate groundwater recharge. Chloride is regarded as a suitable environmental tracer due to its highly solubility and conservativeness [2]. The chloride mass-balance method is amongst the most convenient and inexpensive groundwater recharge estimation methods due to its simple data requirements as Marei et al. [2] indicated. However, recharge can also be estimated by other methods involving the use of stable water isotopes ($\delta^{2}H$ and $\delta^{18}O$) and groundwater level fluctuations. Applications of the stable isotopes' $\delta^{2}H$ and $\delta^{18}O$ are increasingly becoming popular in the fields of hydrology and ecohydrology [3]. Two tracing techniques, the chloride mass-balance and stable isotope methods were used to estimate groundwater recharge rates for the basin via selected flow paths at different sites of the Etosha-Cuvelai sub-basin. δ^2H and $\delta^{18}O$ are conservative tracers which can be measured in low concentrations hence ideal for investigating subsurface flow processes [4].

Groundwater resource management is complicated regarding the given spatial variations in recharge [5]. If the total extraction from a given aquifer is much more than the total recharge to the aquifer system as a whole then the water levels will decline over time. It is therefore important that management approaches not be overgeneralized [5]. Also, in order to manage aquifers sustainably, an accurate determination of recharge rates is crucial [3]. This study adapts the hydro-calculator method developed by Skrzypek et al., [6] for the direct quantification of potential annual groundwater recharge through the unsaturated zone in the Cuvelai-Etosha Basin (CEB) using the stable isotopic composition of groundwater. Contemporary aquifer recharge rates are a fundamental consideration in the sustainability of groundwater resource development [7]. Figure 1 diagrammatically represented the typical groundwater flow regime and residence times in semiarid regions. Understanding aquifer recharge mechanisms and their linkages with land-use is essential for integrated water resources management [7].

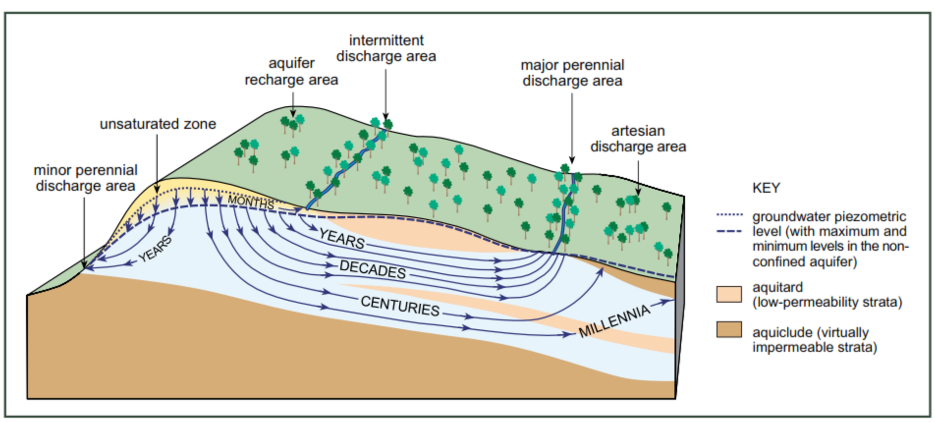

Figure 1: Typical groundwater flow regime and residence times in semiarid regions [7].

1.2 Objectives of the Study

The main objective of this study was thus to improve groundwater recharge estimates and groundwater management for the Cuvelai-Etosha Basin. The specific objectives of this study were to:

1. Estimate recharge rates at different aquifers for the Cuvelai-Etosha Basin (CEB).
2. Compare and contrast results from two recharge estimation methods (chloride mass-balance and stable isotopes)
3. Determine possible groundwater management strategies

1.3 Significance of the Study

This study demonstrates the use of the Chloride Mass-Balance (CMB) method and stable isotope data ($\delta^{2}H$ and $\delta^{18}O$) from groundwater bodies to estimate groundwater recharge. This study may be useful to stakeholders in suggesting which management strategies are most effective in managing groundwater resources within the Cuvelai-Etosha Basin for sustainable development.

1.4 Study Area

The study was done on the Cuvelai-Etosha Basin (CEB) which is an extensive sedimentary basin and part of the much larger Kalahari Basin [8]**.** The CEB is a transboundary endorheic watershed shared almost equally by Angola and Namibia with a total size of 173,000 km^2 [3]. Figure 2 shows the CEB map with its four sub-basins and the six (6) identified flow paths A-A' to F-F' used in this study. Evaporation rates can reach up to 3000 mm/a and exceed yearly rainfall by a factor of five [3]. Mendelson et al. [9] have indicated that people and their livestock in the basin rely on groundwater, mostly over large areas south of Etosha Pan and in eastern Oshikoto and western Omusati. Etosha Pan is the lowest point in the basin with an elevation of about 1,085 metres above sea level [9].

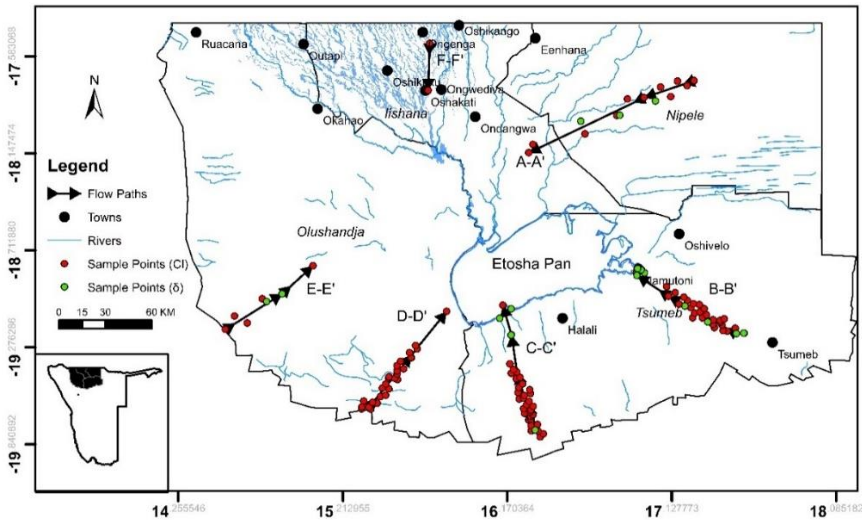

Figure 2: Cuvelai-Etosha Sub-Basins with its principal features and the selected flow paths and sites for groundwater recharge estimation and management strategies (Adapted: [9]).

1.4.1 Geology

The CEB is mainly overlain by sedimentary sands, clays, silt and calcrete as shown in figure 3. Sedimentary rocks which were deposited in late Precambrian age on top of the mid-Proterozoic crystalline basement covers of up to 8,000 m in thickness [10]. The geological fundament is built by the Pre-Damara Basement which is over 4,000 m below ground level and formed about 2,600 to 1,700 Ma ago [11]. The main sequences include Karoo, Damara and Kalahari. The Damara Sequence, comprising the Nosib, Otavi, and Mulden Groups, is the oldest geological unit covering the entire basin [12]. Bittner [10] further indicated that the sediments of the Nosib, Otavi and Mulden groups of the Damara Sequence were covered by up to 360 m thick sedimentary deposits and volcanics of the Karoo Sequence during the Lower Permian to Jurassic. A succession of up to 600 m thick, semi-consolidated to unconsolidated sediments of the Kalahari Sequence overlay the intrusive and extrusive rocks of Karoo Age [10]. Younging direction is towards the basin centre, with older rocks forming the basin rim and younger deposits filling the basin centre [10].

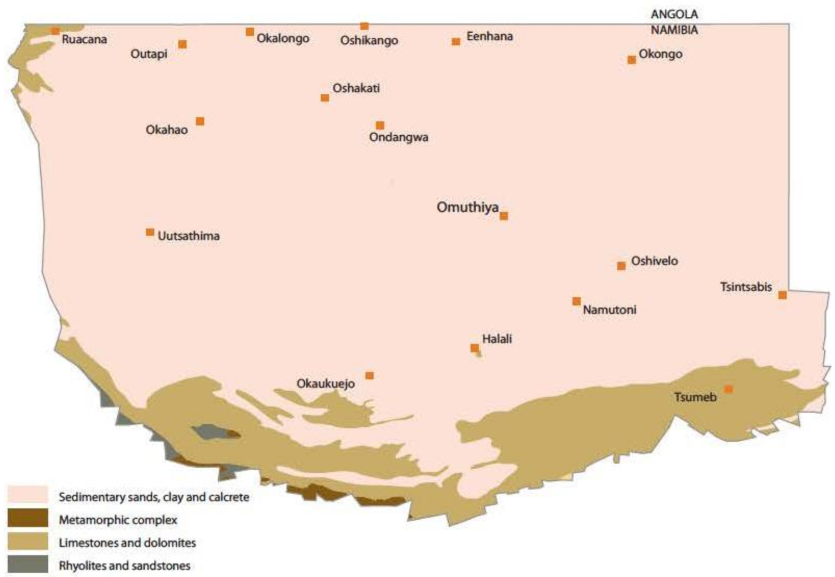

Figure 3: The geology of the Cuvelai-Etosha Basin [9].

As studied by Bittner [10], the Damara Sequence evolved on a rifting margin with sedimentation starting at 900 Ma with terrestrial-fluvial sandstone of the Nosib Group which was subsequently followed at 730 to 700 Ma ago with carbonates of the Otavi Group. In the CEB Karoo Sequence rocks do not crop out at surface. With evidence from boreholes stratigraphy, Bittner [10] outlined that the Karoo consists of fluvio-glacial sediments of the *Dwyka Formation*, giving rise to tillite, sandstone and shale and the fluviatile reworking of the Dwyka Formation and a post-glacial environment led to the deposition of shales, sandstones and carbonates of the Prince Albert Formation. The Kalahari Sequence ranges from late Cretaceous to Quaternary and is entirely continental, ranging from aeolian to fluvial [10]. Deposited under an arid to semi-arid environment, sediments of this period, spanning the Cretaceous to recent age and found in the entire basin are known as the Kalahari Group [12] (figure 4). Bittner [10] further indicated that aeolian material consists of fine-grained well-sorted sands, while the material deposited in a fluvial environment ranges from gravel to clay and often represents braided stream conditions. The fluvial sedimentation dominates, with some reworking of aeolian sand.

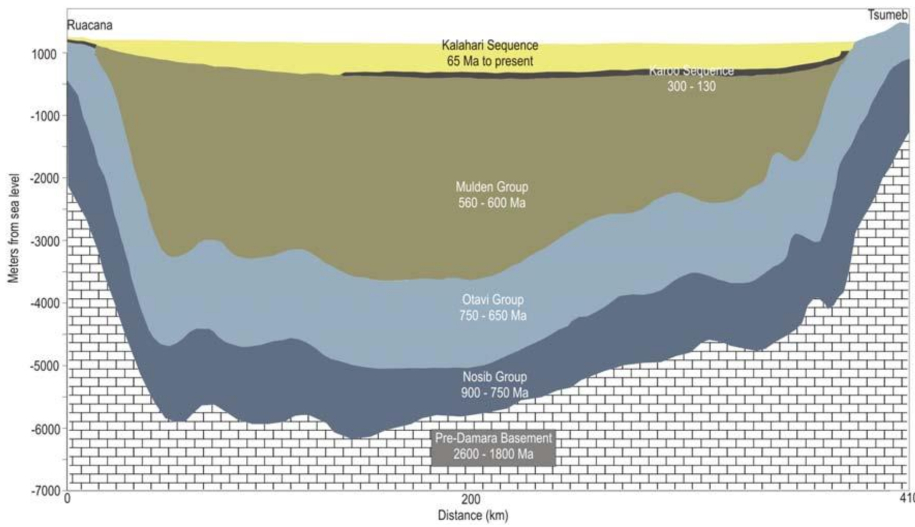

Figure 4: Geological cross-section across the Owambo Basin from Ruacana to Tsumeb [12].

1.4.2 Hydrogeology

Groundwater recharge is defined as the movement of moisture downwards through the unsaturated zone to the saturated zone [2]. Groundwater then flows from regions of high hydraulic head to areas of low hydraulic head. The availability of groundwater depends on hydrogeological setting, which could present significant hydrogeological diversity [7]**.** Groundwater within the CEB flows towards Etosha Pan, which is the area of lowest elevation in the basin [9, 10]. Three main groundwater flow systems can be distinguished within the CEB [10]. No perennial river exists and the mean annual precipitation ranges between 200 and 600 mm/a (figure 5) which is generally decreasing from the east to the west of the basin [9]. Rainfall distribution is not uniform within the basin, with the north-eastern portion (mostly Nipele sub-basin) having more precipitation than in the central and southern areas (Olushandja and Tsumeb sub-basins).

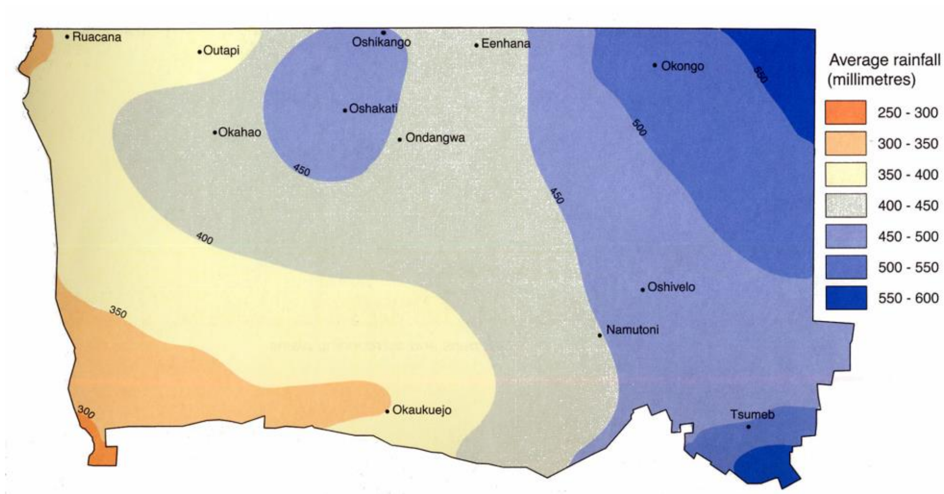

Figure 5: The annual average rainfall across north-central Namibia [11].

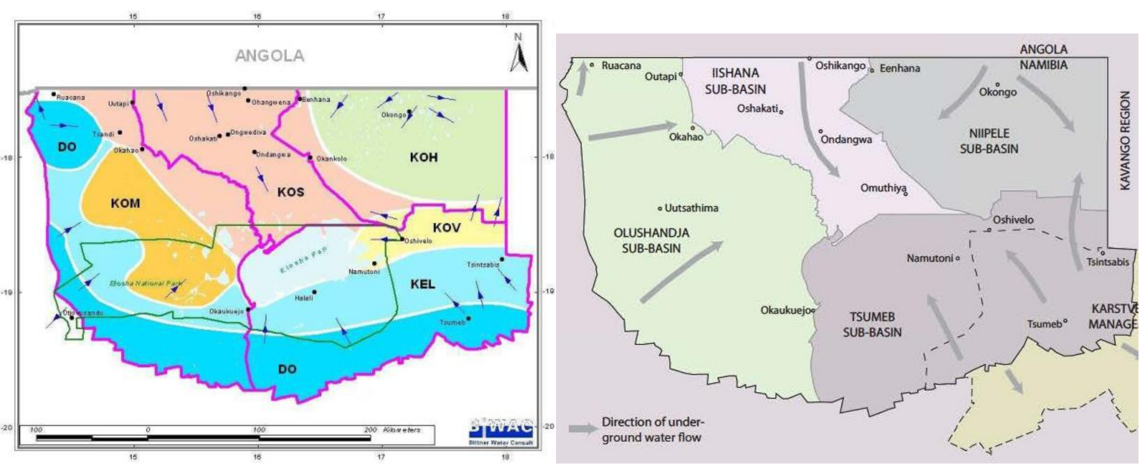

Figure 6: Groundwater systems of the CEB with main aquifers and arrows indicating groundwater flow direction [9, 10].

Groundwater recharged in the fractured dolomites of the Damara Sequence, forms part of the southern and western rim of the basin, flows north and eastwards and feeds the aquifer system of the Karoo and Kalahari sequences [10]. Mostly, part of the north/eastbound groundwater flow is shallow, and discharges through numerous springs along the southern margin of the Etosha Pan, where it rapidly evaporates [10] .

Table 1: The six main CEB aquifer systems and their characteristics [9].

Aquifer system	**Main rock type**	**Depth below Surface [m]**	**Quality of water**	**Yield [m^3/h]**
Ohangwena Multi-layered Aquifer (KOH)	Sand, sandstone	60-300	Fresh to brackish	1-50
Oshivelo Multi-layered Aquifer (KOV)	Conglomerate, sandstone, sand, dolocrete, calcrete	30-150	Fresh to brackish	5-100
Etosha Limestone Aquifer (KEL)	Dolocrete, calcrete, sand	10-100	Fresh, locally high nitrate concentrations	3-100
Oshana Multi-layered Aquifer (KOS)	Sand, calcrete/ limestone	10-80	Saline to hyper saline	1-30
Omusati Multi-zoned Aquifer (KOM)	Sand, clay and calcrete, dolocrete	10-50	Brackish, freshwater in places	1-30
Otavi Dolomite Aquifer (DO)	Dolomite	20-250	Fresh	>50

A deep-seated multi-layered Kalahari Aquifer is recharged in Angola and groundwater flows in a southern direction towards the Etosha Pan and the Okavango River [10]. A shallow Kalahari Aquifer (formerly described as the brine lake area) superimposes both previously described aquifer systems in the central part of the CEB [10]. The mainly saline groundwater originates from regular floods in the Cuvelai drainage, which has its headwaters in central Angola. The six main aquifer systems (table 1 and figure 6) can be distinguished within the CEB, namely the Otavi Dolomite Aquifer (DO) located on the western and southern rim, followed in the north by the Etosha Limestone Aquifer (KEL), the Oshivelo Multi-layered Aquifer (KOV) in the eastern area, the Ohangwena Multi-layered Aquifer (KOH) in the north-eastern parts, the Oshana Multi-layered Aquifer (KOS) covering the area of the Cuvelai drainage system and the Omusati Multi-zoned

Aquifer (KOM) situated in the west adjacent to the KOS [10]. The central Ohangwena 2 Aquifer (KOH2) lies below the shallower aquifers at depths of about 300 metres [9].

