

AGE DATING OF GROUNDWATER IN PERCHED AQUIFERS  
OKONGO AREA, OHANGWENA REGION

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## **DECLARATION**

I hereby declare that this thesis and the work reported herein was composed by and originated entirely from me. Information derived from the published and unpublished work of others has been acknowledged in the text and references are given in the list of sources.

Windhoek, September 2019

A handwritten signature in black ink, appearing to read "Nicco Libuku Masule". The signature is stylized and cursive.

(Nicco Libuku Masule)

## **Abstract**

Knowledge of groundwater age / residence time in Okongo perched aquifer is important in understanding key issues in the evolution of groundwater, recharge rates, recharge mechanisms, resource renewability, flow rate and distribution of recharge areas. The build-up in the atmosphere of trace gases such as sulfur hexafluoride ( $\text{SF}_6$ ) and tritium ( $^3\text{H}$ ) from over a centenary ago offers a convenient way of dating groundwater up to the age of 60 years. These gases are well mixed in the atmosphere; therefore, their input functions help to provide information about groundwater age, distribution and recharge patterns. In this study, sulfur hexafluoride and tritium were used as an age dating tracer for shallow groundwater.

The focus of the study was to understand how age dating of groundwater in a perched aquifer system can help to determine recharge dynamics, e.g. recharge rates, processes, and vulnerability of these aquifers to pollution. The study consequently contributes to the knowledge on shallow groundwater in respect to the effectiveness of age dating methods to determine age / residence time of groundwater in perched aquifers.

The study's objective was to determine the residence time, investigate the distribution of recharge and examine the origins of recharge to the perched aquifer using sulfur hexafluoride, tritium and hydrochemistry, stable isotopes ( $^2\text{H}$  and  $^{18}\text{O}$ ) methods. A total number of 26 groundwater samples were collected during two separate sampling seasons / campaigns namely in October 2016 (for tritium and stable isotopes testing) and April 2017 (sulfur hexafluoride, hydro-chemistry and stable isotope). Samples were then grouped into sub-sets of six samples ( $^{18}\text{O}$  and  $^2\text{H}$ ) and five sample sets ( $\text{SF}_6$ ,

<sup>3</sup>H) by method of analysis and by the six (6) sampling sites namely Omboloka 1 and 2, Ohameva, Okamanya, Oshanashiwa and Epumbalondjaba.

The results on concentration of SF<sub>6</sub> in the groundwater samples indicate that recharge to the perched aquifer happened in 2000 for Omboloka 2, with a groundwater age of 17 years; Ohameva in 2010 with an age of 7 years; Okamanya in 2012 with an age of 5 years; and Omboloka 1 and Oshanashiwa in 2016 with an age of 1 year. Epumbalondjaba borehole was not sampled during the sampling campaign due to the site being flooded. Applying a conservative mixing ratio model, the samples were observed to have a higher proportion of young water compared to old water. This proves that the groundwater in the perched aquifer is young with a short residence time. Furthermore, the tritium method used to calculate theoretic/hypothetic activities suggests that groundwater at Ohameva, Okamanya, Omboloka 1 and Oshanashiwa, is sub-modern. While results for Epumbalondjaba and Omboloka 2 portray a mix of both sub-modern and modern water.

The ionic composition of groundwater in the perched aquifer presents three groups of water types characterised by mixed zone water, Na<sup>+</sup>-K<sup>+</sup>-HCO<sub>3</sub> and Ca<sup>2+</sup>-Mg<sup>2+</sup>-HCO<sub>3</sub>. The perched aquifer system is dominated by the Ca<sup>2+</sup>-Mg<sup>2+</sup>-HCO<sub>3</sub> water type which is a result of the dissolution of calcrete and the formation of carbonate-rich rocks derived from recent recharge with short residence times. Stable isotopes show that groundwater in perched aquifer systems is enriched in heavy isotopes and has been subjected to evaporation, which is caused by the prevailing climatic and hydrological conditions in the area. This shows that groundwater recharge to the perched aquifer originate from the local catchment systems. Therefore, it is recommended that the trace

gases (sulfur hexafluoride and tritium) methods should be applied to a wide range of groundwater in the perched aquifers of the Okongo area in order to understand recharge areas better. It is necessary to further investigate the groundwater chemistry and isotopic composition of perched groundwater aquifer in more detail. It is further recommended that a long-term monitoring programme consisting of sampling stations for water levels, water quality and stable isotopes is established.

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My heartfelt appreciation also goes to the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) for funding my project and other projects aimed at improving the global understanding of groundwater resources. This study would not have been possible without their generous sponsorship.

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## List of Abbreviations

a.s.l:	above sea level
CEB:	Cuvelai Etosha Basin
CFCs:	Chlorofluorocarbons
DWAF:	Department of Water Affairs and Forestry
DWSSC:	Directorates of Water Supply and Sanitation Coordination
ESRL:	Earth System Research Laboratory
Fmol/L:	Femtomole per Litre
GC-ECD:	Gas Chromatography and Electron Capture Detector
GMWL:	Global Meteoric Water Line
GNIP:	Global Network of Isotopes in Precipitation
GWRP:	Groundwater Resources Program
H:	Hydrogen
<sup>3</sup> H:	Tritium
IAEA:	International Atomic Energy Agency
LMWL:	Local Meteoric Water Line
m.a.s.l:	metres above sea level
m:	metre
pptv:	parts per trillium volume
NOAA:	National Oceanic and Atmospheric Administration
Q:	Discharge
%:	percent

‰:	per mille
RWL:	Rest Water Level
SASSCAL:	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SF <sub>6</sub> :	Sulfur Hexafluoride
TU:	Tritium Unit
UNAM:	University of Namibia
V:	Volume
V-SMOW:	Vienna Standard Mean Ocean Water
WMO:	World Meteorological Organisation



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# CHAPTER 1: INTRODUCTION

## 1.1 Background of the study

The use of anthropogenic trace gases such as sulfur hexafluoride and tritium in groundwater as indicators of residence time is based on the recorded concentration increase of these gases in the atmosphere dating back to 60 years (Kazemi et al., 2006). These gases are well diffused in the atmosphere; hence their input function aids with information about groundwater age, distribution and recharge patterns. The relationship between groundwater residence time and chemistry can enable the use of chemistry measurements as substitutes for groundwater age. Groundwater is generally potable at source, is available in-situ and has a low temporal variability, making it the most important source of water. “Groundwater development is however, complicated by highly variable hydrogeological conditions, rendering its management fraught with uncertainty” (Taylor and Barrett, 1999). Shiklomanov (2000) defines groundwater as water that fully saturates voids such as fractures and pore spaces in sediments and rocks of the Earth’s subsurface. Groundwater constitutes approximately 29.9% of the available fresh water and it is therefore an integral part of the hydrological cycle. It sustains ecosystems all over the world, supports industry and global food production, and accounts for roughly half of the world’s potable water supply (World Water Assessment Programme, 2009).

Located in Sub-Saharan Africa, Namibia is the most arid country in the continent, with a rainfall gradient of 250 mm/a in the west and 600 mm/a in the east (Bittner, 2006).

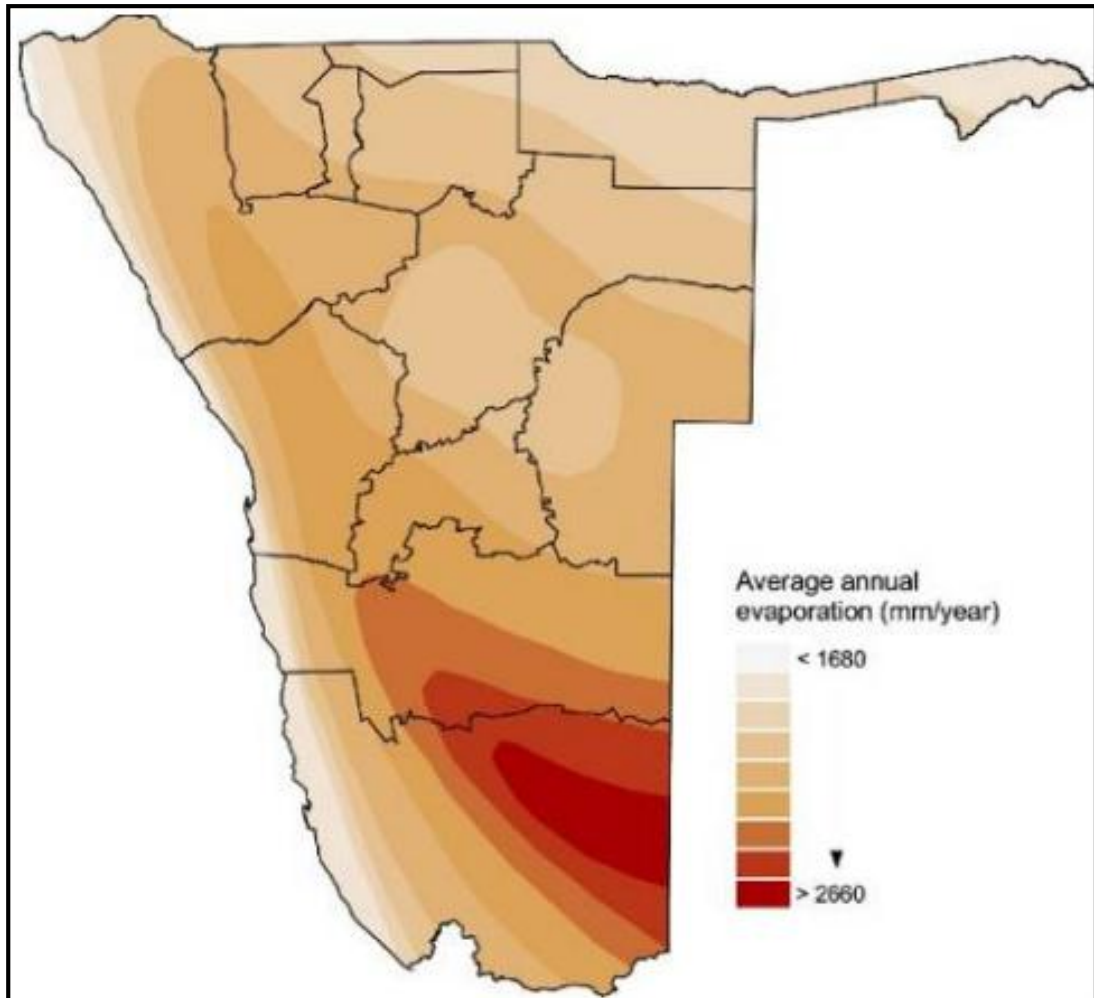


Figure 1: Average annual evaporation for Namibia (Dragnich et al., 2007).