Groundwater becomes mineralised due to rock water interactions resulting in the dissolution of certain minerals and chemical elements which remain in solution in the groundwater [7]. Owen et al., [7] further explained that the degree of dissolution depends on the length of time that the rock/water is in contact, the length of the flow-path through the rock, the solubility of the rock materials and the amount of dilution by fresh recharge water. All groundwater is to a lesser or greater degree mineralised and in certain circumstances and environments some of these naturally occurring solutes may be toxic [7]. For multi-layered aquifer systems, dipping of an aquifer underneath much less permeable strata (confining layer) does not completely isolate it from the entire groundwater system for there is constant movement of water due to pressure and gravity. The rate at which groundwater moves through the saturated zone is well explained by Darcy’s Law, stating that groundwater movement is directly proportional to rock permeability and the hydraulic gradient.

2. Literature Review

This section aims to review the two tracer technique methods applied for estimating groundwater recharge, and previous studies on groundwater recharge estimation done using the chloride mass balance and the staple isotopes methods.

2.1 Chloride Mass Balance Method

Chloride is regarded as a suitable environmental tracer since it is highly soluble, conservative and not substantially absorbed by vegetation [2]**.** The CMB method uses the tracer properties of a chlorine ion and tracks its mass balance between the atmosphere and groundwater which is basically a one dimensional vertical flow through unsaturated and saturated zones without evapotranspiration or chloride input; therefore, the concentration of dissolved chloride in an aquifer would be the same as the dissolved chloride concentration in precipitation recharging the aquifer [13]. The time scales represented by recharge rates estimated using chloride mass balance range between 5 to 10 000 years [14]. Various studies have utilised the chloride mass balance method to estimate groundwater recharge of which they treated the chloride content as a point source rather than an integral. CMB method is convenient and inexpensive because of its simple data requirements [2]. For the chloride mass-balance method recharge is estimated by:

$$R = P \times \frac{Cl_p^{\,-}}{Cl_{gw}^{\,-}} \quad (Eq. 1)$$

Where, where R is recharge (mm/year); P is rainfall (mm/year); Cl_p^- is weighted average chloride concentration in rainfall (mg/l); and Cl_{gw}^- is average chloride concentration in groundwater (mg/l). The weighted average (Cl^-) is calculated based on the following equation:

$$Cl_p^{\,-} = \frac{P_1 \times C_1 + \ ... + P_n \times C_n}{P_1 + \ldots + P_n} \quad (Eq. 2)$$

where P_1 is the first rainfall event (mm) and C is the corresponding chloride concentration in the rainfall (mg/l), for 1 to n events. The application of the mass balance method in the saturated zone (groundwater) means the chloride content in groundwater is not a point measurement but rather an integral from the recharge zone up to that point. Somaratne and Smettem [15] described the theory of generalising chloride mass balance method for recharge estimation in groundwater basins characterised by point and diffuse recharge, indicating that the application of the conventional chloride mass balance (CMB) method to point recharge dominant groundwater basins can substantially under-estimate long-term average annual recharge by not accounting for the effects of localized surface water inputs. In unsaturated zones where water both evaporates and transpires, chloride becomes concentrated in the pore water as it undergoes evaporation [13].

As seen in [[16], p. 119] “when surface water recharges groundwater it has to pass the unsaturated zone. Therefore, the chemistry of the recharge water is a result of the interaction of rain water chemistry, input from dry deposition and reactions with the soil matrix.” That indicates that chloride in groundwaters should not be treated as point sources but rather as an integral from the recharge zone up to that point. Klock [16] further indicated that the chloride mass balance method in the unsaturated zone is limited to the parts where upward flux is negligible. Areas where a smaller percentage of precipitation is recharged will result in higher chloride concentration in soil and groundwater because chloride is evapo-concentrated in the upper part of the unsaturated zone where evapotranspiration is active [13].

2.1.1 Previous Studies

Several studies have applied the chloride mass balance method to estimate groundwater recharge locally and regionally. Hamutoko [17] studied the interaction of perched and regional aquifers in semi-arid environments (Cuvelai-Etosha Basin) using the chloride mass balance method and concluded that the calculated mean groundwater recharge rates varied from 5.5% to 19.4% and 5.1 to 32.4% of the annual precipitation for regional aquifers. Another study by Wanke et al., [18] estimated groundwater recharge using the chloride mass balance method in areas of Okongo, Okanguati and Omusati-Oshana considering dry depositions of 20% and 50%, it estimated groundwater recharge to vary between 1 mm/a and a 100 mm/a in most cases and greater than 100 mm/a at depression settings. David [19] assessed recharge for perched aquifers in the Ohangwena Region based on soil water balance modelling and the chloride mass balance method and has concluded that recharge into perched aquifers ranges between 46.8 mm/a to 53.6 mm/a (4.8 to 12 percent of annual precipitation) from this method.

A study by Liu et al., [20] applied the chloride mass balance method in estimating groundwater recharge in Luanjing Irrigation Area and concluded that groundwater recharge from precipitation, estimated by the chloride profile method, is less than 0.1 mm/a which accounts for just 0.06% of the long-term average annual rainfall, indicating that rainfall presently plays a minor role in the groundwater recharge. Liu et al. [20], further indicated that recharge events only occurred after heavy rain or sustained rainfall events. The chloride profile method indicated that the average annual recharge is 268 mm/a with an infiltration rate of 32.5%, which is reasonably consistent with the 33.1% obtained by the water balance method in 2007 [20]. The study showed that about one third of that water is discharged back to the groundwater.

A study by [2] similarly applied the chloride mass balance method in West Bank, Palestine and results revealed a replenishment potential which was within the estimated replenishment volumes of previous studies for the same area. Also, the estimated recharge ranged between 15 and 50% of total rainfall, which is still within the range of previous studies [2] has shown. Geological structures and climatic conditions of the western slope clearly played an important role in the increment of total volume [2] has indicated.

Another study by Naranjo et al. [21] that estimated natural recharge by means of the Chloride Mass Balance method in a volcanic aquifer North-eastern Gran Canaria (Canary Islands, Spain) concluded that the application of the chloride mass balance method resulted in an estimated average recharge of about 92 mm/year which is 24% of precipitation after subtracting chloride loss with surface runoff.

2.2 Stable Isotopes Method

Techniques based on the heat or chemical isotopic tracers are gaining much importance in the estimation of groundwater recharge [22]. Groundwater recharge is low in most cases, however, its estimation by classical methods is problematic; isotope techniques are likely more efficient [7]. The principles of evaporative losses calculation are based on the so-called Craig–Gordon (C–G) model which explains how the stable isotope compositions of liquid water and vapour change during progressive evaporation in response to conditions during the evaporation process [6]. Water isotopes oxygen-18 ($\delta^{18}O$) and deuterium($\delta^{2}H$), being conservative tracers, are ideal for investigating subsurface flow processes, they reveal information about soil water fluxes (e.g. evaporation, transpiration and downward infiltration) that are difficult to determine by other techniques [4].

The isotopic composition of a water sample is expressed as the per mille [‰] and the deviation of the isotopic ratio, R =D/H or $O^{18}/ {}^{16}O$ from that of a standard. The standard of reference in general use is VSMOW (Vienna Standard Mean Ocean Water) as shown in figure 7 [23].

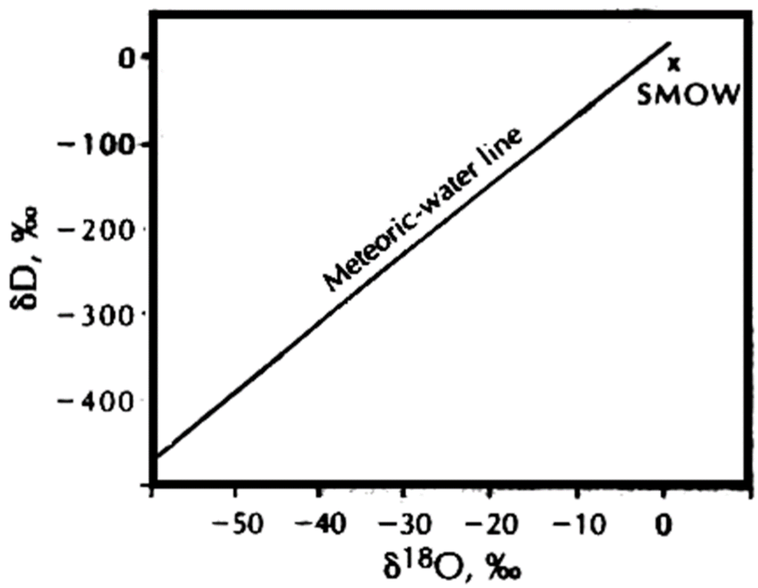

Figure 7: Plot $\delta^{18}O$ [‰] versus $\delta^{2}H$ [‰] for Meteoric water together with STANDARD MEAN OCEAN WATER (SMOW), [23].

2.2.1 Previous Studies

Beyer et al., [3] who estimated groundwater recharge via deuterium labelling in the semi-arid Cuvelai-Etosha Basin indicated that the methodology is particularly beneficial in data-scarce environments, where recharge pathways and mechanisms are poorly understood. Applying the displacement peak analyses of the $\delta^{2}H$, [3] has shown its practicality in semi-arid environments. Various studies [24, 25, 26, 27], have applied the stable isotope method to study and examine groundwater processes. Water in deep wells are a mixture reflection of water influenced by evaporation and water that infiltrated through fast preferential pathways, whereas shallow wells are strongly influenced by evaporation [26]. They further concluded that the differences in hydrochemical composition as well as the processes governing perched aquifers must be taken into account when planning groundwater management in the basin. [28] discussed the stable isotope signatures of meteoric water in the Cuvelai-Etosha Basin looking at seasonal characteristics, trends and relations to southern African patterns has concluded that the slope of the LMWL from the GNIP stations correlates with latitude, however, such a correlation cannot be found within the CEB. Wanke et al., [28] further indicated that precipitation in the CEB has δ^2H values range from -136.4 to 42.8 ‰ with a mean value of -47.2 ‰ and $\delta^{18}O$ values ranges from -18.69 to 5.94 ‰ with a mean value of -7.12 ‰ for events. Estimated recharge values are shown in table 2. Adomako et al., [4] who estimated groundwater recharge from water isotope (δ^2H, $\delta^{18}O$) depth profiles in the Densu River basin, Ghana, concluded that the measured data showed isotope enrichment in the pore water near the soil surface due to evaporation. Seasonal variations in the isotope signal of the pore water were observed to a depth of 2.75 m. Below that depth, the seasonal variation of the isotope signal was attenuated due to diffusion/dispersion and low water flow velocities [4].

Table 2: Recharge rates estimated by different studies in the CEB.

Study	**Recharge [mm/a]**	**Method**
Beyer et al., [3]	40-45	Stable Isotopes
Wanke et al., [18]	1-100	CMB
Hamutoko [17]	22.95 -162	CMB
David [19]	46.8 - 53.6	CMB
Hamutoko et al., [29]	1-224	CMB

3. Methodology

Two different approaches were used to quantify integral recharge along representative flow paths within the CEB. The first method estimated recharge using the chloride content of groundwater samples (Chloride Mass Balance method) which looked at the chloride concentration in groundwater samples along each flow paths. The second approach considered the use of stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$) which looked at the isotopic composition of groundwater samples along flow paths to calculate fractional losses. This study derived six representative transects while looking at aspects such as groundwater flow direction, basin geology, precipitation, chloride content in groundwater, isotopic composition of waters, aquifer type and catchment slope.

3.1 Data Collection and Analysis

This study collates existing chloride content and stable isotopes' data in groundwater within the CEB from representative hydrological years. Long term data obtained from the national borehole database (GROWAS), the Federal Institute of Natural Resources and Geosciences (BGR), [17, 25, 30, 31, 32] were used. An average rainfall contour map (figure 5) generated by Mendelsohn et al. [11] indicating the long-term average annual rainfall of the CEB and this was used as an input parameter for the study area's precipitation to determine recharge at starting points. Maps (figure 6) showing the directions of groundwater flow (change in hydraulic gradients) within the CEB by [9, 10] were used to hypothetically deduce flow paths A-A' to E-E' within a transect threshold of 5 kilometres using ArcMap whilst assuming that recharge happening at endpoint A' is an integral of what happened along the flow path from point A to A'. Additional information about chloride contents in rainwater was extracted from [16] who calculated the weighted average chloride concentration in the rainwater of the CEB to be 0.81 mg/l which was also used as an input component of equation 1 to calculate recharge (mm/a) along these flow paths. A total of 121 samples were used for the CMB method whilst 23 for stable isotopes along these transects, with data sampling dates ranging from 1973 to 2017. The specific number of samples per transect for each method and their sources are shown in table 3.

Table 3: Number and reference of groundwater data along transects.

Transect	**A-A'**	**B-B'**	**C-C'**	**D-D'**	**E-E'**	**F-F'**
Number of Cl samples	14	36	38	25	6	2
Number of Isotope samples	5	8	6	-	4	-
Source (s)	GROWAS, BGR, [32], [30]	GROWAS, BGR, [30], [25], [31]	GROWAS, BGR, [30], [25]	GROWAS, BGR	GROWAS, BGR, [28], [25], [17]	BGR

3.2 Recharge Estimation

Natural recharge of aquifers is a function of precipitation, along with many other factors such as geology, soils, vegetation, land use, climatic conditions, topography, land form and groundwater conditions [2]. The selected transects do not consider micro-recharge but rather macro-recharge for the Cuvelai-Etosha Basin's regional recharge from main aquifer systems. Recharge was estimated along each transect individually of which these flow paths were then considered as representatives of the entire study area's processes**.** Results from the two methods were compared, contrasted and the level of significance difference was determined. Knowing the recharge value for each transects' starting point, change in recharge values along the flow path until the endpoint were then determined. It was then assumed that the change in recharge values indicate progressive evaporation for the stable isotope's method and chloride conservation for the CMB method.

3.2.1 Chloride Mass Balance Method

This method was used to determine the recharge values along the six flow paths. Recharge was calculated using equation 1. By obtaining the chloride content for each point along each transects, we are able to estimate an integral recharge value from one point to another (until the endpoint) along the flow path. Based on hydraulic gradients and groundwater flow directions, it is assumed that what is happening at the end point (low elevation) of a transects in terms on chloride concentration and recharge values is representative of what has been happening upstream of the aquifer. A graphical representation of this process is shown in figure 8, assuming the hydraulic gradient and the entire transect processes are happening towards A from A'. Change in recharge values along flow paths was then calculated relative to each point's chloride concentration along the flow path from the starting point. Marei et al. [2] has outlined the four assumptions necessary for successful application of the chloride mass-balance method which are:

1. The absence of additional chloride sources such as dissolution of minerals, use of road salts and any potential source of pollution like wastewater.
2. Chloride is of a conservative nature in the system meaning that the ion neither leaches from, nor is absorbed by, aquifer sediments and does not participate in any particular chemical reaction.
3. The depth of the groundwater table should be deep enough to prevent groundwater evaporation.
4. Surface run-off should be minimal.

Water is assumed to evaporate in its pure form and therefore no chloride is lost through evaporative fluxes [15].

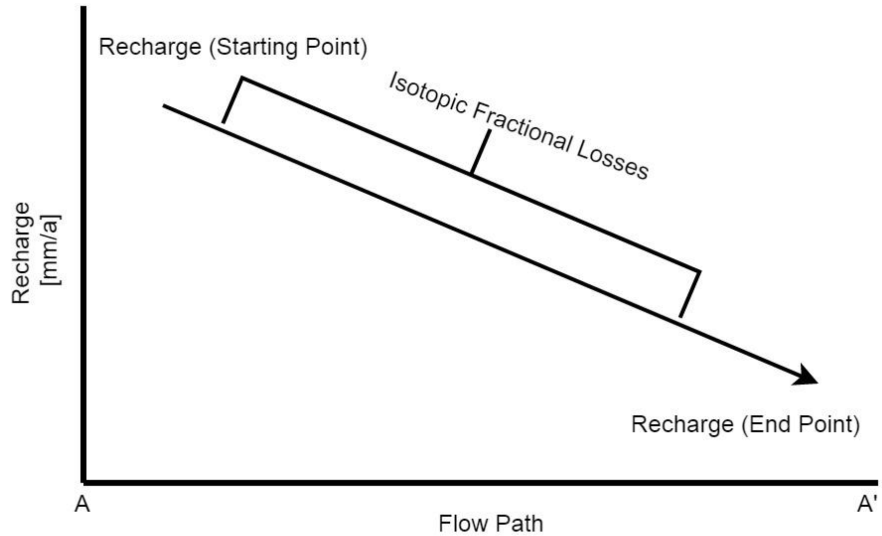

Figure 8: Determination of recharge along flow paths.

3.2.2 Stable Isotopes

Reviewing and combining the most recent equations required for estimation of evaporative losses based on the Craig–Gordon model, Skrzypek et al. [6] developed the hydrocalculator (obtained from http://hydrocalculator.gskrzypek.com) that allows quick and robust estimation of evaporative losses based on isotopic composition of water. The hydrocalculator was used to determine fractional loses, hence determining recharge values along flow paths. In this approach, the stable isotopic composition of water ($\delta^{18}O$ and $\delta^{2}H$) were used to calculate annual long-term groundwater recharge rates for the basin's representative transects based on fractional losses along sample points. The calculations were collectedly performed for a long-term annual basis between 1993 and 2017. Knowing all the required input parameters, this calculator automatically derives fractional losses based on the input whilst considering empirical relations. A non-steady state model was considered where water levels change over time is assumed to indicate progressive evaporation.

Similarly, to the CMB method approach of estimating recharge from the starting point up to the endpoint, sample points' water isotopic composition ($\delta^{18}O$ and $\delta^{2}H$) values were determined and then plugged into the hydrocalculator to determine fractional losses from one point to another until the endpoint. As shown in figure 9, for a non-steady model and the available data, the main three steps involved as outlined by [6] were:

- Selecting the hydrological regime of the studied water body which was a steady-state model where inflow (I) equal evaporation (E) plus outflow, hence indicating progressive evaporation.
- Calculating δ_A from the stable isotope composition of precipitation (δ_{Rain}) for the studied location and season;
- Entering analysed stable isotope composition of water δ_P- initial value for water in the pool; δ_L– final value for water in the pool; T – temperature; h – relative humidity of air (as fraction); δ_A– the stable isotope composition of moisture in ambient air (if known); δ_{Rain}–the stable isotope composition of precipitation (δ_A is unknown)**;** LEL – if known for the study area.

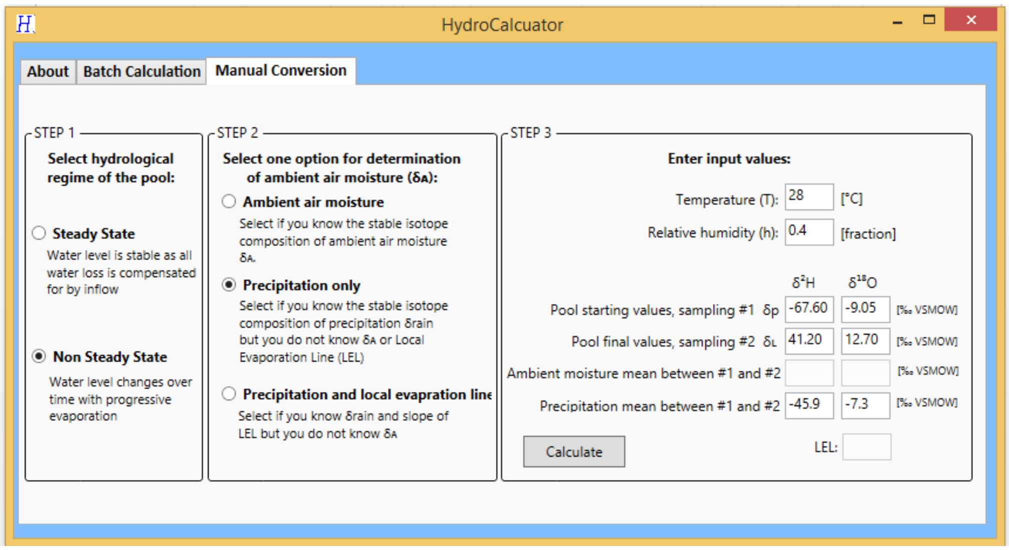

Figure 9: Example of input variables and steps for isotopic fractional loss calculations (transect A-A').

3.3 Groundwater Management Plan

In semi-arid areas recharge rates are the crucial input parameters for groundwater management studies [33]. Groundwater management has to be based on a good understanding of the groundwater characteristics of the total groundwater system [7]. From the findings and literature, an overview of possible groundwater management strategies was developed for the CEB by considering main aquifers systems, recharge and discharge zones, water quality and quantity whilst integrating other important components of water resources management within the Cuvelai-Etosha Basin.

4. Results

4.1 CEB Chloride-Stable Isotopes Spatial Distribution

The distribution of chloride content and isotopic composition of groundwater within the entire Cuvelai-Etosha Basin are shown in figure 10 and 11**.** The chloride content in groundwater increases towards the basin's central area of which according to [9] is identified to be an area of the lowest elevation and part of the basin's major drainage area. Chloride content ranges from >0.1 mg/l to 34300 mg/l with an average value of 505 mg/l. The lowest chloride point values are mostly observed along the south-eastern and north-eastern rims of the basin in the Tsumeb and Nipele sub-basins. For stable isotopes, $\delta^{18}O$ values ranges between -10‰ and 21‰ while $\delta^{2}H$ varied from -70‰ to 41.2‰, similar to the distribution trends displayed by the chloride content in groundwater, enrichment of heavier isotopes in groundwater increases towards the Etosha Pan from all basin rims with the south-eastern and north-eastern rims of the basin giving more depleted values in the heavier isotopes.

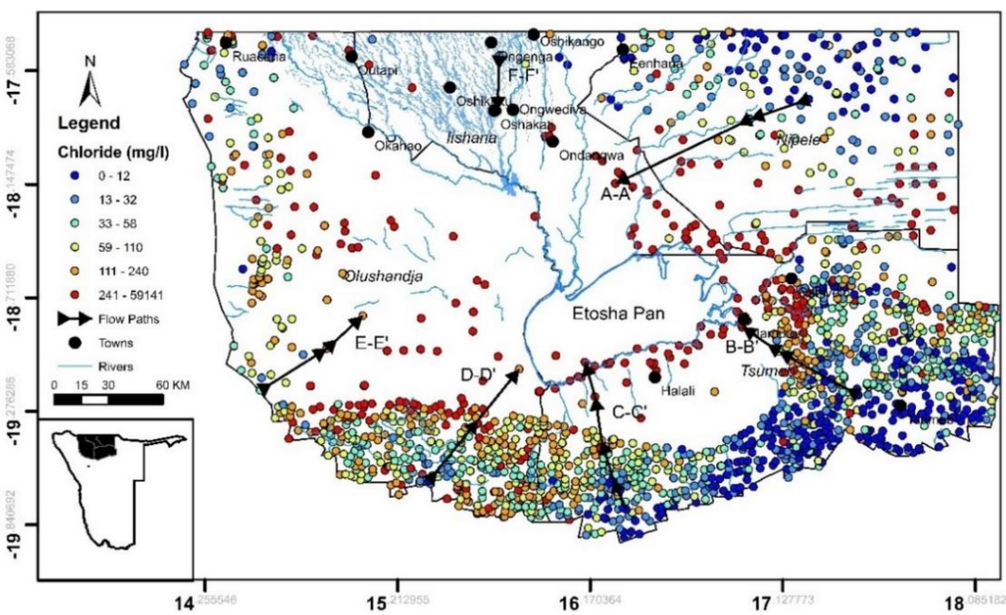

Figure 10: Distribution of chloride content in groundwater for CEB (source of original data given in table 3).

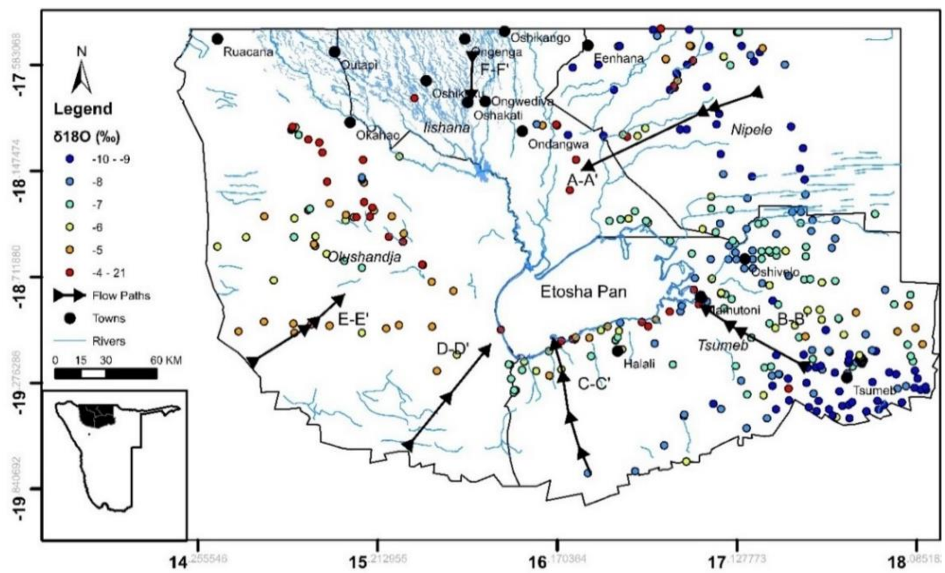

Figure 11: CEB groundwater delta-O-18 distribution (source of original data given in table 3).

4.2 Flow Path Results

4.2.1 Transect A-A’

4.2.1.1 Chloride and Stable Isotopes Distribution

With a length of 112 km this flow path runs through the Ohangwena Multi-layered Aquifer (KOH) and the Oshana Multi-layered Aquifer (KOS). This flow path consists of 14 chloride groundwater samples and 5 stable isotope sample points. Displaying a clear trend, the evolution of both chloride content in groundwater and the concentration of stable isotopes from point A to A’ indicates a progressive increase from point A to A’ as shown in figure 12 and 13. The chloride concentration ranged from a minimum value of 9 mg/l at the starting point up to a value of 13800 mg/l, the transect endpoint which is only about 4 kilometres ahead of the maximum point has a concentration value 4330 mg/l. The minimum values of $\delta^{18}O$ and $\delta^{2}H$ were -9.5‰ and -70‰, respectively, while the maximum values were 12.7‰ for $\delta^{18}O$ and 41.2‰ for $\delta^{2}H$. The dual isotopic composition plot along this flow path yield a slope of 4.9 with the regression line equation of δD=4.9δ^{18}O-21 where reliance (R^2) is 0.99. The flow path has an initial isotopic composition of water source of -9.5‰ for $\delta^{18}O$ and -70 ‰ for δ^2H. All stable isotope data along this transect plot below the GMWL.

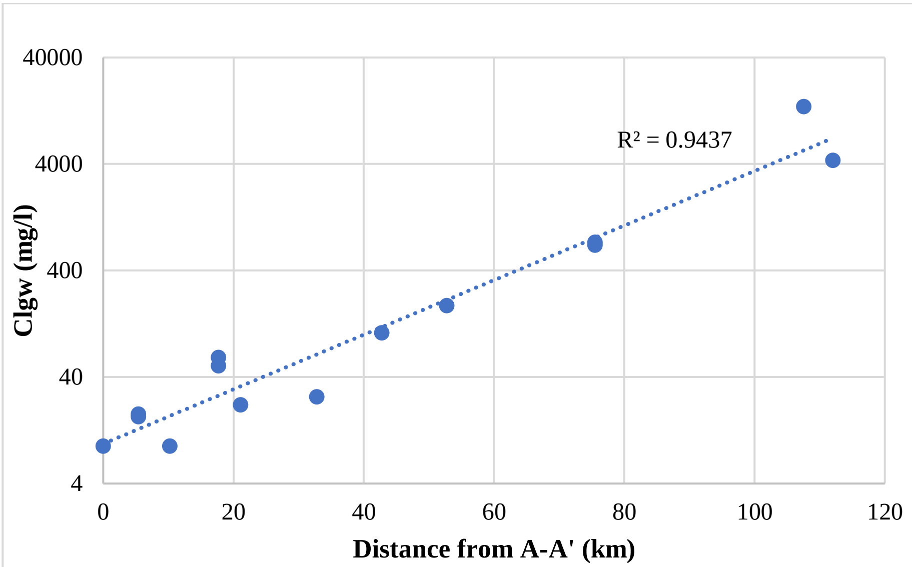

Figure 12: Development of chloride concentration in groundwater samples along flow path A-A'.

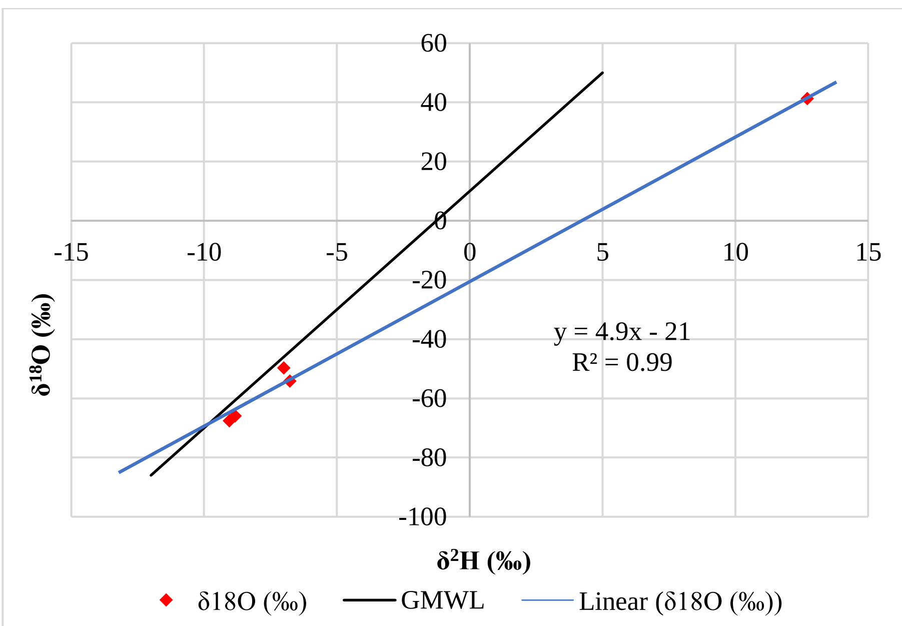

Figure 13: Dual isotopic composition plot of groundwater samples along flow path A-A'.

4.2.1.2 Groundwater Recharge

Recharge values along this flow path decrease towards the Etosha Pan. The calculated integral recharge rates range between 0.08 mm/a and 40.5 mm/a for the CMB method while for the stable isotopes' method the initial recharge value integrated to 3.24 mm/a along this flow path. The CMB method has an endpoint recharge percentage of 0.21% whereas the stable isotopes give an endpoint recharge percentage of 8% relative to the transects' 40.5 mm/a the starting point recharge value. Therefore, the stable isotopes method yields a higher endpoint recharge value with a difference of about 7.79% in comparison to the CMB method as shown in figure 14.

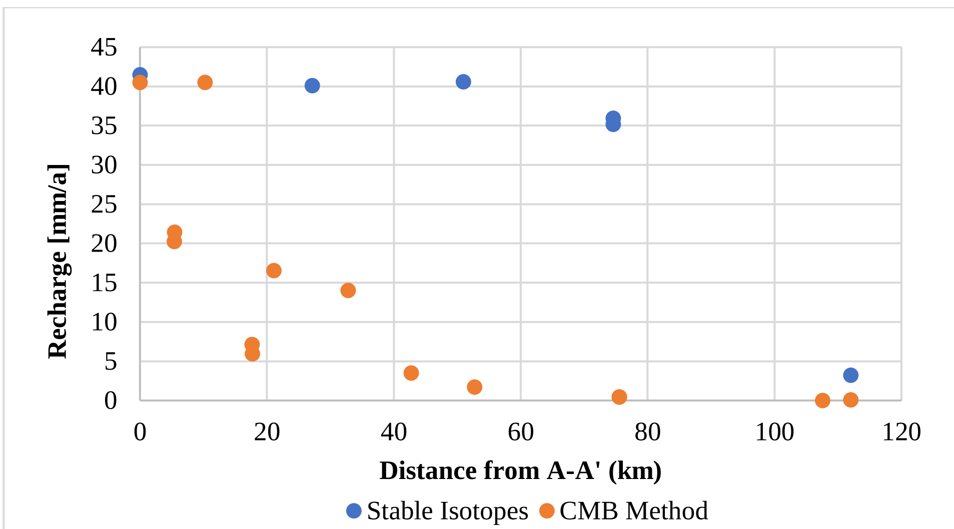

Figure 14: Integral recharge development along Transect A-A' from both the CMB and Stable Isotopes methods.

4.2.2 Transect B-B'

4.2.2.1 Chloride and Stable Isotopes Distribution

A total of 36 chloride and 8 stable isotopes groundwater samples were used along this transect. Cutting across the Etosha Limestone (KEL) and the Oshivelo Multi-layered (KOV) Aquifers this flow path has a length of 74 km. The development and evolution of chloride concentration in groundwater samples along this transect is as shown in figure 15, displaying an increase towards the basin's central area. This flow path has a minimum chloride concentration value of 4 mg/l which is also the starting point, a mean value of 159 mg/l, maximum of 731 mg/l and an endpoint value of 692 mg/l. The dual isotopic plot (figure 16) determined the evaporation slope and the initial isotopic composition of source water. The minimum values of $\delta^{18}O$ and $\delta^{2}H$ were -9.2‰ and -64.9‰, while the maximum values of $\delta^{18}O$ and $\delta^{2}H$ were -0.81‰ and -16.93‰, respectively**.** Isotopic data along this path yields the greatest slope (5.4) in comparison to all other transects and a regression line equation of δD=5.4$\delta^{18}O$ – 14.5 with a reliance (R^2) of 0.99. The initial isotopic composition of water source is -9.2‰ for $\delta^{18}O$ and - 64.9‰ for $\delta^{2}H$.

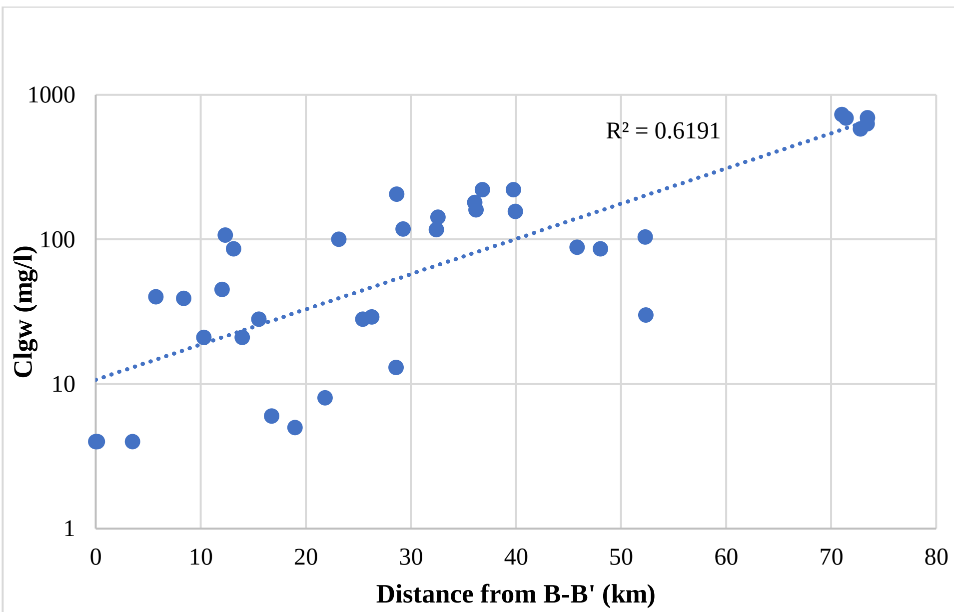

Figure 15: Development of chloride concentration in groundwater samples along flow path B-B'.