Bittner (2006) further highlights that annual evaporation rates in Okongo area (Fig. 1), and the entire Cuvelai-Etoshia Basin (CEB) is high due to high annual temperatures of 25°C. This means that most rainwater is lost from the system through evaporation and the remaining percentage is for plant growth and groundwater recharge. Groundwater, specifically shallow groundwater in semi-arid regions, is the main source of water for most people in the rural areas of Namibia including Okongo.

Okongo is located in Ohangwena Region in central-northern Namibia, bordering Angola further north of the country. It is one of the most densely populated areas in Namibia (about 50% of the country's population lives in the CEB). According to

Turewicz (2013), CEB is one of the fastest economically growing areas in the country, making sufficient water supply very important in order to unlock the economic potential of Okongo. Communities in the study area, especially the rural areas, depend mainly on surface water during the rainy season, while hand-dug wells are normally used during the dry periods. However, due to population growth, the water resources are not sufficient anymore. It is worth noting that groundwater is the most important water source in the study area and it is found in a complex system of stratified aquifers containing fresh to saline water. Yet, the groundwater age / residence time in the perched aquifer is not yet known.

## **1.2 Statement of the problem**

Namibia is the driest country south of sub-Saharan Africa, and as such, an understanding of shallow aquifers recharge dynamics is crucial in water resources management, particularly in rural areas where communities depend on these systems. An important aspect of recharge dynamics necessary for water management is the residence period (age), and equally important is the origin / source of aquifer recharge and distribution. This groundwater residence time is important to know because it helps in understanding the mechanisms that water molecules take to travel from the recharge area to the discharge area of the aquifer (Modica et al., 1998).

Studies for determining groundwater residence time in a given aquifer for the sustainable management of groundwater resources are referred to as groundwater Age Dating (Stewart and Morgenstern, 2001). Modica et al. (1998) state that young groundwater can be dated using isotope techniques whose dating range extends from less than a year to about 50 years. In Okongo, a detailed knowledge of hydrological



systems forms an integral part of the sustainable resource development of the groundwater system.

After an extensive review of literature where the methodologies were assessed, it was discovered that empirical studies did not focus on the use of sulfur hexafluoride and tritium as an age dating method and critically in perched aquifer systems. The literature rather presents the use of hydro-chemistry (major ion) and stable isotopes methods to look at the availability of groundwater and identified possible recharge mechanisms in perched aquifers of Okongo. The results of the empirical methods show that perched aquifers in Okongo area are dominated by cations of sodium and potassium water type, while stable isotopic composition suggest that perched aquifers are recharged by less intense/small rainfall events and they are highly influenced by evaporation.

The methodology used is important because it helps to understand and provide knowledge on the age of water in perched aquifers and the potential recharge years. The advantage of the sulfur hexafluoride method is that it can provide information about groundwater residence time dating back to 50 years in age and the accompanying mixing processes, while the tritium method is the only tracer that is part of the water molecules. Based on the gap identified, there was a need to undertake a groundwater age dating study in the Okongo perched aquifer system in order to add to the already existing knowledge using sulfur hexafluoride and tritium.

### **1.3 Aim and objectives of the study**

#### **1.3.1 Aim**

The main aim of this study was to contribute to the knowledge base on effectively determining the age / residence period of groundwater in shallow perched aquifers using a case study of Okongo in Ohangwena Region.

#### **1.3.2 Objectives**

1. To investigate the distribution of recharge areas for perched aquifers.
2. To examine the origin or recharge points to the perched aquifer.
3. To determine the residence time of groundwater in perched aquifers.

### **1.4 Significance of the study**

The research contributes new knowledge and understanding of groundwater residence time in perched aquifer systems of Okongo, Ohangwena Region. This knowledge helps to understand the age of groundwater used by rural communities for water supply as stipulated in Namibia's key development frameworks, namely, Vision 2030, National Development Plans (NDPs) and Millennium Development Goals (MDGs). The Namibian Water Resources Management Act 11 of 2013 also encourages research for water resources management and sustainable development. Therefore, the study on age dating of groundwater in perched aquifers contributes considerably in understanding the residence time, distribution of recharge and origin of recharge to the perched aquifer.

## **1.5 Thesis outline**

This section provides a brief outline and description of the seven different chapters of this thesis. Overall, the chapters from one (1) to four (4) highlight the general background on the key concepts guiding the research, and the need for and potential contribution of the study to the broader knowledge base. The latter chapters highlight the research methodology and findings, conclusion and recommendations. The following section gives a brief description of what is contained in each chapter.

- 1.5.1 Chapter 1: Contains the description of the study area where the research was conducted, the problem statement and objectives of the research.
- 1.5.2 Chapter 2: Contains the synthesis of the relevant and different literature reviewed that relate to the topic under study, such as the characteristics and features of perched aquifers, groundwater age and residence time, history of groundwater age dating, dating modern groundwater, methods that were used, isotope hydrology, groundwater recharge process, and previous work in the study area.
- 1.5.3 Chapter 3: Contains a general description of the study area including the location, social and economic background (land use and population density) and natural environment (climate, topography and landscape, soil, surface water drainage, geological settings and hydrogeology).
- 1.5.4 Chapter 4: Contains information about the methodology used, research design, field procedures for data collection, laboratory and analysis procedures adopted.
- 1.5.5 Chapter 5: Presents the analysis and interpretation of the results obtained.
- 1.5.6 Chapter 6: Discusses the results in detail.

1.5.7 Chapter 7: Presents the conclusions drawn from the study findings and recommendations.

## **CHAPTER 2: LITERATURE REVIEW**

### **2.1 Characteristics and features of perched aquifers**

According to Fitts (2002) as cited in Ananias (2015), perched aquifers are zones of saturation completely surrounded by unsaturated zones. Ananias (2015) further explains that perched aquifers are unconfined water-bearing units within a vadose zone. A perched aquifer occurs above the regional water table and it is a relatively small body of water with an impermeable base under which lies an unsaturated zone. In northern Namibia, these are unique water bodies not widely distributed, but only accessible to the rural community for domestic use through hand dug wells. Perched aquifers develop from surface water infiltrating through the unsaturated zone and accumulating on a layer of less permeable lithology such as clay. Perched aquifers are of limited areal extent and they are wells which only yield temporary and / or small quantities of water when tapped.

According to Ananias (2015), perched water bodies are given little importance in terms of water supply because of their limited yielding potential. However, in areas with insufficient water supply sources, these types of aquifers are important drinking water sources for local communities. It should nevertheless be noted that limited research has been conducted on perched aquifers, and where research was conducted, it mainly focused on the role of water bodies on local and regional groundwater investigations.

## **2.2 Groundwater age and groundwater residence time**

One could suggest that groundwater age equals groundwater residence time at the discharge area. In essence, groundwater residence time is defined as the time it takes for water molecules to travel from the recharge area to the discharge area of an aquifer (Modica et al., 1998), that is, the time interval of water molecule infiltration into the ground and ex-filtrating out of the subsurface media. Considering these definitions, most researchers measure the age of groundwater and not its residence time, but in the present case, both were measured.

Modica et al. (1998) regard shallow groundwater as the depth of water in the subsurface which is below the unsaturated zone. This groundwater is usually found at depths from 0 to 30m in unconsolidated sediments. Modica et al. (1998) further postulate that groundwater age is the amount of time that has elapsed since a particular water molecule of interest was recharged into the subsurface environment system until this molecule reached a specific location in the system where it is either sampled physically or studied theoretically for age-dating.

Bethke and Johnson (2008) also suggest that groundwater age is closely related to the rate it migrates. Considering simple migration in one dimension, flow velocity is the reciprocal of the age gradient, which is the rate of changes with distance along the direction of water flow. The more sharply age increases, the more slowly water migrates. The present study determined the age of groundwater in six shallow specific boreholes.

### 2.2.1 History of groundwater age dating

According to Kazemi et al. (2006), groundwater dating studies started using isotopic and geochemical tracers from the earliest methods like tritium ( $^3\text{H}$ ) to the latest ones such as chlorofluorocarbons (CFCs) and sulfur hexafluoride ( $\text{SF}_6$ ). The authors further mention that the use of tritium for age dating of groundwater started to occur in 1952 after nuclear tests. In subsequent years, other methods were discovered and used, which include carbon ( $^{14}\text{C}$ ) in 1957 and chlorine ( $^{36}\text{Cl}$ ) in 1982. Transient environmental tracers such as the tritium-helium ( $^3\text{H}$ - $^3\text{He}$ ) isotope pair or chlorofluorocarbons (CFCs) have proven to be excellent tools for studying the mixing dynamics of lakes (Kazemi et al., 2006). Tritium-helium ( $^3\text{H}/^3\text{He}$ ) dating received widespread application of age dating of young groundwater, particularly in combination with other techniques such as CFCs and  $^{85}\text{Kr}$  (Kazemi et al., 2006).

In addition to these well-established methods, sulfur hexafluoride ( $\text{SF}_6$ ) has been introduced as a promising tracer in hydrology (Busenberg and Plummer, 2000) as well as in physical limnology. All these environmental tracers provide direct information on the time that passed since the last contact of water molecules within the atmosphere, called the water age. The age information is derived from the transient atmospheric histories of the CFCs and  $\text{SF}_6$  and from the build-up of the  $^3\text{He}$  concentration as a result of the radioactive decay of  $^3\text{H}$ .

Furthermore, the atmospheric history of  $\text{SF}_6$  is imprinted in surface water by gas exchange. Because  $\text{SF}_6$  behaves quasi-conservatively in water, its concentration can be interpreted in terms of the water residence time with respect to gas exchange at the

surface. The calculation of apparent SF<sub>6</sub> ages is based on the history of atmospheric SF<sub>6</sub> concentrations, which have increased steadily since the 1970s (Stewart and Morgenstern, 2001).

### **2.2.2 Dating modern groundwater**

According to Stewart and Morgenstern (2001), dating modern groundwater is necessary because it helps researchers to have a good understanding of recharge, flow and storage volumes for the sustainable management of groundwater resources. This has been corroborated by Gleeson et al. (2015) who also defined “modern groundwater” as the water that is most recently recharged and most vulnerable to global changes. Modern groundwater contains tritium which has been recharged in the past few decades. Therefore, it is against this background that tritium has become the most important tracer in dating modern groundwater.

Kazemi et al. (2006) proffer that a number of environmental tracers exist and these can be used to determine the age of shallow groundwater from 0 to 60 years old, and the groundwater dating exercise should be undertaken using a number of tracers conjunctively; also referred to as multi-tracer dating. Furthermore, Kazemi et al. (2006), and Busenberg and Plummer (2000) emphasize that the application of two or more tracers for the same age range is recommended, especially for water table aquifers. According to the United States Geological Survey (1999), this young groundwater is typically found at depths from 0-30m, which is the similar depth for the shallow boreholes that were drilled in the study area (Okongo).