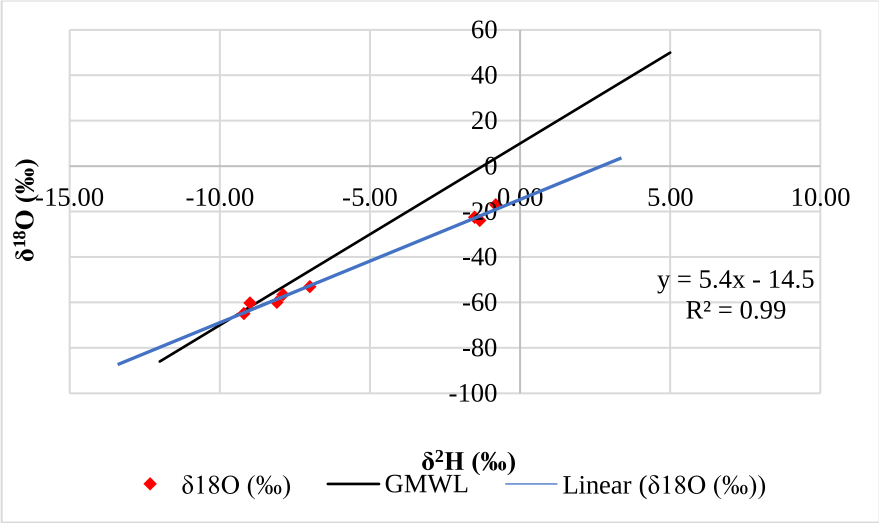

Figure 16: Dual isotopic composition plot of groundwater samples along flow path B-B'.

4.2.2.2 Groundwater Recharge

From the two methods, an integral endpoint recharge value of 0.53 mm/a was obtained from the CMB method while a value of 51.27 mm/a was obtained from the stable isotopes' method relative to the starting point's 91.13 mm/a as shown in table 5. Stable isotopes show a greater conservation of recharge along this flow path in comparison to the CMB method with a difference in endpoint recharge of 50.74 mm/a. The stable isotope's method gives a more gradual discharge slope in comparison to the CMB method.

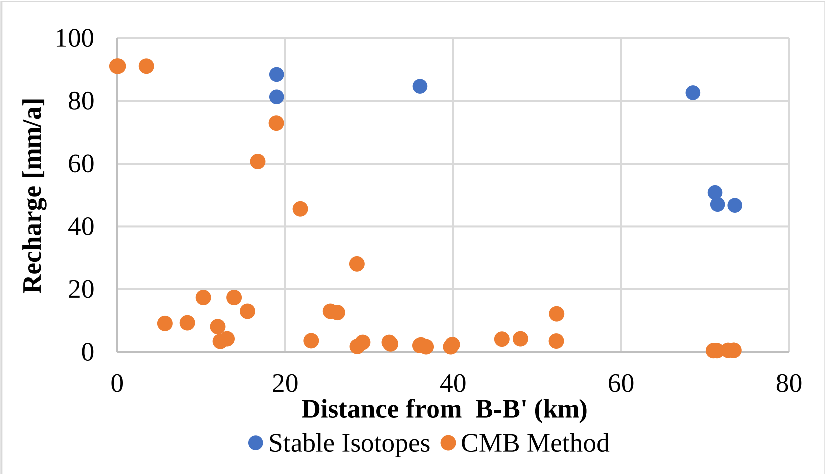

Figure 17: Integral recharge development along Transect B-B' from both the CMB and Stable Isotopes methods.

4.2.3 Transect C-C'

4.2.3.1 Chloride and Stable Isotopes Distribution

Within the Tsumeb sub-basin, this preferential flow path has a length of 88 km cutting across the Etosha Limestone (KEL) and Otavi Dolomite (DO) Aquifers. There are 38 Cl groundwater samples and 6 samples for stable isotopes along this path. The observed minimum chloride concentration is 8 mg/l and 2510 mg/l for the maximum. Sample points along this flow path (figure 18) clearly indicate an increase in the chloride concentration of groundwater samples as moving inwardly towards the Etosha Pan. The dual isotopic plot is shown in figure 19. The isotopic composition of water varies between -9.6‰ and - 1.21‰ for δ^{18}O and from -70‰ to -23.74‰ for δ^{2}H, respectively. The δ^{18}O vs δ^{2}H plot yields a slope of 5.1 and a regression line equation of δD=5.1δ^{18}O-17 with a reliance (R^2) value of 0.98. The initial isotopic composition of source water is -9.6‰ for δ^{18}O and - 70‰ for δ^{2}H.

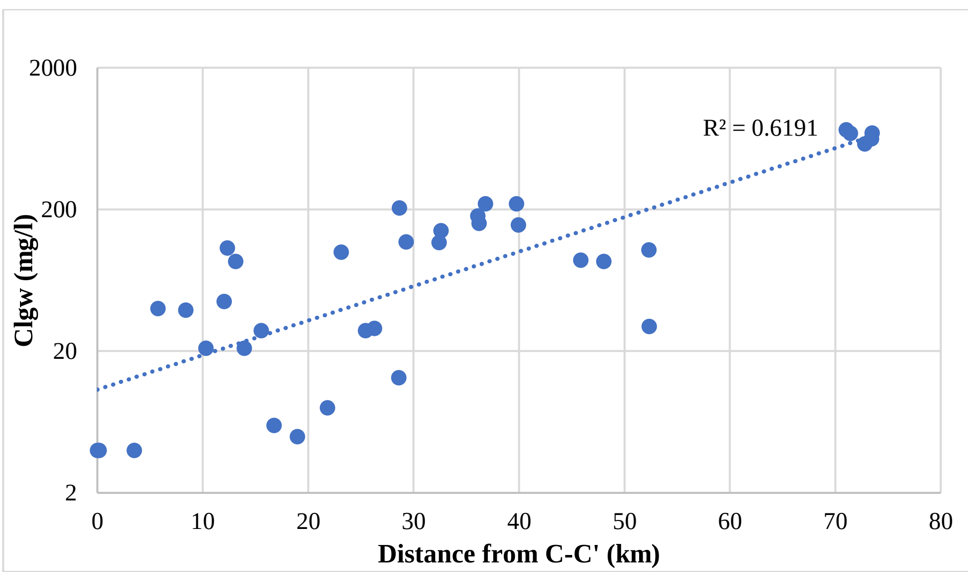

Figure 18: Development of Chloride concentration in groundwater samples along flow path C-C'.

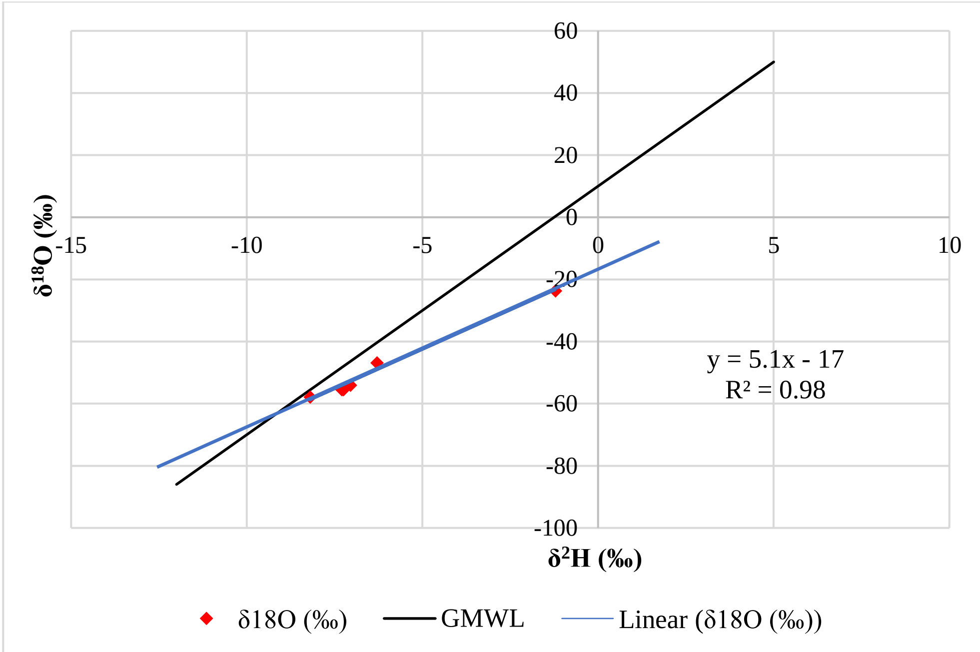

Figure 19: Dual isotopic composition plot of groundwater samples along flow path C-C'.

4.2.3.2 Recharge Estimation

Estimated recharge development along this transect from both methods is shown in figure 20 and table 5. For the CMB method recharge values ranged from 45.56 mm/a to 0.40 mm/a (end point), based on this method, only about 2.32% of the initial recharges reaches the discharge zone. However, using the stable isotopes method there is a much higher endpoint recharge value in comparison to the CMB method, about 67.32% of the initial recharge value is retained up to the endpoint along this transect based on the stable isotopes' method.

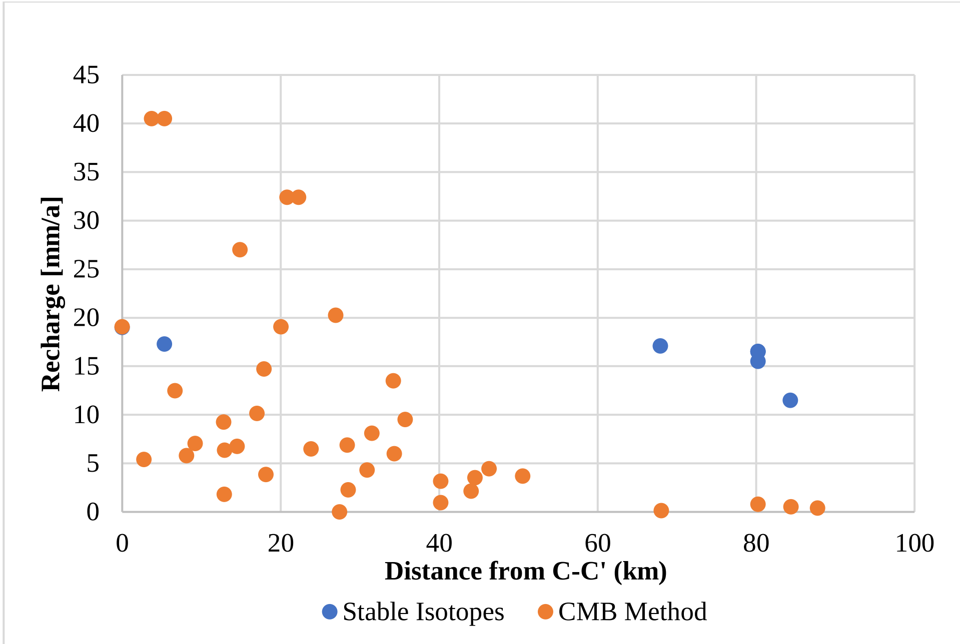

Figure 20: Integral recharge development along Transect C-C' from both the CMB and Stable Isotopes methods.

4.2.4 Transect D-D'

4.2.4.1 Chloride Distribution

Points along this transect (figure 21) do not indicate steepness but there is a progressive increase of chloride content in groundwater along this 82-kilometres which increases with increasing distance from the starting point to the endpoint and the entire drainage area. This transect moves across the Otavi Dolomite (DO) and the Etosha Limestone (KEL) Aquifers and it consists of 25 chloride points with a minimum value of 12 mg/l, a maximum value of 290 mg/l and an average value of 86 mg/l.

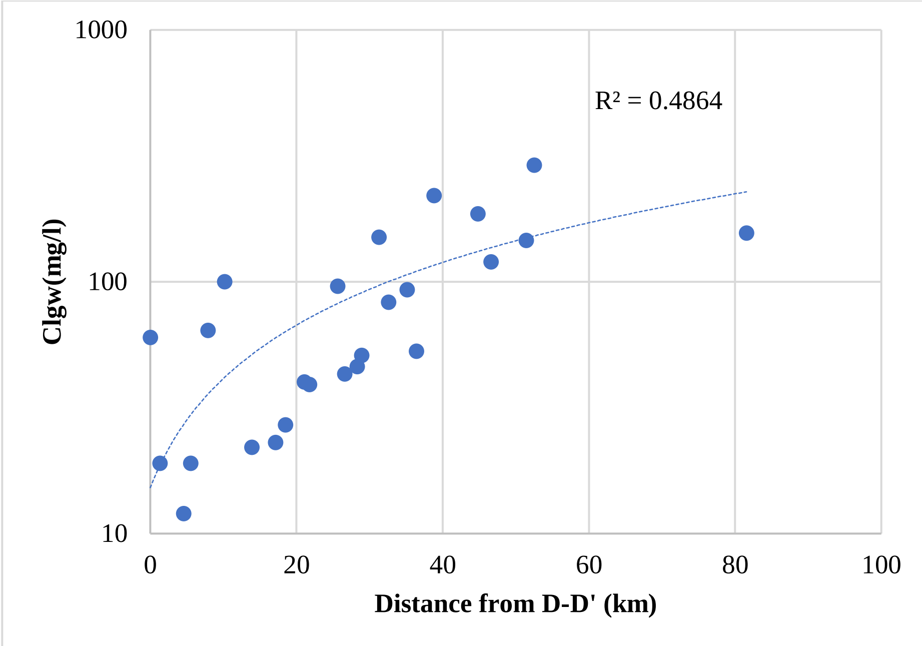

Figure 21: Development of Chloride concentration in groundwater samples along flow path D-D'.

4.2.4.2 Groundwater Recharge

Recharge variation along this flow path is shown in figure 22 with a starting point recharge of 4.05 mm/a and 1.56 mm/a for the endpoint from the CMB method, however, recharge values get as high as 20.25 mm/a along the transect at distance of about 5 kilometres from the starting point. About 38.5% of the initial recharge is taken along the flow path. Unfortunately, no isotopic data in the required threshold to estimate recharge rates are available along this flow path.

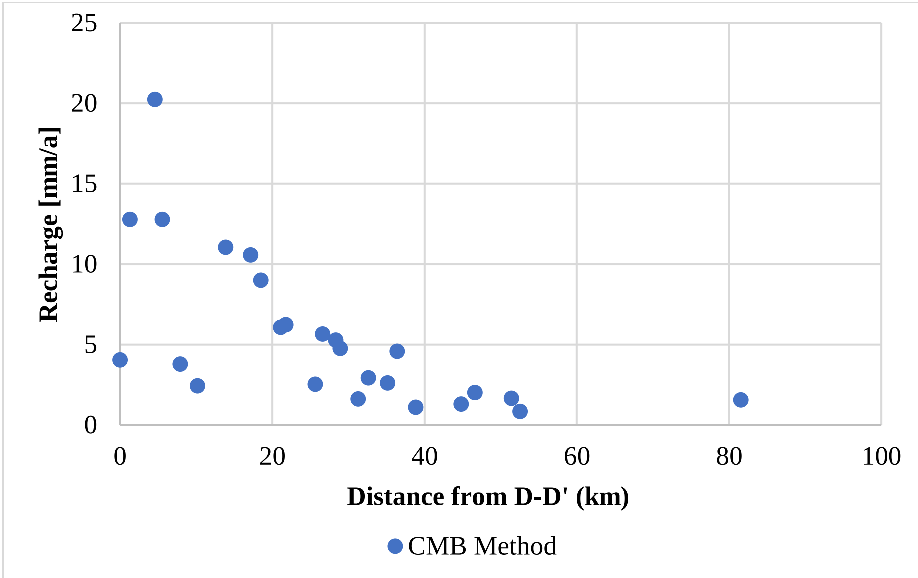

Figure 22: Integral recharge development along Transect D-D' from the CMB method.

4.2.5 Transect E-E'

4.2.5.1 Chloride and Stable Isotopes Distribution

This flow path cuts through the Otavi Dolomite (DO), Etosha Limestone (KEL) and Omusati multi-zoned (KOM) Aquifer units and has a length of 68 kilometres. Four chloride samples and four stable isotopes samples were used along this flow path. Chloride constitution in groundwater from these samples is shown in figure 23, which shows an increase moving towards the endpoint. Samples along this flow paths have a chloride minimum value of 32 mg/l, mean value of 121 mg/l and a maximum of 235 mg/l as the endpoint. The dual isotopic plot (figure 24) gives the evaporation slope and the initial isotopic composition of water source was determined through intersecting the GMWL. $\delta^{18}O$ [‰] values ranged from -7.6‰ to -1.65‰ while $\delta^{2}H$ values extended between -52‰ and -25.27‰. The dual isotopic plot gives a slope of 4.1 with a regression line equation of $\delta D = 4.1\delta\ ^{18}O - 19$ and reliance (R^2) of 0.92. The initial isotopic composition of water source is -7.6 ‰ for $\delta^{18}O$ and -52 ‰ for $\delta^{2}H$.

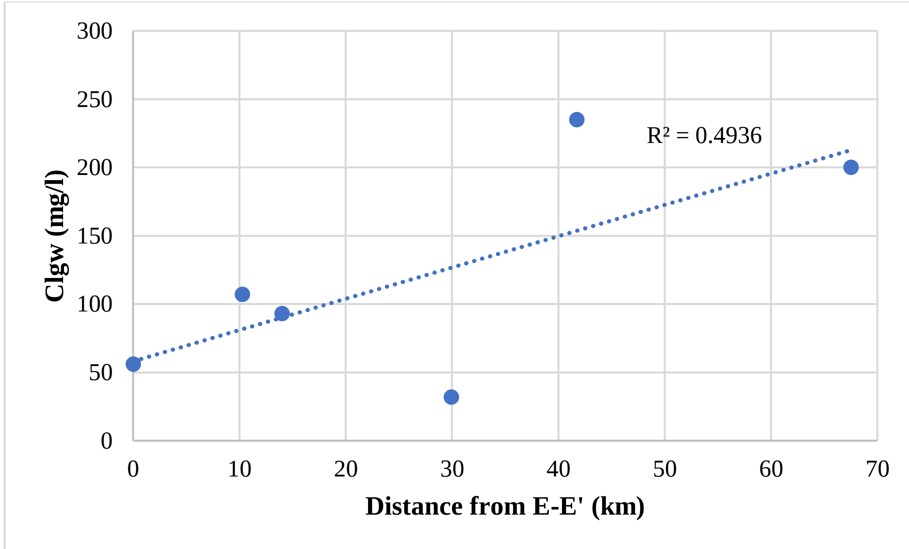

Figure 23: Development of Chloride concentration in groundwater samples along flow path E-E'.