### 2.2.3 Sulfur Hexafluoride (SF<sub>6</sub>)

Sulfur Hexafluoride (SF<sub>6</sub>) is primarily of anthropogenic origin but also occurs naturally in the soil. It is a substance for which no chemical reactions are known to occur in shallow groundwater conditions (Fulda and Kinzelbach, 2000), hence the concentration in groundwater of anthropogenic atmospheric gases such as SF<sub>6</sub> can provide information on groundwater residence times and mixing processes for water of up to 50 years in age (Gooddy et al., 2006). Findings by Fluda et al. (2000) and Cosgrove and Walkley (1981) reveal that the solubility of SF<sub>6</sub> in water is low, the lowest in all environmental gas tracers being  $4.08 \times 10^{-4}$  and  $2.46 \times 10^{-4}$  mol kg<sup>-1</sup> atm<sup>-1</sup> at 10 and 25°C, respectively. Contrary to the above mentioned, the SF<sub>6</sub> gas is currently of interest as it has an extremely high greenhouse warming potential (International Atomic Energy Agency, 2006).

Similarly, Busenberg and Plummer (1997, 2000) state that the troposphere's concentration of SF<sub>6</sub> has increased from a steady state value of 0.054 pptv (parts per trillion volumes)  $\pm$  0.009 to more than 4 pptv during the past 40 years. Thus, SF<sub>6</sub> is a relatively conservative tracer in groundwater environments and it can be used to estimate recharge dates for aquifers. Furthermore, Busenberg and Plummer (1992) and Busenberg and Plummer (2000) explain that groundwater can be dated with SF<sub>6</sub> if the water is in equilibrium with atmospheric SF<sub>6</sub> at the time of recharge because it does not contain significant SF<sub>6</sub> from other sources. The dating range of SF<sub>6</sub> is currently 0 to 30 years. Therefore, an analytical procedure was developed for measuring concentrations of SF<sub>6</sub> to less than 0.01 fmol/l in water.

Generally, atmospheric trace gases such as SF<sub>6</sub> and others are increasingly being used as tracers of groundwater residence time (IAEA, 2006). Busenberg et al. (2000) state that this tracer was successfully used to date shallow groundwater of the Atlantic coastal plain sand aquifers of the United States and springs near the top of the Blue Ridge Mountains of Virginia. Busenberg et al. (2000) further explain that significant concentrations of naturally occurring SF<sub>6</sub> were found in some igneous, volcanic, and sedimentary rocks and in some hydrothermal fluids. This prompted the research on SF<sub>6</sub> by using it as a methodical tool to measure groundwater from an alluvial aquifer of the Swakop River in Namibia, in order to determine groundwater recharge (Marx, 2009).

Once SF<sub>6</sub> in the groundwater zone is isolated from the unsaturated zone air, the dissolved concentrations can be matched back to the recharge date (Busenberg and Plummer, 2000). The SF<sub>6</sub> recharge relates to the time that has elapsed since the introduction of the tracer to the water as it enters the saturated zone and not to the age of the water itself. This means that the SF<sub>6</sub> clock starts at the groundwater zone and it does not account for travel time through the unsaturated zone (Van der Raaij, 2003). The following table describes the advantages and disadvantages of this (sulfur hexafluoride) method.

<b>Advantages of the Sulfur Hexafluoride method</b>	<b>Disadvantages of the Sulfur Hexafluoride method</b>
<ul style="list-style-type: none"> <li>• The concentration of SF<sub>6</sub> in the atmosphere continues to rise and the method is therefore going to hold effective until this trend is stopped or reversed.</li> </ul>	<ul style="list-style-type: none"> <li>• Groundwater age obtained by the SF<sub>6</sub> method does not include the travel time of groundwater in the unsaturated zone. Therefore, if this time is long, the age obtained is substantially different from what is defined as groundwater age. Although this deficiency may hold true</li> </ul>

<ul style="list-style-type: none"> <li>• The atmospheric input is relatively well known, and the subsurface addition of SF<sub>6</sub> is thought to be insignificant.</li> <li>• The narrowness of the dating range is a plus in those situations where precise time scales are of interest.</li> </ul>	<p>for other methods, because the age range of this method is narrow (0-35 years), it becomes more pronounced.</p> <ul style="list-style-type: none"> <li>• The method, being recently introduced, has to be proven by more case studies to see if subsurface or natural production of SF<sub>6</sub> microbiological degradation and other unfriendly causes restrict or reduce the applicability of the method.</li> <li>• The main anthropogenic source of SF<sub>6</sub> is in the middle latitude of the northern hemisphere, and this may present some doubt on the applicability of the methods in the other parts of the world e.g. the southern hemisphere, including Namibia where measurements of atmospheric concentration of SF<sub>6</sub> are limited.</li> <li>• Low concentrations of SF<sub>6</sub> due to its low solubility makes the sampling and analysis a delicate task. They also make the method very vulnerable to the excess air problem because solubility of SF<sub>6</sub> changes significantly with temperature.</li> <li>• Researchers (Santella et al., 2002) have shown that the concentration of SF<sub>6</sub> in air over large urban centres is up to twice that of SF<sub>6</sub> in clean air, and this anomaly may extend up to 100 km from the urban centres. This makes SF<sub>6</sub> dating of urban and near-urban groundwater complicated, and most likely impossible, unless a correction is applied using measurements of vadose zone air's SF<sub>6</sub> concentrations, provided that the excess has been relatively stable over time.</li> </ul>
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Source: Kazemi et al. (2006).

#### 2.2.4 Tritium ( $^3\text{H}$ )

Mazor (1997) and Motzer (2015) define Tritium as a heavy isotope of hydrogen whose atoms are unstable and disintegrate forming stable tritium-helium ( $^3\text{He}$ ) atoms. The authors further explain that  $^3\text{H}$  is produced in the upper atmosphere and enters the hydrological cycle through precipitation. It is also one of the nuclides produced during nuclear weapon testing and the only environmental tracer that is part of the water molecule with a half-life of 12.32 years (Aggarwal et al., 2005). On the contrary, all other tracers are solutes which dissolve in water (Kazemi et al., 2006). Schwartz and Zhang (2003) state that the concentration of  $^3\text{H}$  has varied over time depending on the detonation of nuclear devices since 1952. Its concentration is reported in tritium units (TU), where 1 TU is equivalent to  $10^{18}$  atoms of hydrogen (H) (Kazemi et al., 2006). In precipitation, the tritium concentration is much lower in the southern hemisphere than in the northern hemisphere (Aggarwal et al., 2005). According to Singhal and Gupta (1999), water containing tritium ( $^3\text{HHO}_2$ ) infiltrates through the soil in the same manner as normal water does and therefore, its concentration in the soil profile provides useful data regarding groundwater recharge. Stadler (2005) states that today's atmospheric background levels in the southern hemisphere is in the order of 3 TU. Therefore, tritium is not affected by chemical reactions and microbial processes occurring in the subsurface between the groundwater, soil sediments and aquifer materials (Stewart et al., 2001).

The tritium dating method was the first technique that was developed to date groundwater in the year 1957 by Begemann and Libby (1957) as cited in Kazemi et al. (2006). In hydrology, tritium has proven useful in studies on the movement of water through the unsaturated zone, on time scales for physical processes occurring in

surface and ground water and interactions between groundwater and surface water systems (Aggarwal et al., 2005). Frequently, it has been used to provide information on time scales that are not easily obtained using other methods (Aggarwal et al., 2005). Tritium concentration alone generally cannot be used to quantitatively date ground water but it can be used to qualitatively determine if ground water is modern (less than approximately 50 years in age) or pre-modern (older than approximately 50 years in age) (Clark and Fritz, 1997). The following table describes the advantages and disadvantages of the tritium method.

<b>Advantages of the tritium method</b>	<b>Disadvantages of the tritium method</b>
<ul style="list-style-type: none"> <li>• It is a well-established and known method with plenty of references</li> <li>• Laboratory facilities exist worldwide and the cost of analysis is relatively low</li> <li>• It is the only tracer that is part of the water molecule</li> </ul>	<ul style="list-style-type: none"> <li>• If the groundwater is older than 50 years, its full-scale utilisation is most probably not possible, therefore this method is highly misleading.</li> <li>• Due to the strong latitudinal variation, it is difficult to precisely determine the initial value even if the bomb-peak tritium effects on the environment are completely vanished</li> </ul>

Source: Kazemi et al. (2006)

### **2.2.5 Isotope hydrology**

An isotope is a chemical element having the same atomic number as another (i.e. the same number of nuclear protons), but having a different atomic mass (i.e. a different number of nuclear neutrons), while a stable isotope is an isotope that does not transmute into another element with the emission of corpuscular or electromagnetic radiations. Stable isotope methods are applied to trace the origin of the water, define the recharge location and determine the mean residence time and mixing conditions (Barbecot et al., 2000). Stable isotopes are used as fingerprints to reveal groundwater sources and other constituents (Barbecot et al., 2000). Hence, stable isotopes provide an applicative tool for studying the origin and history of groundwater as well as recharge mechanisms (Vogel and Van Urk, 1975). Meteoric processes, for example, modify the stable isotope composition of water so that recharge waters from a particular environment have a characteristic isotopic signature. This signature serves as a natural tracer for the provenance of groundwater. The results of the isotopic samples for stable isotopes are expressed as a deviation from a standard part per thousand (‰).

### **2.3 Groundwater recharge process**

Groundwater recharge can be defined as the water that replenishes the underground water. Natural recharge mechanisms can either be direct, localized or indirect (Simmers, 1997). Groundwater recharge is often difficult to quantify because of its spatial and temporal variability and because of the challenges of measuring it directly. On the other hand, McMahon et al. (2011) state that recharge estimates are an important component of water budgets that are developed to accurately assess groundwater availability. Thus McMahon et al. (2011) allude that the Groundwater

Resources Program (GWRP) has been used to support efforts in evaluating the use of groundwater age data to improve the overall understanding of recharge and improve groundwater availability. Fig. 2 below indicates the various elements of recharge in a semi-arid environment.