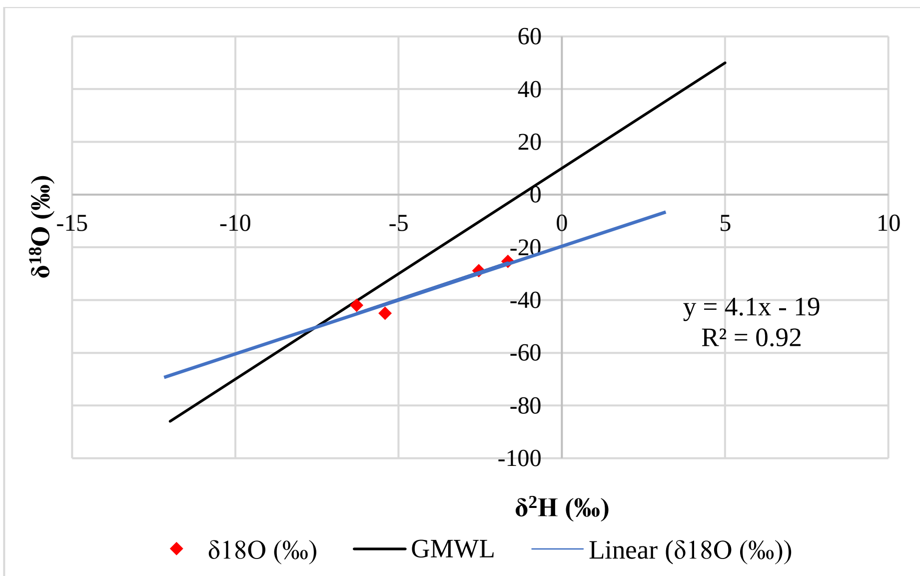

Figure 24: Dual isotopic composition plot of groundwater samples along flow path E-E'.

4.2.5.2 Groundwater Recharge

Development of estimated recharge rates using the two methods along this transect are shown in figure 25. Similarly, recharge development along this transect decreases towards the drainage area. For the CMB method an endpoint value of 1.22 mm/a was obtained, however, recharge went as high as 7.59 mm/a thirty kilometres from the starting point.

The stable isotopes method gives an endpoint integral recharge of 3.11 mm/a which is about 43% greater than that of estimated by CMB method along the same flow path.

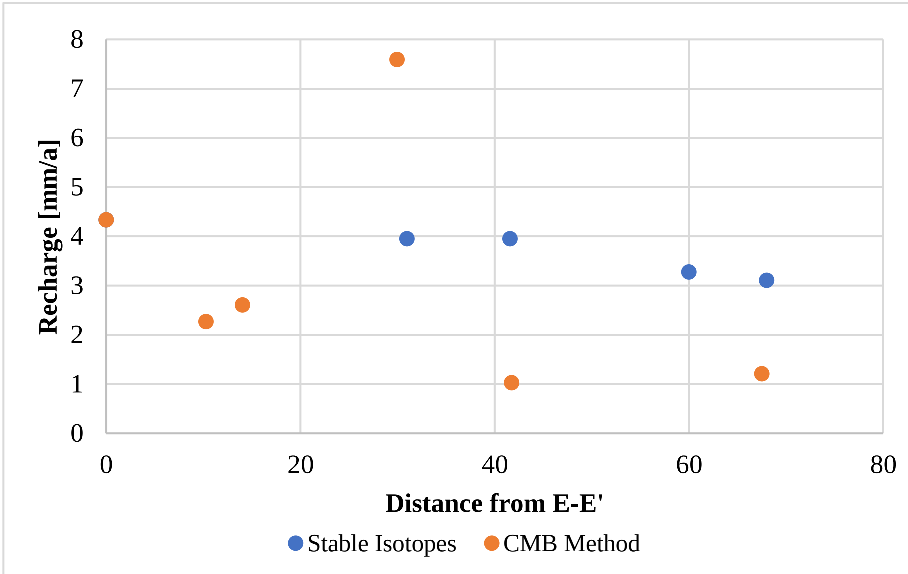

Figure 25: Integral recharge development along Transect E-E' from both the CMB and Stable Isotopes methods.

4.2.6 Transect F-F'

4.2.6.1 Chloride and Stable Isotopes Distribution

With only two chloride sample points within the study threshold, flow path F-F' has a length of 30 km across the Oshana Multi-layered (KOS) Aquifer unit. It has a lowest value of 28 mg/l and the highest value of 10700 mg/l. The evolution of chloride content in these groundwater samples and recharge development along this transect are shown in figure 26 and 27.

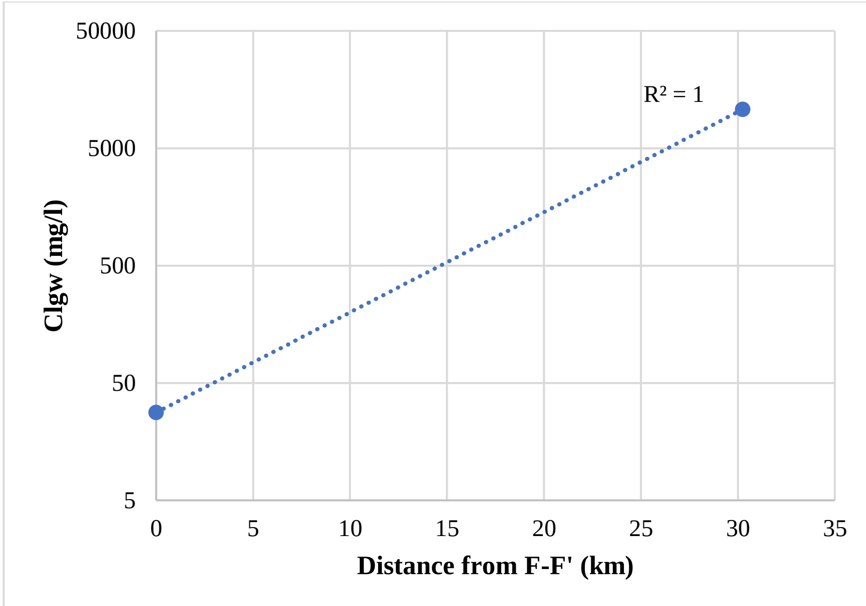

Figure 26: Development of Chloride concentration in groundwater samples along flow path F-F'.

4.2.6.2 Groundwater Recharge

This transect displays no trends different from the other 5 flow paths, with chloride content in groundwater decreasing towards the Etosha Pan which is inversely proportional to the estimated recharge. Recharge ranges from 12 mm/a to 0.03 mm/a from the starting point inwardly towards the Etosha Pan, meaning about more than 99% is retained along the flow path.

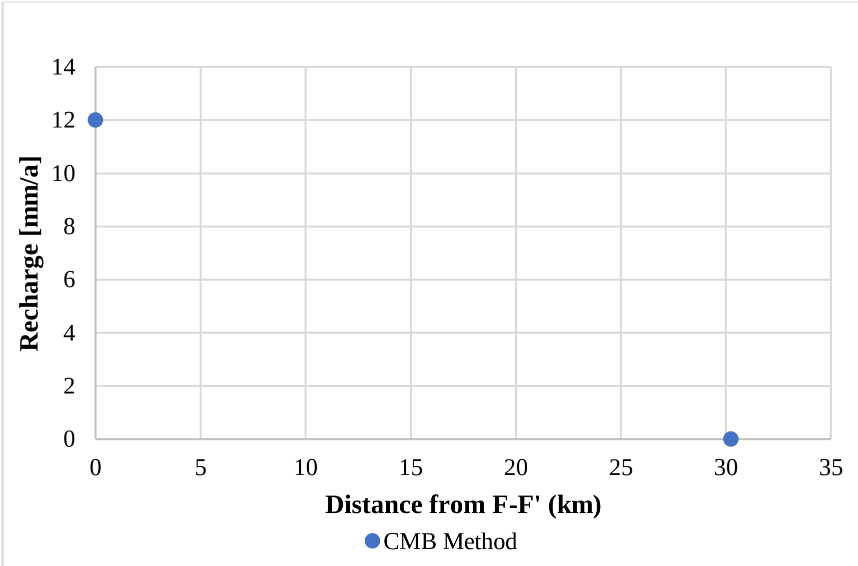

Figure 27: Integral recharge development along Transect C-C' from the method.

4.3 Overall Transects Results Description

Overall, for the representative transects, chloride concentration in groundwater samples ranges from 4 to 13800 mg/l with an average of 390 mg/l. Generally, $\delta^{18}O$ ranged from -9.6‰ to 12.7‰ with an average value of -5.52‰ while $\delta^{2}H$ ranged from -70‰ to 41.2‰ with a mean value of -45.42‰ for the stable isotopes. Overall trends displayed by the six transects are similar and homogeneous in terms of the estimated recharge, groundwater chloride content and stable isotopic composition of waters. Temperature ranges between 19 and 31.2 °C with an average of 25.5 °C. pH ranges between 6.37 and 9.66. Descriptive parameters for each flow path are shown in table 4.

Table 4: Descriptive statistics parameters for each transect.

Transect			**A-A’**	**B-B’**	**C-C’**	**D-D’**	**E-E’**	**F-F’**
Cl_{gw} (mg/l)	Min		9	4	8	12	32	28
	Max		13800	731	2510	1320	235	10700
	Mean		1433	159	170	133	121	5364
	Median		56	87	49	60	100	5364
$\delta^{18}O$ [‰]	Min		-9.5	-9.2	-9.6		-7.6	
	Max		12.7	-0.81	-1.21		-1.65	
	Mean		-4.74	-5.61	-6.7		-4.7	
	Median		-7.92	-7.45	-1.21		-5.42	
$\delta^{2}H$ [‰]	Min		-67.6	-64.9	-70		-52	
	Max		41.2	-16.93	-23.74		-25.27	
	Mean		-44.4	-44.76	-51.95		-38.59	
	Median		-60.1	-54.85	-2.74		-41.89	
Dual isotope plot regression line	Slope		4.9	5.4	5.1		4.1	
	Intersect	$\delta^{18}O$ [‰]	-9.5	-9.2	-9.6		-7.6	
		$\delta^{2}H$ [‰]	-70	-64.9	-70		-52	
Initial isotopic composition of water source	$\delta^{18}O$ [‰]		-9.5	-9.2	-9.6		-7.6	
	$\delta^{2}H$ [‰]		-70	-64.9	-70		-52	
Temperature (°C)	Min		19	19.6	24		22.6	
	Max		27.9	27.6	27.8		26.6	
pH			9.3	7.5	7.6		8.4	
Length (km)			112	74	88	53	68	30

For transects with both datasets, recharge rates calculated from both methods were plotted against each other. Transect E-E’ yields the highest percentage of endpoint groundwater recharges from the stable isotopes method with approximately 72% while transect D-D' gives the highest endpoint value of about 28% from the CMB method. The initial isotopic composition of water source along transect E-E' has enriched isotopic values at higher altitudes with -7.6‰ for $\delta^{18}O$ and -52‰ for $\delta^{2}H$ in comparison to the rest of the transects, such can be explained by the rainout effect or amount effect, where in precipitation, the initial liquid phase of rain is enriched in heavier isotopes ($\delta^{18}O$ and $\delta^{2}H$) in comparison to the later precipitation. Transect D-D' does not contain isotopic data. However, for all the six transects from both methods, recharge values are smallest towards the Etosha Pan and the entire drainage area of the basin. It should be noted that a minimum/maximum value along a transect does not necessarily mean it is the starting/endpoint for recharge calculation. Regression Lines from the dual isotopic compositions plots of transects A-A' , B-B', C-C' and E-E' are given in figure 13, 16, 19 and 24. Unfortunately, no isotopic data for transects D-D' and F-F' in a threshold of 5 kilometres were available. The dual isotopic plots show the development and changes in isotopic composition of waters along the four flow paths relative to their starting points and the Global Meteoric Water Line (GMWL).

Generally, the isotopic ratios for transect A-A' were more depleted and suggested a greater contribution to discharge in comparison to other transects. Regression lines from both transects slightly deviate from to the Global Meteoric Water line (GMWL), which indicates progressive evaporation along these flow paths. Table 4 summarizes the descriptive statistics for each transect. From the dual isotopic plots evaporation slopes generally ranges between 4.1 and 5.4 for transects A-A', B-B', C-C' and E-E'. The estimated recharge results for each transect are shown in table 5. Flow path A-A' yield the highest evaporation losses of 92% along a flow path of 112 kilometres and transect B-B' discharges about 49% of the recharge amount relative to its starting point along a flow paths of 74 kilometres. Fractional losses for transect C-C' account for about 32% and 28% for transect E-E' respectively. The relationship between the estimated recharge and mean annual precipitation along flow paths is shown in figure 28. Starting points with larger mean annual precipitation values yield greater endpoint recharge values, where starting point recharge is directly proportional to the mean annual precipitation value along the transect given by y=0.37x-112.41 where R^2 = 0.55. However, the end point recharge is inversely proportional to the precipitation amount, where y = -0.01x+3.66 and R^2 = 0.75 which is difficult to explain when assuming that larger precipitation events should yield greater endpoint recharge values in comparison to lower rainfall amounts, and this may require further detailed studies.

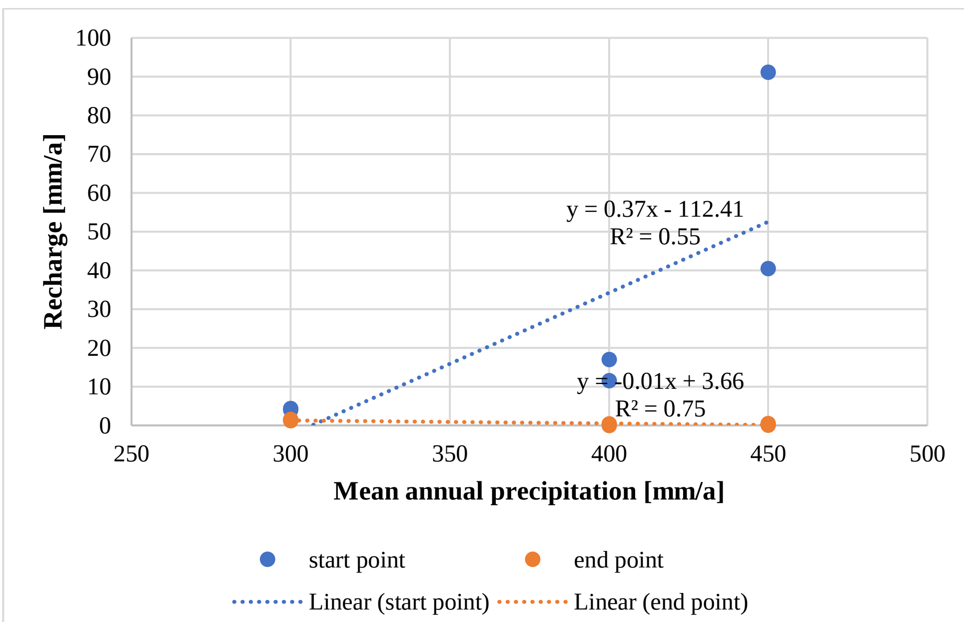

Figure 28: Estimated recharge and mean annual precipitation along flow paths

Table 5 also gives the input parameters which were used to estimate recharge for each method and summarizes the estimated recharge rates from applying both the CMB and stable isotope methods.

Table 5: Recharge calculations for transects A to E.

Transect	**A-A'**	**B-B'**	**C-C'**	**D-D'**	**E-E'**	**F-F'**
Chloride Mass Balance Method						
Cl (mg/l) content at Starting Point	9.00	4	19	60	56	28
Rainfall (mm/year)	450	450	400	300	300	400
Weighted average chloride con. in rainfall (mg/l)	0.81	0.81	0.81	0.81	0.81	0.81
Starting Point Recharge [mm/a]	40.50	91.13	17.05	4.05	4.34	11.57
Cl (mg/l) content at End Point	4330	692	820	156	200	10700
End Point Recharge [mm/a]	0.08	0.53	0.40	1.56	1.22	0.03
End Point Recharge (%)	0.21	0.58	2.32	38.46	28.00	0.26
Stable Isotopes						
$\delta^{18}O$ (‰) Starting Point	-9.50	-9.2	-9.6		-7.6	
$\delta^{2}H$ (‰) Starting Point	-70.00	-64.9	-70		-52	
$\delta^{18}O$ (‰) End Point	12.70	-1.34	-1.21		-1.65	
$\delta^{2}H$ (‰) End Point	41.20	-23.87	-23.74		-25.27	
Temperature (°C)	28.00	26	27		27	
$\delta^{2}H$ Fraction Loss	0.98	0.99	0.45		0.31	
$\delta^{18}O$ Fraction Loss	0.86	0.31	0.33		0.25	
Starting Point Recharge [mm/a]	40.50	91.13	17.05		4.34	
End Point Recharge [mm/a]	3.24	46.72	11.48		3.11	
End Point Recharge (%)	8.00	51.27	67.32		71.72	

5. Discussion

Generally, for each individual method, results from transects considered display similar patterns in terms of the estimated recharge rates, chloride content and the stable isotopic composition of groundwater samples. However, there are significant differences in results from the CMB method and the stable isotopes' method. Results from each method are detailly discussed in 5.1 and 5.2. Regardless the significant differences in results obtained from the two methods, groundwater recharge rates determined by both methods agree well with the ranges of values found in previous studies such as [3, 17, 18, 19, 29] as shown in literature and figure 29. However, the CMB method displays much lower recharge values along similar transects in comparison to the stable isotope's method.