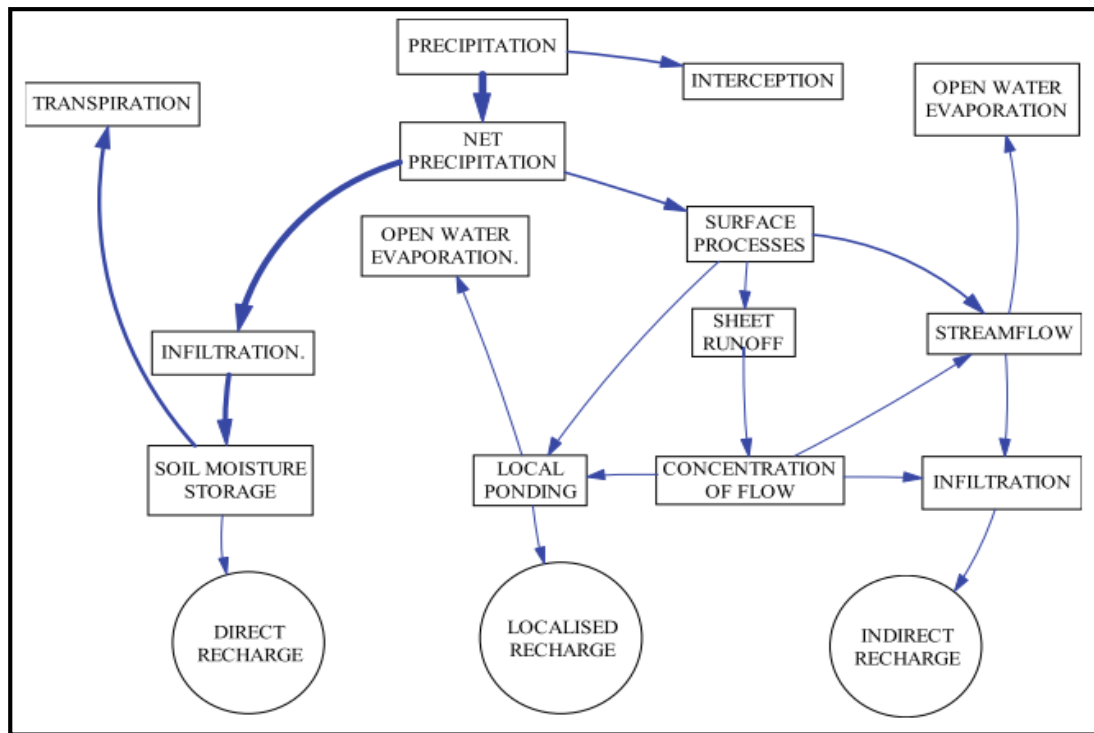


Figure 2: The various elements of recharge in a semi-arid area (modified from Lloyd, 1986)

## 2.4 Previous work in the study area

A study was conducted through the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) project by different researchers, being Hamutoko et al. (2017), the study characterized available groundwater and identified possible recharge mechanisms for perched aquifers. The results of that study show that hydrogen carbonate is the dominating anion in both well types, whereas cations vary between calcium and magnesium in deep wells, and sodium and potassium in shallow wells. Meanwhile, stable isotopic composition

suggests that deep groundwater is recharged by high-intensity rainfall events, whereas the shallow wells are recharged by less-intense rainfall events. The results show that water in deep wells reflect a mixture of water influenced by evaporation during or before infiltration, whereas shallow wells are strongly influenced by evaporation after infiltration.

Hamutoko et al. (2016) conducted a study on the estimation of groundwater vulnerability to pollution based on drastic index in the Niipele sub-Basin of the Cuvelai-Etосha Basin, Namibia. The study assessed the discontinuous perched aquifer (KDP) and the Ohangwena multi-layered aquifer 1 (KOH-1). In the study for perched aquifers, point data was regionalized by a hydrotope approach and for KOH-1 aquifer, inverse distance weighting was used. The result suggested that the discontinuous perched aquifers are more vulnerable to contamination than the Ohangwena multi-layered aquifer 1.

Beyer et al. (2015) conducted a study using the deuterium-based labelling technique for the investigation of root depths, water uptake dynamics and unsaturated zone water transport in semiarid environments. A technique utilising the stable isotope deuterium ( $^2\text{H}$ ) was applied as the artificial tracer to investigate the vertical extent of the root zone, characterize the water uptake dynamics of trees and shrubs at different depths, and monitor the transportation of water through the unsaturated zone of dry environments. Results indicate that there is a sharing of water resources between the investigated shrubs and trees in the upper 1m, while tree roots seem to have better access to deeper layers of the unsaturated zone.



The study by Wanke et al. (2015) on hand dug wells observed that wells are usually not monitored or controlled thus a study was carried out in four study areas in Namibia: southern Omusati / Oshana area, Okongo / Ohangwena area, Omatjete/Omaruru area, Okanguati / Kunene area. The results were classified according to the Namibian Drinking Water Quality Guidelines and it was concluded that the constituents making the water unfit for human consumption are fluoride, nitrate, sulphate and total dissolved solids. In general, the water resource in the shallow perched aquifers in the study areas is not fit for human consumption.

Gaj et al. (2015) conducted a study on in-situ unsaturated zone water stable isotope ( $^2\text{H}$  and  $^{18}\text{O}$ ) measurements in semi-arid environments - a soil water balance. Stable isotopes (deuterium,  $^2\text{H}$ , and oxygen-18,  $^{18}\text{O}$ ) of soil water were measured in the field using a liquid water isotope analyser and commercially available soil gas in the semi-arid Cuvelai–Etosha Basin (CEB), Namibia. The results of the study support the applicability of an in-situ measurement system for the determination of stable isotopes in soil pore water.

Furthermore, Beyer et al. (2015) conducted a study with the objective to estimate groundwater's recharge via deuterium labelling in the semi-arid Cuvelai Etosha Basin, Namibia. The stable water isotope deuterium ( $^2\text{H}$ ) was applied as an artificial tracer ( $^2\text{H}_2\text{O}$ ) in order to estimate groundwater recharge through the unsaturated zone and to describe soil water movement in a semi-arid region of northern central Namibia. A particular focus in Beyer et al.'s (2015) study was to assess the spatiotemporal persistence of the tracer when applied in the field on a small scale under extreme climatic conditions and to propose a method to obtain estimates of recharge in data-scarce regions. The results showed that it is possible to apply the peak displacement

method for the estimation of groundwater recharge rates in semi-arid environments via deuterium labelling. Ananias (2015) conducted a study on the estimation of hydraulic parameters of the shallow and perched Ohangwena aquifer (KOH-0) to determine its interaction with the deeper regional Ohangwena aquifer (KOH-1), Ohangwena Region, Namibia. The examination of existing borehole lithology logs indicated that the perched KOH-0 is contained in the Kalahari sand layer from the surface up to 30 m depths, underlain by a multi-layered semi-confining layer with alternating silty sand, clay and calcrete. The results show that KOH-0 is hydraulically potentially connected to KOH-1, especially in the northern part of the study area, with higher hydraulic gradients where most hand dug wells occur and groundwater is younger than 50 years.

Moreover, Hamutoko et al. (2014) estimated groundwater recharge rates for perched aquifers in CEB to be in the ranges of 0.47 to 23.4 mm/month and that direct recharge is mainly caused by local precipitation.

Lohe et al. (2013) reviewed and interpreted existing geological information from recent drilling campaigns to get insights on the development of deposits in central northern Namibia and the description of the perched aquifer based on their findings. They concluded that the perched aquifer in Ohangwena consists of aeolian sheet sands that underlie the natural, broad-leaf forest area in the east and far eastern part with small treeless grassy patches with acacia thorn forests. It was also found that the aquifer sands are largely fine to medium grained, with only minor silt.

A summary of several works (Geyh, 1997; GKW Consult and Bicon Namibia, 2003; Bäumle, 2004; Herczeg, 2004; Margane et al., 2005b; and IAEA, 2007) on isotope hydrology concluded that shallow Kalahari aquifers in the CEB contain mainly saline

groundwater which originates from regular floods in the Cuvelai drainage. The shallow groundwater of the aquifer is often of poor quality and insufficient quantity (Bittner, 2006).

Previous isotope study reports as already mentioned, focused on the south-eastern part of the CEB, such as Margane et al. (2005b) whose investigation comprised of the most recent isotope study in Oshivelo, Oshikoto Region. A summary report of the activities of phase 1 of the project “Groundwater for the North of Namibia” by Lindenmaier and Christelis (2012) contains a preliminary isotope study of the north-eastern part of the CEB.

In addition, Geyh (1997) states that altitude effect causes the depletion of heavy isotopes in recharge from rainfall at a higher elevation due to lower temperatures and an estimated altitude effect of  $\sim -0.25\%/100\text{m}$  for the flow component from Otavi Mountain Land to the Etosha Pan. Beukes et al. (2012) also carried out an isotope survey of deeper aquifers in the Cuvelai-Etosha Basin to improve isotope sampling and intensify isotope determination. The results of stable isotope values when plotted as  $^2\text{H}$  versus  $^{18}\text{O}$  showed evidence that most values for groundwater do not plot on the Global Meteoric Water Line but on an evaporation line.

Margane et al. (2005b) on the other hand did not use an altitude correction since the isotopic composition of rainfall in all the recharge areas cannot be assessed or sufficiently well estimated, it is however important to note that such an effect may still be relevant.

GKW Consult and Bicon Namibia (2003) in the same study area, alluded that all groundwater within the CEB flows towards the Etosha Pan, which is the area of lowest elevation in the basin, although a major part of this groundwater flow is shallow and discharges through numerous springs along the southern margin of the Etosha Pan. Similar studies in other countries were conducted, for instance by Stadler (2005) in which the researcher investigated natural processes leading to nitrate enrichment in aquifers of semi-arid regions, mostly in the uninhabited Kalahari region of Botswana. Results shows that hydrochemical and isotopic data from groundwater investigations of the Ntane Sandstone Aquifer suggest a close link between nitrate concentrations and groundwater residence time. Bekele et al. (2003) also used the chloride tracer method to estimate groundwater recharge to the Parmelia aquifer in the Northern Perth Basin. The results portrayed that the semi-arid climate of the northern Perth basin and the heterogeneous clay-rich weathered sands comprising the Parmelia aquifer, offers little hope that significant groundwater recharge is occurring, despite the vast removal of native plants prior to 1970 and rising water levels. While Cendon et al. (2014) used hydrogeochemistry and isotopic tracers to assess groundwater residence time in the Kulnura-Mangrove Mountain aquifer. The results show that shallow zone contains oxidizing Na-Cl-Type waters, low pH, low SC and containing  $^3\text{H}$  and  $^{14}\text{C}$  activities consistent with modern groundwater and bomb pulse signatures.

Another study was conducted by Land and Timmons (2016), to investigate the groundwater residence time within the southern Sacramento Mountains aquifer system using multiple environmental racers. Their results indicate that groundwater in the southern Sacramento Mountains ranges in age from less than 1 year to greater than 50 years, although the calculate ages contain uncertainties and vary significantly depending on which tracer is used.

However, it can be concluded that previous studies undertaken in the Namibia and other countries did not focus on tritium and sulfur hexafluoride methods to date the age of the perched aquifer system but rather used other methods as indicated above. Therefore, the current study used the different tracer methods, namely sulfur hexafluoride, tritium hydrochemistry and stable isotopes to date the groundwater in perched aquifer system of Okongo.

# CHAPTER 3: DESCRIPTION OF THE STUDY AREA

## 3.1 Location of the study area

The study was conducted in the Okongo area, Ohangwena Region in the north central of Namibia, and in particular situated in the Cuvelai-Etoshia Basin (CEB) (Fig. 3). CEB is an extensive sedimentary basin which is part of the much larger Kalahari Basin covering parts of Angola, Namibia, Zambia, Zimbabwe, Botswana and South Africa. Groundwater sustains ecosystems all over the world, supports industry and global food production, and accounts for roughly half of the world's potable water supply (World Water Assessment Programme, 2009). In Namibia, most people residing in rural areas of Okongo in Ohangwena Region depend on groundwater for domestic water supply. Hand dug wells are used as sources of water for livestock watering and domestic use. These hand dug wells of 0 to 30 m depth draw water from perched/shallow aquifers.

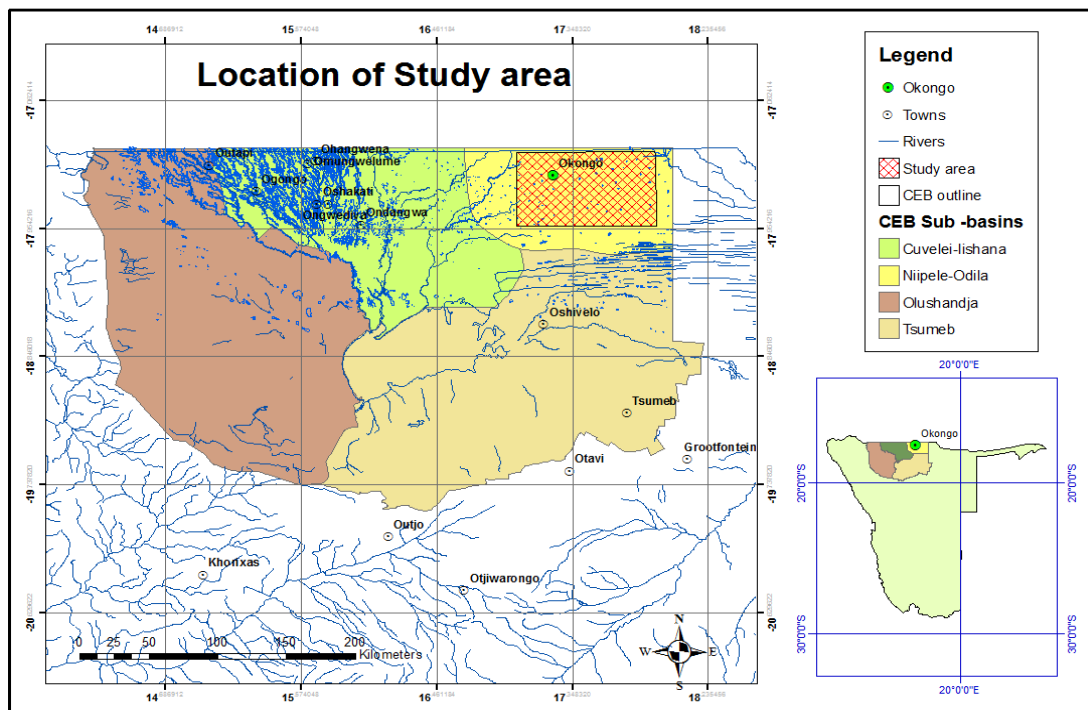


Figure 3: Location of the Study Area

## **3.2 Social and economic background**

### **3.2.1 Land use**

Okongo is one of the most densely populated areas in Ohangwena Region, and the communities depend on rain fed subsistence agricultural farming in which small scale activities such as *mahangu* (pearl millet) cultivation and the keeping of cattle form the predominant activities. Due to climatic conditions, rainfall in the Ohangwena Region supports dry land crop cultivation, especially of pearl millet (*mahangu*) in the western parts and grazing of large stock farming (cattle) as well as small stock farming (goats, donkeys and poultry) in the eastern woodlands (Bittner, 2006).

### **3.2.3 Population density**

The population in Ohangwena Region according to Smit (2012) is 245,100, with a density of 23 persons/km<sup>2</sup>, and most of the population in the communal areas of Okongo lives in concentrated zones where fresh water is available. Therefore, a large number of people are settled in the vicinity of shallow water wells.

## **3.3 Natural environment**

### **3.3.1 Climate**

The prevailing climate in Okongo area is classified as a local steppe climate, classified as hot semi-arid climate (BSh) by Köppen and Geiger (1954, 1961). The temperature in the Okongo area averages 22.9°C with precipitation ranging from 500 to 550 mm/a (Fig. 4). Rainfall is markedly seasonal with a peak in summer from January to March. Rainfall mostly occurs as convective thunderstorms and it is characterized by high intensity over short durations (Bittner, 2006).

The annual evaporation rates are high across the study area and the entire CEB (Bittner, 2006), with the annual potential evaporation increasing in the north-east to the west gradient from 2700 mm to 3000 mm, and the maximum values are recorded between October to December (Mendelsohn et al., 2000).

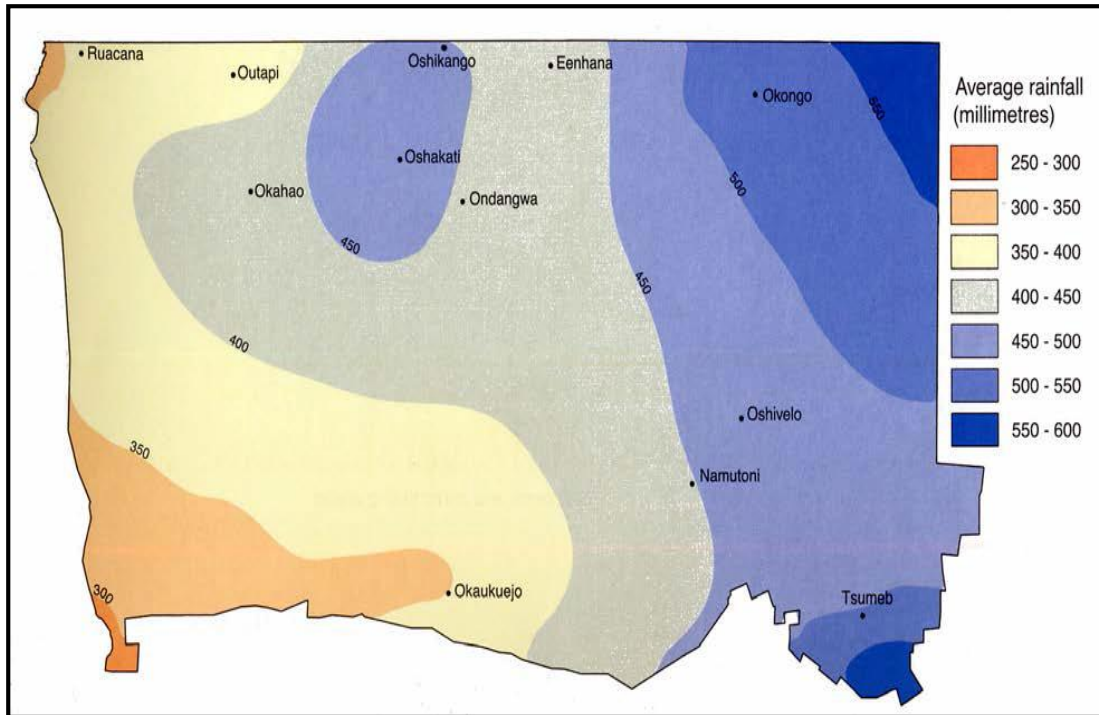


Figure 4: The annual average rainfall across north-central Namibia (Mendelsohn et al., 2000) (as cited in Bittner, 2006)

### 3.3.2 Topography and landscape

The Okongo area consists of deep infertile sands with extremely little water holding capacity. Tall woodlands forestry grows on these sands which are not suitable for crop production such as maize but are suitable for *mahangu* crops. However, there are many small pans in the Okongo area which are formed during wetter times. The soils around the pans contain more clay which holds more water during the rainy season with greater concentrations of nutrients. It is on these soils where most people live in clustered villages and grow crops around the pans (Mendelsohn et al., 2013). The



topography consists predominantly of a broad sandveld of low relief ranging from 1080 metres above sea level (m.a.s.l) at Etosha to 1150 m.a.s.l in the surrounding area (Bittner and Ploethner, 2011) (Fig. 5). The *oshanas* in Okongo area are shallow, often vegetated, poorly defined interconnected flood channels and pans through which surface water flows slowly or may form pools depending on the intensity of the rain.

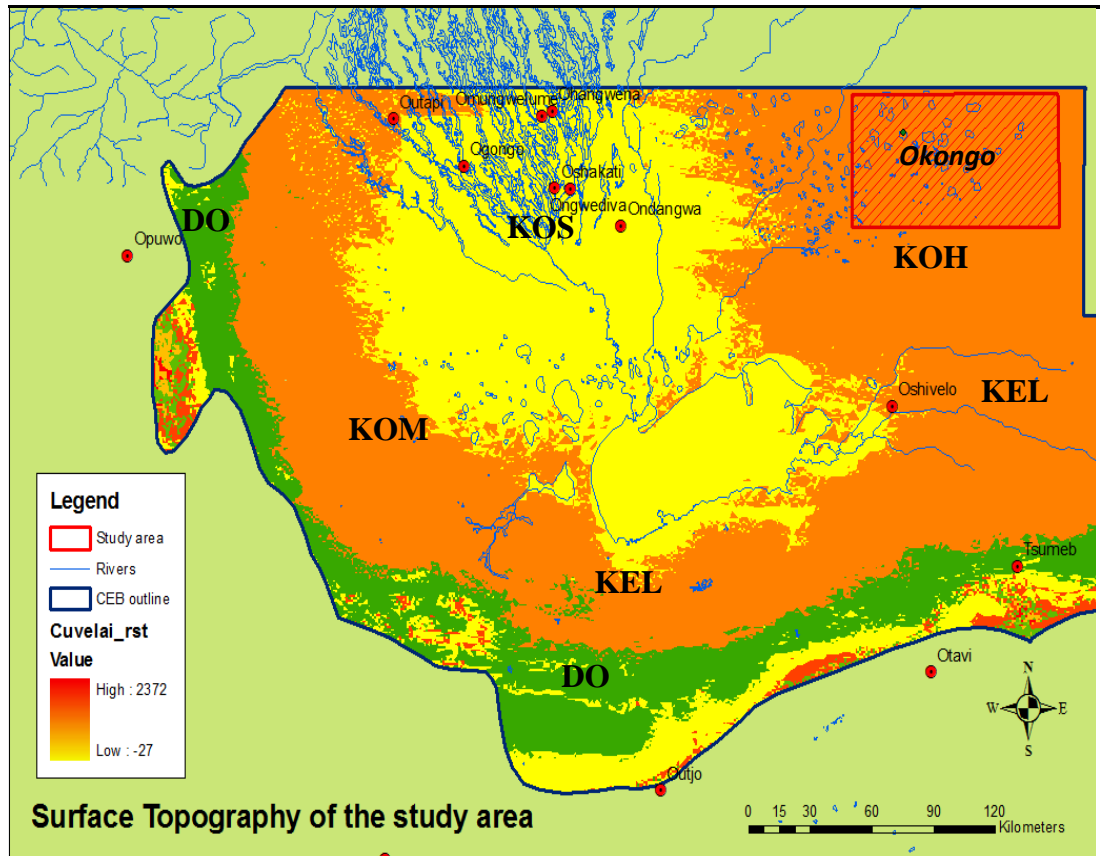


Figure 5: Elevation of the Okongo area based on data in geodatabase at “Department of Water Affairs and Forestry.”