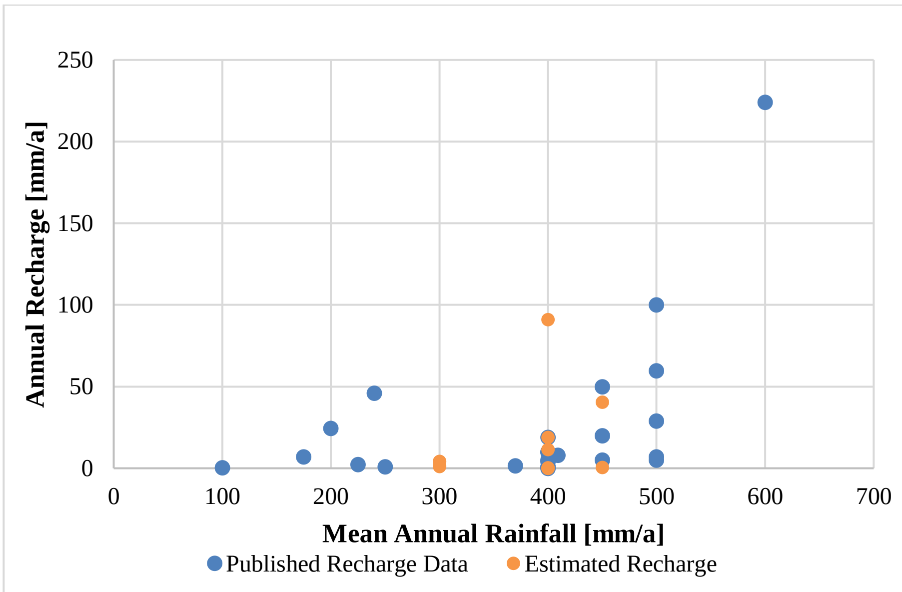

Figure 29: Estimated recharge from the study in comparison to recharge estimated from previous studies.

Overall, temperature is less variable for the groundwater in the entire basin but much lower along transect B-B' which is to the south-east of the basin within the Tsumeb sub-basin. Similarly, contact springs were observed at Halali and Sueda by [25] to have deep cooler temperatures and very high EC, since temperate increases with depth this could indicate that recharge might have taken place at higher altitude where the ambient temperature is lower and if water travels quickly through weathered limestone in that region to the discharge point and does not equilibrate with the aquifer's temperature, it stays cooler provided the travelling time is short.

5.1 Chloride Mass Balance Method

From the CMB method, endpoint recharge rates range from 0.21% to 38.46% of annual precipitation, which is within the range of previous studies as stipulated in literature. The lowest endpoint integral recharge values relative to the starting point's recharge are observed along transect A-A' from either method, 0.21% for the CMB method comparable to the 8% from stable isotopes method. Transect A-A' runs through an area of the Ohangwena-Multi layered Aquifers (KOH). Hamutoko [17] who has done a study on the Ohangwena perched aquifers indicated that deep groundwater is recharged by high intensity/large rainfall events, whereas the shallow wells are recharged by less intense/small rainfall events**.** [17] further indicated that groundwater originates from precipitation and undergoes strong evaporation, carbonate dissolution and alkali enrichment as a result of silicate weathering and cation exchange during percolation through both unsaturated and the saturated zones. Even though [17] studied perched aquifers in the same area, the groundwater system is interconnect and such observations may also affect the deepest part of the aquifer hence the little endpoint recharge along flow path A-A'. With much longer transects such as A-A' giving the highest chloride content values, it could only mean that groundwater-lithology interaction is flow path length dependant. This is supported by [7] as exchange function between geology and groundwater is related to the length of time that the rock and water interact, the length of flow path and type of materials where groundwater interactions with geological materials giving groundwater a specific chemical content**.**

Transects B-B', C-C', D-D' and E-E' fall on the southern part of the basin. These transects are mainly dominated by dolomitic layers of the Otavi Dolomite Aquifer where dissolution and carbonaceous process are most dominant hence the little chloride composition at transect starting points. Chloride data along transect D-D' does not indicate steepness regardless the processes long the transect and this could indicate consistency along this flow path with little or no change in lithology. Groundwater along these transects is recharged in the fractured dolomites of the Damara Sequence, which forms the southern and western rim of the basin, flowing north and eastwards and feeds the aquifer system of the Karoo and Kalahari sequences [10]. And in fractured aquifers, much more rapid preferential flow to the water table may occur, especially after heavy rainfall [7] has indicated. Reference [34] who studied groundwater flow in the southern part of the Etosha Basin using the chemical composition of water along transects from the basin rims towards the Etosha Pan, concluded that water is generally dominated by alkaline-earth metals and hydrogen carbonate at the starting points whilst sodium, sulphate and chloride concentrations increase continuously and form the main components at the endpoint (Etosha Pan) of the transects, which is similarly observed for the chloride content in this study.

Transect E-E' yields the highest endpoint recharge percentage in comparison to all transects for stable isotopes. However, based on the CMB method, the endpoint recharge along this profile is only 1.22 mm/a, which is less than half the values estimated by the stable isotope method on the same profile. According to [17], groundwater in Omusati region is dominated by sulphate, while cation changes from calcium and magnesium (Ca-Mg) dominated water to sodium and potassium (Na-K) dominated water. In addition, some part of transect E-E' runs through the Otavi Dolomite (DO) and the Etosha Limestone aquifers, Marei et al., [2] stated that high chloride contents in some samples can be ascribed to the low permeability chalky limestone formation. The mean chloride content in groundwater samples along transect F-F' is about 73% greater than all other transects. With the depth to water table between 10-50 meters [9], the Omusati Multi-zoned (KOM) Aquifer is shallowest. Transect F-F' falls in the main Cuvelai drainage system from the neighbouring Angola which is a periodically flooded area and that can make it difficult to estimate long-term recharge rate due to chloride input from surface run-off. Incoming water flushes previously precipitated salts into the lower Cuvelai which undergoes evaporation and results in high chloride contents. In addition, high groundwater chloride content may be due to hydrogeological environments as for transect F-F' runs through the Omusati Multi-zoned Aquifer for which chloride concentrations are normally very high and variable in sandy clay layers, which is the main lithology of the Omusati Multi-zoned (KOM) Aquifer. Movement of groundwater across long distances relative to the geological environment and time for chemical reactions, leads to a zonal distribution of dissolved ions in the water during its flow [34].

5.2 Stable Isotopes Method

This approach gives higher endpoint recharge values in comparison to the CMB method for all transects. Flow path A-A' that yields the lowest endpoint integral recharge value of 8% relative to its starting point is greater than two third of the maximum endpoint recharge values obtained by the CMB method. On average, about 50% of the initial recharge reaches the discharge zone from the stable isotopes' method in comparison to only 11% that of the CMB method. The differences in recharge values estimated by the two methods along similar flow paths might be that isotopic composition of waters is not lithology dependent; only the chloride content of groundwater is. Geological environments have a greater influence on the chloride content but the same cannot be said about stable isotopes of waters. The stable isotopic composition is more influenced by precipitation and evaporative fractionation rather than lithological compositions.

Flow path A-A' runs through an area of the Ohangwena Multi-layered Aquifers (KOH), studied by Hamutoko [17], water in deep wells of the KOH-0 aquifers reflect a mixture of water influenced by evaporation during or before infiltration and water that infiltrated through fast preferential pathways whereas shallow wells are strongly influenced by evaporation. Therefore, mixing of highly evaporated new infiltrating water which is enriched in heavier isotopes due to evaporation and the pre-existing groundwater can explain the highly enriched heavier endpoint isotopic values. In addition, at lower altitudes, groundwater mixing of waters is less complex, recent precipitation effect to groundwater is normally noticeable when looking at the change in isotopic composition. Considering the altitude effect, [4] has explained that it results in more enriched precipitation ratios at lower altitudes and that can explain the enrichment in heavier isotopes as we move towards the lower areas of all transects in the basin (towards Etosha Pan, 1085 m.a.s.l) with shallow depths to water tables.

For all the four transects, most groundwater samples plot below the GMWL and that indicates that waters have undergone evaporation along these flow paths. Beyer et al., [3] who estimated groundwater recharge via deuterium labelling in the semi-arid Cuvelai- Etosha basin projected the potential recharge to be 45 mm/a at a depth of 5.6 m and 40 mm/a 0.9 m and this could only mean that groundwater depth plays a major role as for it controls direct evaporation effects. Estimated recharge rates from the stable isotopes' method fall in the ranges of previous studies, however, in comparison to [3] recharge rates obtained are more representative of much deeper profiles with littles evaporation effect. Based on isotopic values [30] indicated that groundwater in the northern Ohangwena Region close to the border to Angola show a relatively young conventional ^{14}C age thus demonstrating the proximity of the recharge area. Another study by [35] determined groundwater age by radiocarbon dating within the main deep aquifers of the CEB and groundwater increases from 2000 years near Okongo to 15 000 years near Okankolo. The obtained regression line average slope is 4.9 which is close to that of 5.1 obtained by [25] who studied groundwater stable isotope profile of the Etosha National Park. Regression Line equations obtained for all samples and each transect are shown table 6.

Table 6: Regression Line equations from all four transects data combined and individual regression line equations from the four transects with isotopic data

	Regression Line Equation	R^2	Number of Samples
All samples	$\delta D = 5\delta^{18}O - 17.6$	0.98	23
Transect A-A'	$\delta D = 4.9\delta^{18}O - 21$	0.99	5
Transect B-B'	$\delta D = 5.4\delta^{18}O – 14.5$	0.99	8
Transect C-C'	$\delta D = 5.1\delta^{18}O - 17$	0.98	6
Transect E-E'	$\delta D = 4.1\delta^{18}O – 19$	0.92	4

Endpoint samples along transects B-B’ (around the Namutoni area) and transect C-C’ (West of Halali) fall in an artesian area (figure 30) of which [25] indicated that artesian water points suggest variability in isotopic composition of waters. For settings as such, groundwater may be discharging to the surface through springs and artesian wells where mixing with surface water bodies and or interact with these bodies causing an enrichment in heavier isotopes of groundwater.

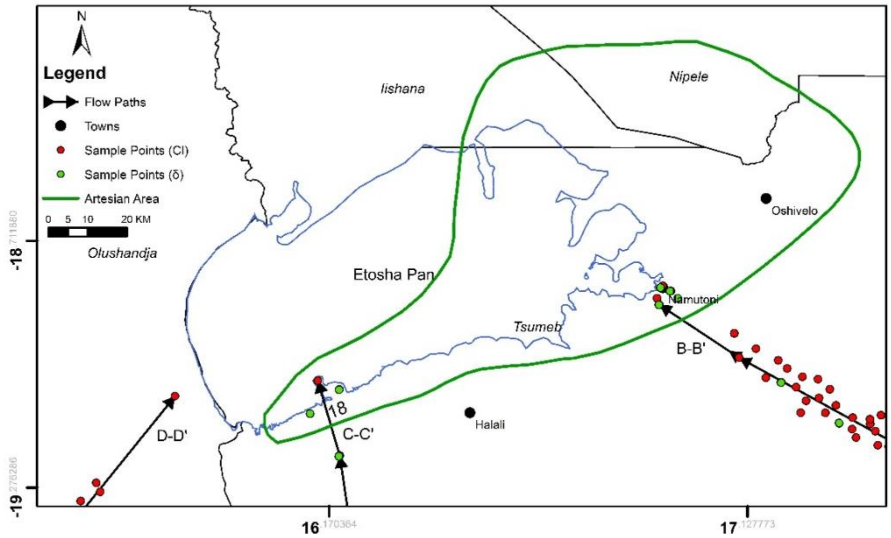

Figure 30: Distribution of sample points relative to the Artesian area.

5.3 Uncertainties

Uncertainties were eliminated by comparing the results with estimations from previous studies. The integral recharge estimated along these flow paths is time representative of more than 40 years, therefore, it could mean that these obtained integral recharge values may have over or under estimated recharge whilst not considering other factors such as aquifer abstraction rates. However, the alignment of observed results with literature seconds the usefulness of this study approach. Even thou according to [2] the CMB method requires/assumes profiles deep enough to avoid evaporation, one cannot ignore the evaporation effect which is clearly represented by the stable isotopes' method along similar profiles. Assuming that all rain water reaches the aquifer system may have caused uncertainties for the stable isotopes' method, because for smaller rain events (e.g. 1 mm) precipitation might completely evaporate causing discrepancies and recharge overestimation. Therefore, precipitation amounts should be differently considered for the two methods. In addition, the study had a weakness by over relying on the assumed mean annual precipitation when applying the stable isotopes method because the identified source water does not have the same isotopic composition as the rain water in CEB. According to [28] the rain events give mean isotopic composition values of -7.12‰ for $\delta^{18}O$ and -47.2‰ for $\delta^{2}H$ while the obtained source water gives more depleted (lower) isotopic values. Meaning, the source water's isotopic composition indicates that events of higher magnitude have contributed more to the source water than the ones of low amounts. If the source water is then composed of higher amount events, that could mean that the original source water is less than the assumed mean precipitation values of 450 mm/a or 400 mm/a used in the study. However, the percentage of evaporation loss (evaporated fraction) may account for it in a semi-arid environment.

6. Recommended Groundwater Management Strategies

6.1 Introduction

Groundwater management has to be based on a good perception of the groundwater characteristics at the scale of the total groundwater system [7]. About 88% of Namibia's water potential lies in its perennial rivers on its northern and southern borders and more than 80% of Namibia's land area relies solely on groundwater [36]. The management strategies and or recommendations presented are based on understandings derived from the study's results and literature. Factors affecting groundwater recharge, usage, demand and quality are discussed in order to enhance and protect groundwater resources within the CEB. [7] outlined that groundwater sustainability development is a function of the type of aquifer system, recharge rate, type and scale of groundwater use. Groundwater utilization has been steadily increasing within the CEB for decades with attempts from water governing bodies such as Namibia Water Corporation (NAMWATER) and the

Ministry of Agriculture, Water and Forestry coordinating, developing, and rationalising national groundwater utilization.

6.2 Recharge and Discharge Zones

With the identified recharge and discharge areas (figure 31), it is important to protect recharge areas such as the southern part of the CEB within the Tsumeb sub-basin of which [10] has too identified as an area of freshwater and deep fractured recharge zones of the Otavi Dolomites. Recharge zone extends to the west of the basin within the Olushandja sub-basin with the extension of the Otavi Dolomites unit. Besides direct infiltration from local precipitation, recharge along flow paths A-A' and F-F' originates from north upstream in Angola**,** this fits with studies by [10] and [35]**.** Protecting these areas ensures that the system continues being functional and there will be more recharge to the groundwater system. Recharge zones should not be covered by urban infrastructure regardless the need for expansion and development in the near future for it will decrease groundwater recharge to aquifer systems. Such sensitive aquifer recharge zones should be protected at all cost. Supplementary recharge (artificial) to groundwater which currently is not being practiced within the CEB for unexplored reasons may be another option to sustainability and boosting groundwater availability. Artificial recharging processes have been ongoing for Windhoek aquifers in central Namibia and have proved to be successful [37] stated. According to [37] the method proved to be useful in reducing evaporation as opposed to storing water in dams and increased water availability. After practicing artificial recharge for Windhoek aquifers between 2006 and 2012, the water demand in the central area of Namibia was well above the 95% safe yield of the available resources [38] has indicated. Therefore, applying a similar approach to CEB aquifer systems under careful considerations may aid in increasing water availability and quality to meet demand. However, [37] has indicated that artificial recharge may rise water levels and the need for protection will increase, which are some of the disadvantages that come with it.

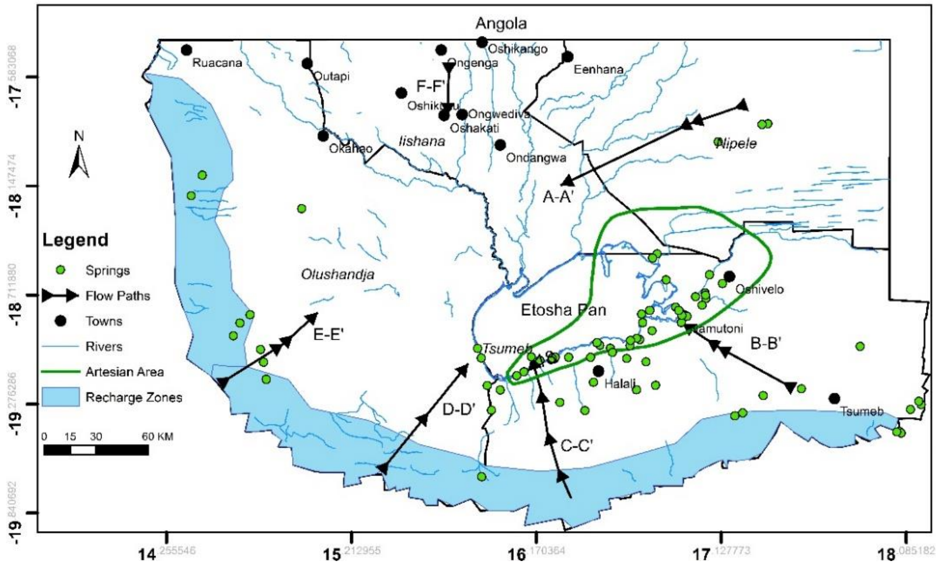

Figure 31: Basin recharge zones and artesian areas (discharge zones) within the CEB.

6.3 Water Quality and Demand

Water quality and quantity should be simultaneously considered for sustainable groundwater use. When water losses its quality, the overall quantity available for use is also decreased, meaning, quantity alone is not enough. Chloride content increases towards the discharge area (Etosha Pan) and major ions groups ($Mg^{2+,}$ Ca^{2+} Na+, K+, NO_3^-, SO_4^-, CO_3^{2-}, HCO_3^- and F^-) occur in association. Studied by [9], water quality for each aquifer unit is shown in table 7 and 8 together with the estimated volumes to aquifer units. Bittner [10] who investigated groundwater in the Cuvelai-Etosha Basin, concluded that the main aquifer systems present in the CEB show similar characteristics regarding the water quality and further stated that salinity generally increases towards the basin centre from the basin margins in the south and west the groundwater due to higher concentrations of chloride, sodium, fluoride and sulphate. Another report by [36] also confirms that groundwater over the greater part of the central basin contains prohibitive levels of salts which makes it unsuitable for human and stock drinking. Therefore, there should be a basin water quality monitoring program where each aquifer unit has at least 10 more constant monitoring groundwater quality sites in addition to the 28 existing monitoring sites per aquifer system from the Ministry of Agriculture Water and Forestry. With the aid of technology while considering cost, this study proposes that groundwater quality monitoring should be in real time where data gets to the end user as quick as possible after collection. Water quality monitoring should prioritise remote area such as Amarika (well-known high natural fluoride contents in groundwater) in the Omusati area of which such is major natural thread to the disadvantaged population. Water quality monitoring should asses the basic field parameters such as Salinity, Total Dissolved Solids (TDS)**,** Electrical Conductivity (EC)**,** Acidity (pH), Chloride, Calcium, Magnesium, Potassium, Fluorides, Sodium, Nitrates and Carbonates making. The quality of water improves as one moves eastwards, westwards and southwards from the central zone [35], however, the main water demanding area with high population density is to the north of Etosha-Cuvelai Basin, not south of it. Thus, it is critical to sustainably abstract groundwater before its quality deteriorates and this can be done through monitoring borehole abstraction to avoid groundwater mining as this will also have a significant impact on Etosha where high and uncontrolled abstraction rates may dry lakes causing an impact to wildlife and amenity of the Etosha. There should be sustainable withdrawals of groundwater aquifers by granting abstraction permits at all levels.