### 3.3.3 Soils in the Cuvet-Etosha Basin

Mendelsohn et al. (2000) divided the soil into nine soil types comprising mainly of sands and clays of aeolian and fluvial origin showing poor water-holding capacity and low nutrients. The Omuramba-Owambo that is located east of the Cuvet System forms a natural border between the occurrences of loams and clays as well as of

duricrust-like calcrete, silcrete and ferricrete deposited around pan margins and along drainage lines in the south-east and the thick Kalahari sand cover in the north-east of the study area (Kleczar, 2004).

The ephemeral rivers such as the Omiramba Owambo, Akazulu and Omuthiya which discharge into the Etosha Pan consist of a highly variable fluvial lithology, comprising a mixture of gravel, sand, silt and clay with frequently inter-bedded hard-pan layers. The seasonally flooded Iishana and the surroundings of the Cuvelai System are characterised by clayish sodic sands (Bittner, 2006).

Meanwhile, the Okongo area consists of sand, calcrete and clay formation which has high infiltration and porosity rate. The water in the study area is easily accessed through shallow hand dug wells in the sand and calcrete formation. The Ephemeral River, Omuramba-Oshigambo passing through Epumbalondjaba consist of a highly variable fluvial lithology comprising of Kalahari sand formation holds water during the rainy season.

#### **3.3.4 Surface water drainage**

The study area is part of the Cuvelai Etosha Basin which extends to the upper catchment of the Cuvelai drainage system in neighbouring Angola, consisting of a system of interconnected river channels and represents an extensive plain (see red drainage system in Fig.6).





### 3.3.5.1 Kalahari sequence

The study area falls in the Kalahari Sequence which ranges from late Cretaceous to Quaternary and is entirely continental, ranging from aeolian to fluvial (Table 1). The 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 (Bittner, 2006). The fluvial sedimentation dominates, with some reworking of aeolian sand. The Kalahari Sequence reaches a maximum thickness of more than 600m in the north-east of Okongo (Bittner, 2006). Braided river conditions within the intra-continental basin environment result in a vertically and horizontally very variable lithology.

Table 1: Stratigraphic column of the Kalahari Sequence (after PLOETHNER et al., 1997; GWK and BICON, 2003 a, b)

System	Sequence (AGE)	Formation	Lithology	Maximum thickness (m)
Quaternary	Kalahari (age)	Alluvium	Calcrete, Sand	n/a
		Etosha Limestone Member	Limestone, Calcrete, Sand	100
Tertiary	Sequence (>120Ma)	Andoni	Sand, sandstone, Silt	275
		Olukonda	Sand, Sandstone, silt	175
		Beiseb	Sandstone, mudstone, gravel	50
		Ombalantu	Mudstone	100
Cretaceous				

### 3.3.6 Hydrogeology

All groundwater flow within the CEB (Okongo) is directed towards the Etosha Pan due to the structure of the basin and the pan is its deepest point. Groundwater recharged in the fractured dolomites of the Otavi Mountain Land flows northwards

and feeds the aquifer system of the Karoo and Kalahari (Bittner, 2006). However, a major part of this northbound groundwater flow is shallow and consists of saline water with origin from regular floods and discharges south-east of Namutoni through numerous springs along the southern margin of the Etosha Pan and through the bottom of the pan from where it rapidly evaporates. East of the groundwater divide (17° 45 E), the groundwater flow is most likely towards the Okavango River (1100 m.a.s.l).

The Kalahari Sequence comprises of the Ombalantu, Beisib, Olukonda and Andoni formations. It is entirely of continental, aeolian to fluvial origin. The aeolian material consists of fine-grained, well-sorted sand, while the material deposited in the fluvial environment ranges from gravel to clay and often represents braided stream conditions, resulting in very variable lithologies both vertically and horizontally. Fluvial sedimentation dominates with some reworking of aeolian sand. Lacustrine clays and associated fluvial silts and sands were most probably transported by Endorheric Rivers flowing south from the north-west, similarly to how the Okavango River now feeds into the Okavango Swamps. The present pan floor consists of evaporitic calcareous sandstones covered by a thin layer of salt-bearing chalk (Bittner and Ploethner, 2011).

At the southern and western margins of the basin, a rim of the Etosha Limestone Member is present close to the surface. It consists mainly of karstified calcrete, sand and minor clay and is interpreted as sedimentary-evaporitic limestone (groundwater calcrete). Stratigraphically, this unit is part of the Andoni Formation, but the carbonate composition of the rock indicates a separate facies and sedimentation milieu. The thickness of the calcrete increases from 20metre near Tsumeb to more than

150metre near Oshivelo and it is therefore assumed to be a groundwater calcrete (Bittner and Ploethner, 2011).

Bittner (2006) categorised different aquifers in the CEB into six main groundwater aquifer systems (Fig.8) as follows: the Otavi Dolomite Aquifer (**DO**) located on the western and southern rim, 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**. The Ohangwena Multi-Layered Aquifer is of interest in this study and it is described in the next section.

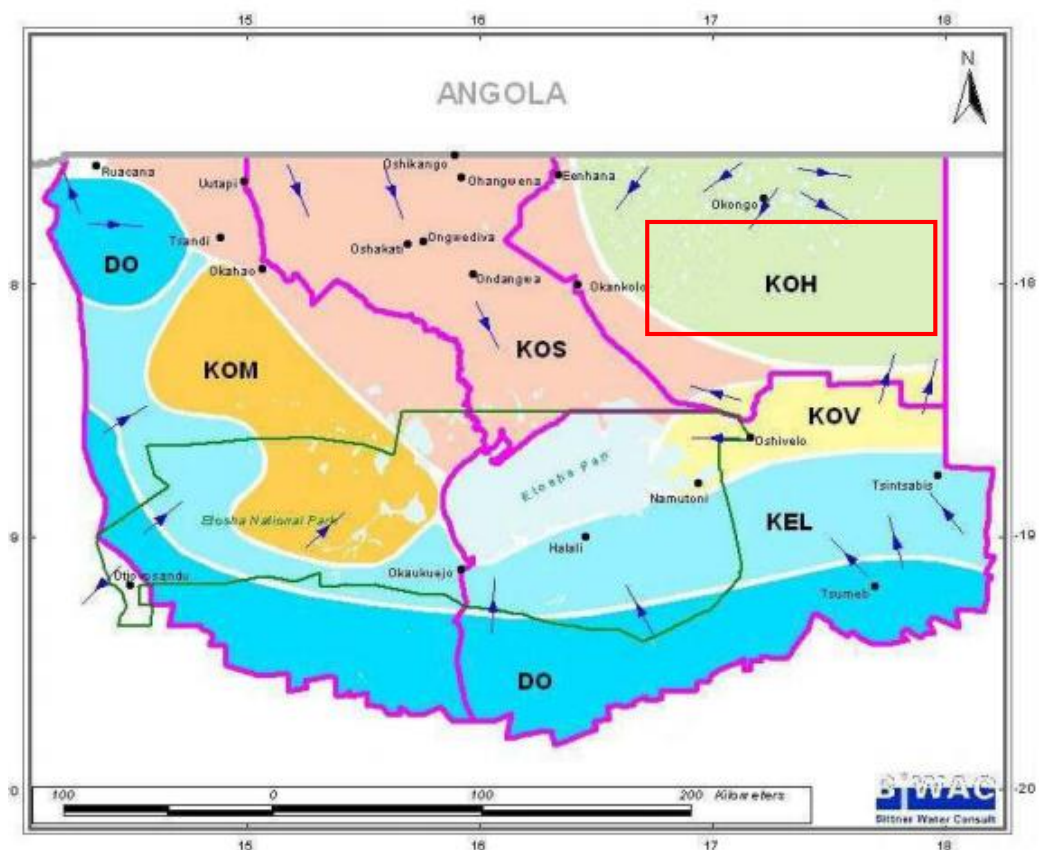


Figure 8: Main groundwater systems of the CEB (Bittner, 2006).

### 3.3.6.1 Ohangwena aquifer system

The Ohangwena Aquifer is a continuous porous aquifer system of the eastern Ohangwena and northern Oshikoto regions. The aquifer is a multi-layered system which contains a shallow perched Ohangwena 0 aquifer (KOH-0) underlain by the Ohangwena I aquifer (KOH-1) and which is in turn underlain in its western, brackish to saline part by the Ohangwena II aquifer (KOH-2) (Fig. 9).

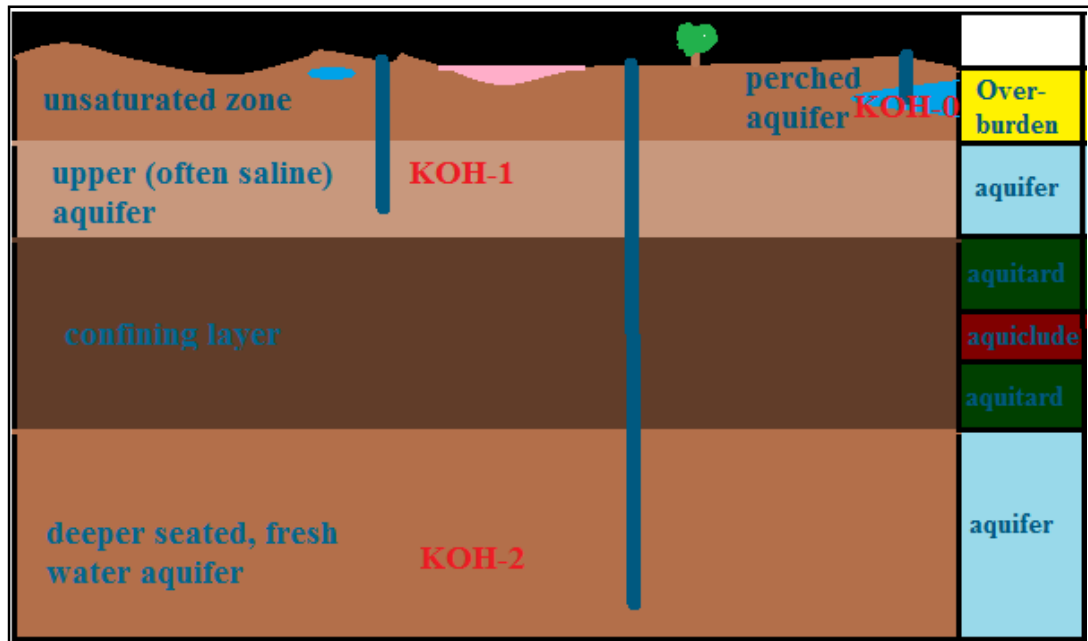


Figure 9: Cross sectional view through the Ohangwena Multi-layered Aquifer showing positions of KOH-0, KOH-1 and KOH-2 in the subsurface (modified after BGR, 2009) (as cited by Ananias, 2015).

KOH-0 was the aquifer of interest in the present study. This aquifer is not a single aquifer, but a series of small perched aquifers occurring predominantly in the Kalahari covered area north-east of Okankolo (Christelis and Struckmeier, 2011). Groundwater is abstracted mainly from the Ohangwena Kalahari Aquifer and the discontinuous perched aquifer (where fresh water is only found in certain parts of the aquifer) by means of boreholes and hand dug wells. The aquifers are mainly recharged by direct infiltration of rainwater and they are exploited by means of *Omufima* (funnel-shaped dug well in shallow areas) and *Ondungu* (cylindrical-shaped deep hand-dug well) (Fig. 10) in isolated villages in the basin (Fig.9).





Figure 10: Types of hand dug wells (up: *Omufima*; down: *Ondungu*)

## CHAPTER 4: METHODOLOGY

For this study, different approaches were used, combining methods from drilling, logging lithology of the soil type and water sampling. The supervisor, the driller (Super drilling cc), DWSSC Regional Head, Regional Councillor of the constituency and other students doing studies in Okongo during the drilling of boreholes and collection of water samples for analyses were consulted. A letter from the University of Namibia seeking permission to conduct the research and also to drill and sample boreholes in the study area was provided (see appendix A).

In order to understand the perched aquifer system in the Okongo, the hydrotope approach employed by Hamutoko (2013) was used. The hydrotopes identified in the study area were sand, dune, pan, depression and the river (paleo-channels) which was used to help in selecting drilling sites. Six sites were selected and drilled in the Okongo area for a total depth ranging from 10-31 m depending on the site location (Fig.11) and the detailed logs provided after drilling in Appendix C. The sites drilled were: Omboloka 1, Omboloka 2, Okamanya, Oshanashiwa, Ohameva and Epumbalondjaba 1 and 2.

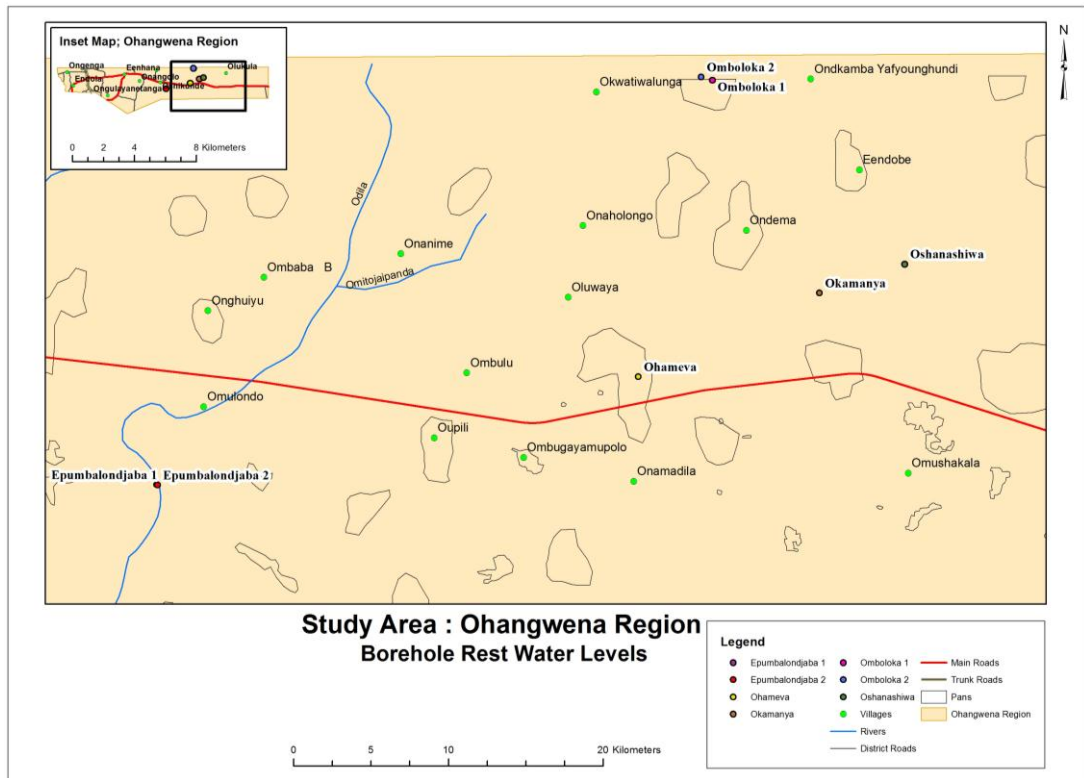


Figure 11: Location of 6 shallow boreholes drilled into KOH-0in Okongo Area.

#### 4.1 Field observation during drilling

The shallow boreholes were drilled next to the hand-dug wells that are used to supply water for livestock and human consumption. The study area has an ephemeral river, trees, bushes, sand dunes, sandy soil and calcrete formations which can be visibly seen or observed around.

Omboloka 1 was drilled in a big pan that has a lot of hand-dug wells used for livestock supply. The water level in these hand-dug wells were observed to be  $\pm 8.5$  metres. The area is also surrounded by *mahangu* fields which are fenced off with wire and some acacia trees.

Omboloka 2 borehole was drilled upstream from Omboloka 1, located in the *Omahangu* field next to one hand-dug well and the palm tree. There is a homestead

about 70 metres away from the hand-dug well, with a total depth of the borehole at 20 metres. Upstream of the site is a school and teachers' houses.

The borehole at Epumbalondjaba was drilled at the bank of the river; on the western side of the river there is a depression of sand soil with a forest. During the drilling, air bubbles were coming out from the ground because of the loss formation of sand soil. The borehole collapsed immediately after drilling a total depth of 25 metres.

Oshanashiwa borehole was drilled next to the hand-dug wells on top of the calcrete formation. A total of  $\pm 8$  hand-dug wells were dug to supply water to the surrounding communities. The topsoil in the surrounding area is reddish in colour. The borehole is surrounded by *Mahangu* fields and homesteads. The borehole was drilled to a total depth of 30 metres.

Okamanya borehole was drilled in the calcrete formation surrounded by the hand-dug wells that supply water to the nearby community. The site is on a depression that acts as a catchment area during the rainy season. Upstream of the site where the borehole was drilled there is a *Mahangu* field and homesteads. The borehole was drilled to a total depth of 31 metres.

Ohameva borehole was drilled in the Omuramba, where there are  $\pm 7$  hand-dug wells, small shrubs and trees. During the rainy-season, the Omuramba (river / paleo-channel) acts as a catchment area to collect water. This site is in a big pen whereby run-off is high. The water levels in the hand-dug wells are  $\pm 15$  metres. Upstream there is a school and homesteads while downstream are *Mahangu* fields which are fenced. During drilling the driller had to change the drilling rode and put the clay cutter in

order to go through the muddy clay formation which was hard to penetrate. The borehole was drilled to a total depth of 26 metres.

#### 4.2 Research design

The study used the experimental research design. The quantitative method was used for data gathering and analysis during the research. The assistance of the flow chart of the research design as indicated in Fig. 12 was used to guide the use of the design.

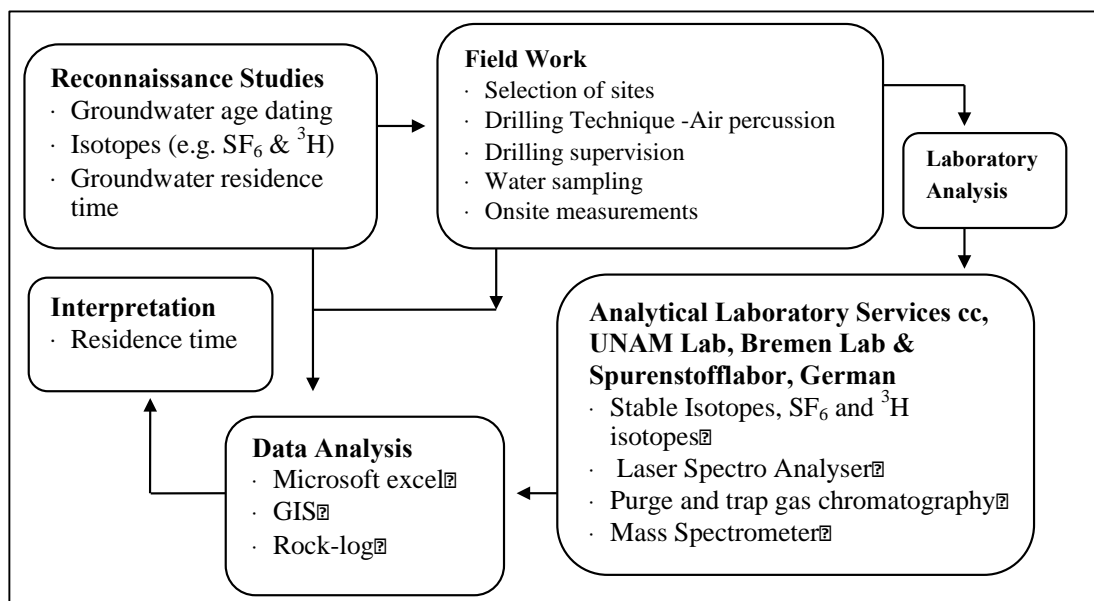


Figure 12: Research design flow chart

#### 4.3 Drilling techniques

The drilling of six (6) shallow boreholes was conducted during the period between 17 and 21 October 2017, in Okongo area, Ohangwena Region. The drilling technique used to drill the boreholes in the study area was the air percussion method (see appendix B). This drilling method is commonly used in hard rock formations like the karst area of Erongo and Karas Regions, but the reason why these boreholes were

drilled with this type of method was to prevent the pores from clogging and to allow water to flow freely into the boreholes.

This type of drilling uses a pneumatic reciprocating piston-driven hammer to energetically drive a heavy drill bit into the rock or soil. The drill bit is a hollow, solid steel and has  $\pm 20$  mm thick tungsten rods protruding from the steel matrix as buttons. The tungsten buttons are the cutting face of the bit (see appendix B). Firstly, the boreholes were drilled with a drilling diameter of 165 mm for 6 m, and then a steel casing was inserted in the hole to prevent the borehole from collapsing because of the loss formation of top sand layer. After installing the steel casing, a small-sized drilling rod was used to drill the remaining metres up to a total depth of 31 m. All the boreholes were installed with 2.9 uPVC plain casing, and then followed by factory slotted casing to the final depth. The last slotted casing was fitted with a bottom cap to prevent mud from entering the borehole.