Demand for water in the right quantity and quality exerts excessive pressure on the available water resources. The Integrated Water Resources Management Plan by [36] has indicated that the demand for Namibia in 2008 was 63.7 Mm^3/a and the estimated demand in 2030 is 85.6 Mm^3/a, using available surface waters through harvesting methods maybe be a greater idea to help meet these water demands and to reducing the exploitation of groundwater from aquifers. The estimated volumes to the main six aquifer systems from both methods are shown in table 7 and 8, where the stable isotopes' method yields the highest recharge values to aquifers systems. The Otavi Dolomite (752 Mm^3/a) and Etosha Limestone (1617 Mm^3/a) aquifer systems show the greatest contribution to groundwater recharge. The Ohangwena aquifer system also shows a greater potential of recharge to the system of about 637 Mm^3/a (stable isotopes method) and 28 Mm^3/a (CMB method) to the aquifer system from the perched aquifers. The CMB method yields a minimum summation value of 64 Mm^3/a whilst the stable isotope's method estimated the minimum volume to aquifer systems to be 1390 Mm^3/a. Opting for maximum values to the aquifer systems seems to overestimate, therefore, minimum values seems to be more representative. However, there might be potential for higher values and that needs further detailed studies applying other independent recharge estimation methods such as water level fluctuations. According to [36] about more than 80% of the population in CEB already depend on groundwater resources. Creation of alternative satisfying water demand measures such as rainfall harvesting, recycling and water imports other than just the use of groundwater increases groundwater availability.

Table 7: Estimated volumes to aquifer system based on the chloride mass balance method and aquifer water quality as studied by [9].

Aquifer System	Area [km^2]	Min Recharge [Mm^3/a]	Max Recharge [Mm^3/a]	Average Recharge [Mm^3/a]	Water Quality
Otavi Dolomite Aquifer (DO)	18561	18	752	188	Low TDS levels (<1000 mg/l), low chloride and fluoride levels, low to high nitrate levels and low sulphates concentration.
Etosha Limestone Aquifer (KEL)	17744	2	1617	261	Low TDS levels, low fluoride levels, low to high nitrate and chloride levels and low sulphates concentration.
Omusati Multi-zoned Aquifer (KOM)	11354	14	18	16	Very high TDS (>6000 mg/l) and fluoride levels, high levels of nitrates (>40 mg/l), very high sulphate and chloride levels.
Oshana Multi-layered Aquifer (KOS)	23097	1	267	49	Very high TDS (>6000 mg/l) and fluoride levels, low nitrate levels (<10 mg/l), very high sulphate levels. Low to medium chloride levels.
Ohangwena Multi-layered Aquifer (KOH)	15882	28	643	273	Low to high TDS levels, low to high fluoride levels, Low nitrate levels (<10 mg/l), low to high sulphate levels.
Oshivelo Multi-layered Aquifer (KOV)	4687	2	3	2	Low to medium TDS levels, high fluoride levels, low to high nitrate and chloride levels, low to high sulphate levels.
Total	**91325**	**64**	**3300**	**788**	

Table 8: Estimated volumes to aquifer system based on the stable isotopes' method and aquifer water quality as studied by [9].

Aquifer System	Area [km^2]	Min Recharge [Mm^3/a]	Max Recharge [Mm^3/a]	Average Recharge [Mm^3/a]	Water Quality
Otavi Dolomite Aquifer (DO)	18561	354	1691	1023	Low TDS levels (<1000 mg/l), low chloride and fluoride levels, low to high nitrate levels and low sulphates concentration.
Etosha Limestone Aquifer (KEL)	17744	70	1570	752	Low TDS levels, low fluoride levels, low to high nitrate and chloride levels and low sulphates concentration.
Omusati Multi-zoned Aquifer (KOM)	11354	35	37	36	Very high TDS (>6000 mg/l) and fluoride levels, high levels of nitrates (>40 mg/l), very high sulphate and chloride levels.
Oshana Multi-layered Aquifer (KOS)	23097	75	831	573	Very high TDS (>6000 mg/l) and fluoride levels, low nitrate levels (<10 mg/l), very high sulphate levels. Low to medium chloride levels.
Ohangwena Multi-layered Aquifer (KOH)	15882	637	645	641	Low to high TDS levels, low to high fluoride levels, Low nitrate levels (<10 mg/l), low to high sulphate levels.
Oshivelo Multi-layered Aquifer (KOV)	4687	219	387	266	Low to medium TDS levels, high fluoride levels, low to high nitrate and chloride levels, low to high sulphate levels.
Total	**91325**	**1390**	**5162**	**3291**	

6.4 Groundwater Monitoring and Reports

Monitoring borehole water levels and having a monitoring network may help in giving the appropriate abstraction rates from an aquifer to avoid over exploitation and groundwater mining. Each of the boreholes should be allocated with its own relevant trigger levels based on its well behaviours. The direction and quantity of groundwater flow is susceptible to changes that occur to the hydraulic gradient [39]. For groundwater level measurements, there should be an automatic reader (e.g. Solinst Levelogger or the equivalent from Schlumberger) which takes daily levels and they should be read out at least every third month. Generally, outflow has been towards the central pan of the CEB**.** Efforts should be made to continuously monitor groundwater discharge at known springs and artesian wells near the Etosha Pan area (figure 31), such monitoring processes will aid in assessing changes to groundwater discharge relative to the overall groundwater flow patterns. While meeting water demands, there should also be abstraction monitoring, restrictions and or sustainable pumping measures, such restrictions could aid in reducing the amount of groundwater use. Groundwater monitoring may protect the most vulnerable aquifers and encourages sustainable use of these groundwater resources especially north of the CEB where the demand is crucial. Annual reports on groundwater basin conditions and management activities will aid in future development strategies, therefore during the monitoring of groundwater levels reports must be always generated.

6.5 Stakeholder Involvement and Capacity Building

The management of groundwater resources is based upon serving the public's interest in a responsible manner [39]. Involvement of entities with an interest in groundwater resources within the CEB should be a compulsory step for management of these groundwater resources. There should always be interactive participation between basin management committees and stakeholders where stakeholders are also allowed to review and contribute the basin's groundwater planning processes, such an opportunity will aid in improving communication and coordination between all levels where effective and efficient stakeholders' participation may be achieved. Future development and management of these groundwater resources lies in the development of the right people with the right skills; hence, capacity building is always a major step. The study course under which this thesis is authored indicates the seriousness of capacity which is amongst the good steps of acquiring knowledge for sustainable development.

7. Conclusion

This study used two tracer techniques, the Chloride Mass Balance (CMB) method and stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$) to estimate groundwater recharge within the Cuvelai-Etosha Basin along six transects. Recharge rates ranged from 0.21% to 38.46% of mean annual precipitation from using the CMB method and 8% to 72% according to the stable isotopes' method, which falls in the range of previous studies as stipulated in literature. From the obtained results, there is much significance between the two methods with the stable isotopes method estimating much higher values whilst the CMB method seems to underestimate, however, the notion of using CMB method to calculate integral recharge instead of point recharge seems more usable. From all the four transects with isotopic data there was a sign of evaporation influence along these flow paths. Similarities in data trends were observed from all methods, enrichment in heavier isotopes of water and an increase in chloride content towards the discharge area. The similarity in patterns from both transects could only emphasizes the reliability of the applied methods and a true representation of the basin's groundwater process at large. To deeply understand the contribution of local processes, these methods may need to be applied at a smaller scale with more samples along the transects to help understand local variability and its contribution to the entire regional groundwater system. Quantity alone is not enough to improve the usage and management of groundwater resources. Therefore, groundwater quality monitoring, controlling of abstraction rates and alternatives of other water sources such as rainwater harvesting, artificial recharge, and water importing should also be considered. Water quality, quantity and availability are key for sustainable groundwater management. From the estimated recharge and volumes to aquifer systems, the Otavi Dolomites, Etosha Limestone aquifers contribute more to the basin's recharge. However, part of the recharge entering the aquifers from the recharge zones may be lost and/or loses its good quality along the flow path, therefore early abstraction before evaporation and quality deterioration is highly recommended. Yet, it should be done under careful monitoring as over abstraction may change groundwater flow direction. Results from these methods indicate that the two approaches are valid when all assumptions necessary for their successful application are being followed.

References

[1] P. Greenwood, “Sustainable use of non-renewable groundwater in northern Namibia,” in *African Ecology: Fall Seminar*, University of Basel, 2017.

[2] A. Marei, S. Khayat, S. Weise, S. Ghannam, M. Sbaih and S. Geyer, “Estimating groundwater recharge using the chloride mass-balance method in the West Bank, Palestine,” *Hydrological Sciences Journal,* vol. 55, no. 5, p. 780–791, 2010.

[3] M. Beyer, M. Gaj, J. T. Hamutoko, P. Koeniger, H. Wanke and T. Himmelsbach, “Estimation of groundwater recharge via deuterium labelling in the semi-arid Cuvelai-Etosha Basin, Namibia,” *Isotopes in Environmental and Health Studies,* vol. 20, no. 1025-6016, pp. 1-17, 2015.

[4] D. Adomako, P. Maloszewski, C. Stumpp, S. Osae and T. Akiti, “Estimating groundwater recharge from water isotope (δ2H, δ18O) depth profiles in the Densu River basin, Ghana,” *Hydrological Sciences Journal,* vol. 55, no. 8, pp. 1405-1416, 2010.

[5] Y. Xu and H. E. Beekman, Groundwater Recharge Estimation in Southern Africa, Paris: UNESCO Paris, 2003.

[6] G. Skrzypek, A. Mydłowski, S. Dogramaci, P. Hedley, J. Gibson and P. Grierson, “Estimation of evaporative loss based on the stable isotope composition of water using "Hydrocalculator",” *Journal of Hydrology,* vol. 523, pp. 781-789, 2015.

[7] R. Owen, M. Mirghani, M. Diene, A. Tuinhof and P. Taylor, “Groundwater Management in IWRM, Training Manual,” Cap-net, South Africa, 2010.

[8] R. Miller, “The Owambo Basin of northern Namibia,” *Sedimentary Basins of the World 3,* 1997.

[9] J. Mendelsohn, A. Jarvis and R. Tony, A profile and Atlas of the Cuvelai-Etosha Basin, Raison and Gondwana Collection, 2013.

[10] A. Bittner, “Desk study report Cuvelai-Etosha groundwater investigation,” DWAF, Geohydrology Division, Windhoek, 2006.

[11] J. Mendelsohn, S. El Obeid and C. Robrts, A profile of north-central Namibia, Windhoek: Gamsberg Macmillan Publishers, 2000.

[12] M. H. T. Hipondoka, The development and evolution of Etosha Pan, Namibia. Doctoral Thesis, Würzburg, 2005.

[13] C. A. Cooper, R. L. Hershey, J. M. Healey and B. F. Lyles, "Estimation of Groundwater Recharge at Pahute Mesa using the Chloride Mass-Balance Method," U.S. Department of Energy, Las Vegas, Nevada , 2013.

[14] M. I. Mutoti, "Estimating groundwater recharge using chloride mass balance in the upper Berg River catchment, South Africa," University of the Western Cape, Western Cape , 2015.

[15] N. Somaratne and R. J. Smettem, "Theory of the generalized chloride mass balance method for recharge estimation in groundwater basins characterised by point and diffuse recharge," *Hydrol. Earth Syst. Sci. Discuss,* vol. 11, p. 307–332, 2014.

[16] H. Klock, Hydrogeology of the Kalahari in north-eastern Namibia with special emphasis on groundwater recharge, flow modelling & hydrochemistry. Doctoral Thesis, Würzburg, 2001.

[17] J. T. Hamutoko, Groundwater recharge of perched aquifers in the Cuvelai-Etosha Basin, Namibia. Doctoral Thesis, Windhoek, 2018.

[18] H. Wanke, A. Nakwafila, J. T. Hamutoko, C. Lohe, F. Neumbo, I. Petrus, A. David, H. Beukes, N. Masule and M. Quinger, "Hand dug wells in Namibia: An underestimated water source or a threat to human health?," *Elsevier ,* p. 104–113, 2014.

[19] A. K. David, "Groundwater recharge estimation for perched aquifers in the Ohangwena Region based on soil water balance modelling and chloride mass balance," Windhoek, 2013.

[20] G. Liu, Y. Wang, Y. Zhang and S. Tao, "Application of chloride profile and water balance methods in estimating groundwater recharge in Luanjing Irrigation Area, Inner Mongolia," *Hydrological Sciences Journal,* vol. 54, no. 5, pp. 961-973, 2009.

[21] G. Naranjo, T. Cruz-Fuentes, M. Del Carmen Cabrera and E. Custodio, "Estimating Natural Recharge by Means of Chloride Mass Balance in a Volcanic Aquifer: Northeastern Gran Canaria (Canary Islands, Spain)," *Water,* vol. 7, no. 2073-4441, pp. 2555-2574, 2015.

[22] R. Khan, S. Islam and R. Singh, "Methods of estimating groundwater recharge," *International Journal of Engineering Associates,* vol. 5, no. 2, pp. 6-9, 2016.

[23] L. J. Terwey, “Isotopes in groundwater hydrology,” *Challenges in African Hydrology and Water Resource,* vol. 144, pp. 155-160, 1984.

[24] J. T. Hamutoko, H. Wanke, P. Koeniger, M. Beyer and M. Gaj, “Hydrogeochemical and isotope study of perched aquifers in the Cuvelai-Etosha Basin, Namibia,” *Isotopes in Environmental and Health Studies,* 2017.

[25] E. S. Riddell, W. Kilian, W. Versfeld and M. Kosoana, “Groundwater stable isotope profile of the Etosha National Park, Namibia,” *African Protected Area Conservation and Science,* vol. 58, no. 1, pp. 1-7, 2016.

[26] J. T. Hamutoko, H. Wanke, M. Beyer, M. Gaj and P. Koeniger, “Spatio-temporal variations of hydrochemical and isotopic patterns of groundwater in hand-dug wells: the Cuvelai-Etosha Basin, Namibia,” *International Association of Hydrological Sciences,* vol. 378, p. 29–35, 2018.

[27] Z. Li, G. Wang, X. Wang, L. Wan, Z. Shi, H. Wanke, S. Uugulu and C.-I. Uahengo, “Groundwater quality and associated hydrogeochemical processes in Northwest Namibia,” *Journal of Geochemical Exploration,* vol. 86, p. 202–214, 2018.

[28] H. Wanke, M. Gaj, M. Beyer, P. Koeniger and J. T. Hamutoko, “Stable isotope signatures of meteoric water in the Cuvelai-Etosha Basin, Namibia: Seasonal characteristics, trends and relations to southern African patterns,” *Isotopes in Environmental and Health Studies* , no. GIEH1505724 , 2018.

[29] J. T. Hamutoko, H. Wanke and H. J. Voigt, “Estimation of groundwater vulnerability to pollution based on DRASTIC in the Niipele sub-basin of the Cuvelai Etosha Basin,” *Namibia. Phys. Chem. Earth* , p. 1–9. doi:10.1016/j.pce.2015.12.007, 2016.

[30] M. A. Geyh, “Isotope Hydrological Study in Eastern Owambo, Etosha Pan, Otavi Mountain Land and Central Omatako Catchment including Waterberg Plateau,” GNGEP Technical Cooperation Project, Windhoek, 1997.

[31] GKWConsult and BiconNamibia, “Tsumeb Groundwater Study: Report of the Geological/Geophysical Surveys and Borehole Siting,” Department of Water Affairs, Windhoek, 2003.

[32] M. N. Uugwanga, “Investigating the isotopic composition of water bodies in the Kuiseb and Cuvelai-Etosha Basin, Namibia. (MSc thesis),” Namibia University of Science and Technology, Windhoek, 2016.

[33] P. Brunner, P. Bauer, M. Eugster and W. Kinzelbach, “Using remote sensing to regionalize local precipitation recharge rates obtained from the Chloride Method,” *Journal of Hydrology* , vol. 294 , p. 241–250, 2004.

[34] L. Rahm and M. W. Buch, “Groundwater flow in the southern part of the Etosha basin indicated by the chemical composition of water,” *MADOQUA*, vol. 20, no. 1, pp. 129-135, 1997.

[35] G. Christelis and W. Struckmeier, Groundwater in Namibia an explanation to the Hydrogeological Map, Windhoek: Ministry of Agriculture, Water and Rural Development, 2011.

[36] MAWF, “Integrated Water Resources Management Plan for Namibia,” African Water Facility , Windhoek, 2010.

[37] G. Tredoux, B. Van der Merwe and I. Peters, “Artificial recharge of the Windhoek aquifer, Namibia: Water quality considerations,” *Boletín Geológico y Minero*, vol. 120, no. 2, pp. 269-278, 2009.

[38] R. Murray, D. Louw, B. Van der Merwe and I. Peters, “Windhoek, Namibia: From conceptualising to operating and expanding a MAR scheme in a fractured quartzite aquifer for the city’s water security,” *ISMAR*, vol. 4, p. 217–223, 2016.

[39] K. D. W. C. District, “Groundwater Management Plan,” California Department of Water Resources, California, 2015.

Appendices

Appendix A: Input groundwater chloride data along each transect.

	OID	Latitude	Longitude	Sub Basin	Sample Name	Cl_{gw}^{-}(mg/l)	Precipitation [mm/a]	Recharge [mm/a]	Distance from Starting Point (km)	pH	Source(s)
Transect A-A'	0	-18.1443	16.2956	Iishana	C0132	4330	400	0.07	112	8.6	GROWAS
	1	-18.0956	16.3194	Iishana	C0546	13800	400	0.02	108	8.2	GROWAS
	2	-18.0348	16.6230	Nipele	I070677/15	736	400	0.44	76	9.5	GROWAS
	3	-18.0345	16.6230	Nipele	DS12430	690	400	0.47	76	9.1	GROWAS
	4	-17.9271	16.8075	Nipele	DS12696	187	400	1.73	53	9	GROWAS
	5	-17.8312	16.8702	Nipele		104	450	3.50	43	8.4	BGR
	6	-17.8236	16.9664	Nipele		26	450	14.02	33	7.9	BGR
	7	-17.8179	17.1224	Nipele		61	450	5.98	18	8.4	GROWAS
	8	-17.8179	17.12251	Nipele	DS12697	51	450	7.15	18	8.5	GROWAS
	9	-17.7621	17.0629	Nipele		22	450	16.57	21	7.9	BGR
	10	-17.7543	17.2171	Nipele	I030267	17	450	21.44	5	7.7	BGR
	11	-17.7542	17.2172	Nipele		18	450	20.25	5	8.2	GROWAS
	12	-17.7277	17.16141	Nipele		9	450	40.50	10	8.8	BGR
	13	-17.7243	17.2577	Nipele		9	450	40.50	0	7.8	BGR
Transect B-B'	0	-19.1964	17.5041	Tsumeb	Y5757	4	450	91.13	0	8	GROWAS
	1	-19.196	17.5027	Tsumeb	GW2988 - Y5758	4	450	91.13	0	7.4	GROWAS
	2	-19.1825	17.4516	Tsumeb	Y5729	40	450	9.11	6	7.9	GROWAS
	3	-19.1794	17.4265	Tsumeb	Y5728	39	450	9.35	8	7.4	GROWAS
	4	-19.1655	17.4975	Tsumeb	Y5759	4	450	91.13	3	6.8	GROWAS
	5	-19.1619	17.3767	Tsumeb	Y5712	21	450	17.36	14	7.1	GROWAS
	6	-19.1474	17.4209	Tsumeb	GW2822 - Y5682	21	450	17.36	10	7.4	GROWAS
	7	-19.1429	17.3676	Tsumeb	Y5713	28	450	13.02	16	7.4	GROWAS
	8	-19.1311	17.4092	Tsumeb	GW2823 - Y5683	107	450	3.41	12	7.9	GROWAS
	9	-19.1296	17.338	Tsumeb	GW2806 - Y5723	5	450	72.90	19	7.4	GROWAS
	10	-19.1202	17.4087	Tsumeb	GW2824 - Y5684	86	450	4.24	13	7.4	GROWAS

	11	-19.1165	17.3688	Tsumeb	GW2808 - Y5725	6	450	60.75	17	7.3	GROWAS
	12	-19.111	17.4336	Tsumeb	GW2821 - Y5681	45	450	8.10	12	7.4	GROWAS
	13	-19.1054	17.3062	Tsumeb	GW2810 - Y5727	100	450	3.65	23	7.4	GROWAS
	14	-19.1052	17.2498	Tsumeb	GW2775 - Y5708	13	450	28.04	29	7.3	GROWAS
	15	-19.0884	17.3305	Tsumeb	GW2809 - Y5726	8	450	45.56	22	7.2	GROWAS
	16	-19.078	17.2621	Tsumeb	GW2795 - Y5685	205	450	1.78	29	7.6	GROWAS
	17	-19.0714	17.2919	Tsumeb	GW2797 - Y5745	29	450	12.57	26	7.2	GROWAS
	18	-19.0515	17.3167	Tsumeb	Y5747	28	450	13.02	25	7.6	GROWAS
	19	-19.0467	17.2393	Tsumeb	Y5711	117	450	3.12	32	7.7	GROWAS
	20	-19.036	17.2056	Tsumeb	GW2768 - Y5771	180	450	2.03	36	7.1	GROWAS
	21	-19.0356	17.2046	Tsumeb	GW2767 - Y5770	160	450	2.28	36	7.6	GROWAS
	22	-19.0284	17.2893	Tsumeb	Y5749	118	450	3.09	29	7.7	GROWAS
	23	-19.0252	17.1701	Tsumeb	GW2769 - Y5773	156	450	2.34	40	7.4	GROWAS
	24	-19.023	17.2539	Tsumeb	GW2794 - Y5767	142	450	2.57	33	7.9	GROWAS
	25	-19.004	17.2189	Tsumeb	Y5766	220	450	1.66	37	7.3	GROWAS
	26	-18.9851	17.1985	Tsumeb	Y5769	220	450	1.66	40	7.4	GROWAS
	27	-18.9792	17.1089	Tsumeb	Y5774	86	450	4.24	48	7.6	GROWAS
	28	-18.9586	17.1476	Tsumeb	Y5776	88	450	4.14	46	7.7	GROWAS
	29	-18.9237	17.0981	Tsumeb	Y5782	104	450	3.50	52	7.7	GROWAS
	30	-18.9233	17.098	Tsumeb	Y5775	30	450	12.15	52	7.3	GROWAS
	31	-18.8582	16.9262	Tsumeb	Y6279	689	400	0.47	71	7.9	GROWAS
	32	-18.8431	16.9211	Tsumeb	GW647 - Y6228	580	400	0.56	73	7.7	GROWAS
	33	-18.8268	16.9527	Tsumeb	Y6281	731	400	0.44	71	8.6	GROWAS
	34	-18.8186	16.9303	Tsumeb	GW642 - Y6280	692	450	0.53	73	8.1	GROWAS
	35	-18.8146	16.9338	Tsumeb	Y6253	630	400	0.51	73	8.9	GROWAS
	0	-19.7974	16.3623	Tsumeb	GW2541 - Y5510	17	400	19.06	0	7.9	GROWAS

Transect C-C'

1	-19.7796	16.3807	Tsumeb	Y5511	60	400	5.40	3	7.2	GROWAS
2	-19.7654	16.3509	Tsumeb	Y5512	8	400	40.50	4	7.4	GROWAS
4	-19.7576	16.33312	Tsumeb	WW40823-GW1	8	400	40.50	5	7.7	GROWAS
3	-19.7623	16.3103	Tsumeb	GW2537 - Y5190	26	400	12.46	7	7.4	GROWAS
6	-19.7254	16.3464	Tsumeb	GW2487 - Y5238	56	400	5.79	8	7.7	GROWAS
5	-19.7312	16.3088	Tsumeb	Y5220	46	400	7.04	9	7.3	GROWAS
8	-19.6935	16.3083	Tsumeb	Y5225	35	400	9.26	13	7.7	GROWAS
9	-19.6932	16.3072	Tsumeb	GW2469 - Y5227	180	400	1.80	13	7.4	GROWAS
7	-19.6992	16.2955	Tsumeb	Y5224	51	400	6.35	13	7.8	GROWAS
10	-19.677	16.3074	Tsumeb	Y5230	48	400	6.75	15	7.6	GROWAS
11	-19.6692	16.3197	Tsumeb	Y5231	12	400	27.00	15	7.5	GROWAS
13	-19.6538	16.3044	Tsumeb	Y5226	32	400	10.13	17	7.9	GROWAS
12	-19.6609	16.2708	Tsumeb	GW2463 - Y5229	22	400	14.73	18	7.4	GROWAS
14	-19.642	16.3076	Tsumeb	Y5232	84	400	3.86	18	7.5	GROWAS
16	-19.6207	16.3212	Tsumeb	Y5248	17	400	19.06	20	7.9	GROWAS
15	-19.633	16.2659	Tsumeb	Y5237	10	400	32.40	21	7.5	GROWAS
17	-19.6105	16.2832	Tsumeb	Y5233	10	400	32.40	22	7.6	GROWAS
18	-19.5909	16.2982	Tsumeb	Y5034	50	400	6.48	24	8	GROWAS
20	-19.5723	16.2646	Tsumeb	Y5033	16	400	20.25	27	7.3	GROWAS
19	-19.5778	16.2407	Tsumeb	Y5035	40	400	8.1	27	7.7	GROWAS
21	-19.5564	16.2686	Tsumeb	Y5040	47	400	6.89	28	7.4	GROWAS
22	-19.5454	16.3058	Tsumeb	GW2441 - Y5262	142	400	2.28	29	7.5	GROWAS
24	-19.5241	16.3015	Tsumeb	Y5261	75	400	4.32	31	7.6	GROWAS
23	-19.5401	16.2332	Tsumeb	Y5039	40	400	8.10	32	8.2	GROWAS
25	-19.5117	16.2375	Tsumeb	GW2416 - Y5038	24	400	13.50	34	7.9	GROWAS
26	-19.5104	16.2377	Tsumeb	GW2415 - Y5037	54	400	6.00	34	7.8	GROWAS
27	-19.4896	16.2597	Tsumeb	GW2346 - Y5041	34	400	9.53	36	7.1	GROWAS
28	-19.4591	16.2226	Tsumeb	GW2338 - Y5045	339	400	0.96	40	8.3	GROWAS

	29	-19.4514	16.2452	Tsumeb	Y5048	103	400	3.15	40	8.1	GROWAS
	31	-19.4207	16.2268	Tsumeb	GW2337 - Y5046	151	400	2.15	44	8.2	GROWAS
	30	-19.4282	16.1936	Tsumeb	Y5054	92	400	3.52	45	8.2	GROWAS
	32	-19.4059	16.207	Tsumeb	Y5060	73	400	4.44	46	8.1	GROWAS
	33	-19.3725	16.1856	Tsumeb	GW2331 - Y5059	88	400	3.68	51	8.4	GROWAS
	34	-19.2035	16.1945	Tsumeb	GW2307 - Y6265	2510	400	0.13	68	8.5	GROWAS
	35	-19.10778	16.1266	Tsumeb	CH73732	420	400	0.77	80	8.1	GROWAS
	36	-19.0518	16.1934	Tsumeb	GW2310 - Y6266	606	400	0.53	84	7.9	GROWAS
	37	-19.0318	16.1444	Tsumeb	Y6254	820	400	0.40	88	8.3	GROWAS
Transect D-D'	1	-19.6349	15.3228	Olushandja	GW1868 - Y2841	60	300	4.05	0	7.1	GROWAS
	3	-19.6232	15.3247	Olushandja	GW1841 - Y4351	19	300	12.79	1	7.8	GROWAS
	2	-19.625	15.3652	Olushandja	GW1843 - Y4352	12	300	20.25	5	7.4	GROWAS
	0	-19.6357	15.3757	Olushandja	GW1844 - Y4353	19	300	12.79	6	7.5	GROWAS
	5	-19.5967	15.3865	Olushandja	GW1839 - Y4346	64	300	3.80	8	7.7	GROWAS
	4	-19.6019	15.4135	Olushandja	GW1854 - Y4344	100	300	2.43	10	7.3	GROWAS
	7	-19.5639	15.432	Olushandja	GW1851 - Y4339	22	300	11.05	14	7.4	GROWAS
	8	-19.5554	15.4631	Olushandja	GW1853 - Y4338	23	300	10.57	17	7.5	GROWAS
	10	-19.513	15.4435	Olushandja	Y2221	27	300	9.00	19	7.6	GROWAS
	9	-19.5187	15.4821	Olushandja	GW1850 - Y2222	40	300	6.08	21	7.5	GROWAS
	11	-19.4904	15.4636	Olushandja	GW1663 - Y2220	39	300	6.23	22	7.7	GROWAS
	13	-19.4566	15.4785	Olushandja	GW1662 - Y2225	96	300	2.53	26	7.8	GROWAS
	15	-19.4478	15.482	Olushandja	Y2224	43	300	5.65	27	7.6	GROWAS

	14	-19.456	15.5157	Olushandja	GW1728 - Y2227	46	300	5.28	28	7.6	GROWAS
	12	-19.4646	15.532	Olushandja	Y2229	51	300	4.76	29	7.7	GROWAS
	16	-19.4318	15.53	Olushandja	GW1727 - Y2226	150	300	1.62	31	8	GROWAS
	17	-19.4143	15.5287	Olushandja	GW1726 - Y2228	83	300	2.93	33	8.2	GROWAS
	19	-19.3843	15.5286	Olushandja	Y2192	93	300	2.61	35	8.1	GROWAS
	18	-19.4017	15.5672	Olushandja	GW1696 - Y2231	53	300	4.58	36	7.6	GROWAS
	20	-19.3579	15.5497	Olushandja	GW1693 - Y2193	220	300	1.10	39	8.2	GROWAS
	21	-19.3375	15.6123	Olushandja	Y2237	186	300	1.31	45	7.8	GROWAS
	23	-19.3072	15.6017	Olushandja	Y2234	120	300	2.03	47	7.9	GROWAS
	24	-19.2862	15.6463	Olushandja	GW1698 - Y2236	146	300	1.66	51	7.6	GROWAS
	25	-19.2658	15.6373	Olushandja	GW1697 - Y2235	290	300	0.84	53	7.9	GROWAS
	26	-19.0672	15.8174	Olushandja	Y6225	156	300	1.56	82	7.9	GROWAS
Transect E-E'	0	-19.1723	14.5304	Olushandja	GW1225 - Y1640	56	300	4.34	0	7.4	GROWAS
	2	-19.0942	14.5834	Olushandja	GW1228 - Y1657	107	300	2.27	10	7.7	GROWAS
	1	-19.135	14.6577	Olushandja	GW1226 - Y1641	93	300	2.61	14	7.8	GROWAS
	3	-18.994	14.7442	Olushandja	GW600 - Y6263	32	300	7.59	30	7.3	GROWAS
	4	-18.9644	14.8612	Olushandja	GW602 - Y1647	235	300	1.03	42	7.9	GROWAS
	5	-18.8017	15.0397	Olushandja	GW614 - Y6237	200	300	1.22	68	8.1	GROWAS
Transect F-F'	1	-17.5084	15.7188	Iishana		28	400	11.57	0	8.3	BGR
	0	-17.7816	15.7096	Iishana	C0138	10700	400	0.03	30	7.7	BGR

*C_p^- (weighted average chloride concentration in rainfall) = 0.81mg/l obtained from [16].

Appendix B: Input groundwater stable isotope data along each transect.

	Borehole No	Longitude	Latitude	Type	Aquifer	Sample No	Sample Date	T (°C)	Distance from Starting Point (km)	Recharge [mm/a]	pH	δ^{18}O (‰)	δ^{2}H (‰)	Sub-Basin	Source (s)
Transect A-A'	WW34637	17.0338	-17.8435	Ground water	KOH	OE-014	15/10/1994	27.9	27	40.10	8.6	-8.84	-66	Nipele	[30]
	WW8219	16.8259	-17.9265	Ground water	KOH	OE-001	24/10/1993	27.8	51	40.62	9.6	-9.05	-67.6	Nipele	[30]
	WW93425	16.5988	-17.9606	Ground water	KDP	1000028	07/10/1997		75	35.18		-7	-49.8	Nipele	BGR
	Omufima	16.5988	-17.9606	Ground water	DPA	OE-016	10/07/1997		75	35.97		-6.77	-54.2	Nipele	[30]
	ETS2	16.2711	-18.0877	HDW				19	112	3.24	9.66	12.7	41.2	Iishana	[32]
Transect B-B'	WW38408	17.5042	-19.1964	Ground water		SI/075+3H	25/02/2001	27.6	0	91.13	6.5	-9.20	-64.9	Tsumeb	[31]
	WW38683	17.3377	-19.129	Ground water		SI/114+3H	27/06/2001		19	88.46		-9.00	-60.2	Tsumeb	[31]
	WW38683	17.3377	-19.129	Ground water		SI/055	18/01/2000	25.7	19	81.34	7.9	-7.00	-53.1	Tsumeb	[31]
	WW39088	17.2052	-19.0363	Ground water		3H/0183H	01/01/2000	25.2	36	84.69	7.8	-7.90	-56.6	Tsumeb	[31]
	WW6318	16.9686	-18.8434	Artesian	KOV2	SWA 62	30/06/1971		69	82.64		-8.10	-60	Tsumeb	[30]
	Etosha	16.9504	-18.8268	artesian			May-13	24.8	71	50.83	9	-0.81	-16.93	Tsumeb	[25]
	Etosha	16.9250	-18.8585	artesian			May-13	23	72	47.06	8.7	-1.51	-22.47	Tsumeb	[25]
	Etosha	16.9288	-18.8191	artesian			May-13	24.4	74	46.72	9	-1.34	-23.87	Tsumeb	[25]
Transect C-C'	WW40823	16.3331	-19.7577	Ground water		40823	08/02/2005		5	17		-8.2	-57.90	Tsumeb	BGR
		16.1925	-19.2053	Ground water		E-023	15/07/1995	27.1	68	17	6.9	-7.05	-54.10	Tsumeb	[30]
	WW91424	16.1267	-19.1078	Ground water	KOV2	55206	15/07/1995		80	17	7.4	-7.3	-55.50	Tsumeb	BGR
	WW9576	16.1267	-19.1078	Artesian		E-022	15/07/1995	27.8	80	17	7.4	-7.25	-55.50	Tsumeb	[30]

	Etosha	16.1265	-19.1072	artesian			May-13	27	80	16	7.9	-6.29	-46.88	Tsumeb	[25]
	Etosha	16.1931	-19.0525	artesian			May-13	24	84	11	8.5	-1.21	-23.74	Tsumeb	[25]
Transect E-E'		14.77	-19.01	gw					31	3.95		-6.29	-41.8915	Olushandja	[28]
Transect E-E'	Etosha	14.8602	-18.96552	gw			May-13	26.6	42	3.96	8.1	-5.42	-44.97	Olushandja	[25]
Transect E-E'	Omufima	15.4508	-18.6463	Ground water	DPA	JT01-19	Jun-14	23.2	60	3.28	8.21	-2.54	-28.8238	Olushandja	[17]
Transect E-E'	Omufima	15.4547	-18.6483	Ground water	DPA	JT01-20	Jun-14	22.6	68	3.11	8.85	-1.65	-25.2734	Olushandja	[17]