During the drilling, the cuttings or chips were blown out of the borehole and collected at the surface. After every 1 m drilling, lithology samples were collected and logged (appendix B). The driller inscribed the borehole numbers (UNAM SASSCAL 1-6) and placed names on each borehole cap (appendix B). The inscription of the caps on a borehole is a form of numbering system which was put for the easy identification of boreholes in the field.

#### **4.4 Field procedure**

A total number of 26 groundwater samples were collected respectively from six (6) new shallow boreholes after purging was conducted, of which 6 were for tritium and 5 for stable isotopes which were collected in October 2016 after drilling, while 5

samples for sulfur hexafluoride, 5 for stable isotope and 5 for hydro-chemistry (major ions) were collected in April 2017 during sampling campaign after 5 months of drilling. Epumbalondjaba borehole was not sampled because the borehole was flooded during the time of sampling in April 2017. Therefore, the HDW sample next to the borehole was used. The GPS coordinates of each borehole were recorded in the field and other data attributes and added to a Microsoft excel sheet. Borehole caps were opened in order for the water level to be measured. A dip-stick meter was used to measure the water level in the boreholes, while a depth meter was used to measure the total depth of each borehole sampled. A submersible pump was used to purge the stagnant water from the boreholes to ensure that water samples collected is a representation of in-situ groundwater. Purging of the borehole in practice involved the removal of sufficient water so that the field physicochemical parameters (pH, temperature and electrical conductivity (EC)) are stable. For this case, this involved the removal of three times the volume of standing water in the borehole. Formula 1 below was used to calculate the purging time.

$$V = \pi r^2 * L \tag{1}$$

Whereby;  
*V is the volume,*  
*r is the radius of the borehole, and*  
*L is the length of the casing from the water level to the bottom of the borehole.*

During purging of the boreholes, on-site parameters, that is, pH, temperature and EC were measured and recorded during sampling (see table 4).

A total of 26 samples for stable isotopes were collected in 50 ml glass bottles, the SF<sub>6</sub> were collected in 500 ml glass bottles with a stop cock and a metal clip, hydro-chemistry were collected in 1 litre glass bottles, and <sup>3</sup>H samples was collected in 1 litre HDPE bottles (see appendix D). For SF<sub>6</sub>, the borehole was purged (this involved the removal of three times the volume of the standing water in the borehole by a

submersible water pump) and the pumping rate was adjusted in order to prevent occurrence of air bubbles in the sampling tube. The 1 litre glass bottle with its glass stop was placed together with a brazen can and all items needed for closing these into a 10-litre bucket. The sampling tube was placed on the base of the bottle and filled the bottle from bottom to top. The water overflowed into the can and also into the bucket. Finally, when the bucket overflowed, the tube was removed and the bottle was carefully closed while still in the water. Thereafter, the cane was taken out of the bucket and checked if it was completely leak-proof (see procedures in appendix D).

## **4.5 Laboratory procedure and analysis**

### **4.5.1 SF<sub>6</sub>**

Five SF<sub>6</sub> samples (one from each site) were collected in 500 ml glass bottles and analysed at Spurenstofflabor Oster, Wachenheim, Germany, by purge and trap gas chromatography procedure with an electron capture detector (GC- ECD) following cryogenic pre-concentration (IAEA, 2006), and the units were measured in fmol/l (USGS, 2012). The detection limit for SF<sub>6</sub> concentrations in water is 0.1 fmol/l. The measured concentrations of dissolved gases in water from the laboratory were converted to atmospheric concentrations under local recharge temperature, altitude and salinity conditions using a procedure described in IAEA (2006) and Leibundgut et al. (2009), applying Henry's law (see formula 4).

The procedure was as follows; the value was converted from fmol/l to pptv by applying the law of Henry for dissolution of gas in water. The measured value is the dissolved amount of SF<sub>6</sub> in water. The dissolution tool took place at a given recharge



temperature of 25°C at a given altitude of 1150 and salinity of 0.435‰. Therefore, the gas law states that;

$$C_{measured} = C_{air} * K(t, p) \quad (2)$$

$$C_{air} = C_{measured} * 1/K(t, p) \quad (3)$$

$K(t, p)$  is Henry's law giving the dissolution constant at given temperature and given pressure.

The equation of Henry's law is;

$$C_{in} = C_{out} / k_H \cdot (p_{air} - p_{H_2O})$$

as adopted by Leibundgut et al. (2009)

and IAEA (2006). (4)

Whereby;

$C_{in}$  is volumetric ratio of gas in air in parts per trillion by volume (pptv)

$C_{out}$  is the measured concentration of SF<sub>6</sub> (fmol/l)

$k_H$  is Henry's law constant (mol/l.pa)

$p_{air}$  is the total atmospheric pressure (pa)

$p_{H_2O}$  is the water vapour pressure (pa)

The results were compared to the SF<sub>6</sub> input curve (Fig. 13) to get the recharge year. The age of groundwater was then calculated by subtracting the recharge year from the sampling year (in this case 2017), for example, X-2000, whereby X is the date the groundwater was sampled for dating (Age: 2017-2000 = 17 years old). The principle of interpreting SF<sub>6</sub> is based on the assumption that the water recharge is in equilibrium with the soil gas when it arrives in the saturated zone (Darling and Gooddy, 2007). For the southern hemisphere, the maximum concentration in the atmosphere is 9.60 pptv as described in 2018 (NOAA/ESRL, 2018), hence residence time is defined through a comparison of the atmospheric and groundwater composition. Graphs were drawn using Microsoft Excel for statistical analysis and visualisation of results.

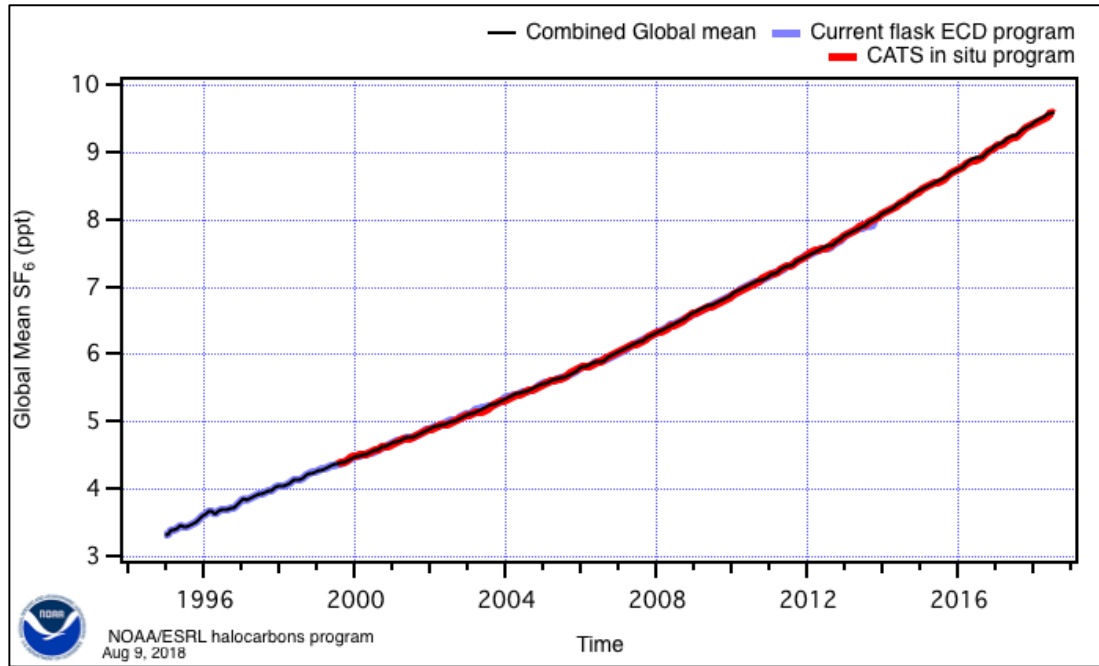


Figure 13: Input function and initial atmospheric values of SF<sub>6</sub> in pptv (NOAA/ESRL, 2018)

For the conservative mixing of old and young water, formula 5 was used to calculate the fraction of the old water from each site. The fraction was then multiplied by 100 to get the percentage of old water. Thereafter, the percentage of young water was then calculated by subtracting the percentage of old water from 100.

$$C_{mix} = f_{old} * C_{old} + (1-f_{old}) * C_{last\ year} \quad (5)$$

where  $C$  is the concentration of SF<sub>6</sub>(2010)

$old$  and  $years$  indicate the conservative mixture and end-member old and last year water (1.6 fmol/l) and

$$f_{old} \text{ is the fraction of old water} \\ (1-f_{old}) \text{ replaces } f_{last\ year} \text{ as } f_{last\ year} + f_{old} = 1 \quad (6)$$

#### 4.5.2 <sup>3</sup>H

Six (6) water samples for <sup>3</sup>H were analysed and measured at the Bremen University laboratory, Germany and reported in Tritium Unit (TU). 1 T.U. is equal to an abundance of one atom of <sup>3</sup>H per 10<sup>18</sup> atoms of hydrogen and is equivalent to 7.1 disintegrations of <sup>3</sup>H per minute per litre of water (Stadler, 2005). Liquid Scintillation Counting (LSC) was used for tritium measurements, and conducted on a *PerkinElmer*

*Quantulus* 1220 liquid scintillation spectrometer (Stadler, 2005). Table 2 below was used to define the boundary of the tritium concentrations from the six borehole sites.

Table 2: Tritium activities and associated age ranges according to Motzer (2015)

Range (TU)	Description
<0.8	Indicates sub-modern groundwater (prior to 1950s)
0.8 to 4	Indicates a mix of sub-modern and modern water
5 to 15	Indicates modern water (<5 to 10 years)
15 to 30	Indicates some bomb tritium
>30	Recharge occurred in the 1960s to 1970s

#### 4.5.3 Major Ions

A water classification based on ionic composition, the Piper diagram (Piper, 1953) (Fig. 20), was used to assess the main water types at the sampled water points in the Okongo area. The main purpose of the Piper diagram was to cluster groundwater samples that have a similar chemical composition. The total cations and anions are set equal to 100%. The data points in the two base triangles are projected into an adjacent diamond grid. Analysing the composition of major ions in groundwater contributes to a better understanding of the hydro-geochemistry of a system and thus can provide more information on the origin and quality of groundwater. The analysis of anions and cations was conducted at Analytical Laboratory Service cc based in Windhoek, Namibia. The methods used at the laboratory are summarised in Table 3. The samples were analysed for Ion (F<sup>-</sup>), potassium (K<sup>+</sup>), sodium (Na<sup>+</sup>), chlorine (Cl<sup>-</sup>), magnesium (Mg<sup>2+</sup>), calcium (Ca<sup>2+</sup>), sulphate (SO<sub>4</sub><sup>-</sup>), nitrate (NO<sub>3</sub><sup>-</sup>) and bicarbonate (HCO<sub>3</sub><sup>-</sup>), (Fig. 17 and 20).

Table 3: Analytical methods used for analyses of major ions at the laboratory

<b>Group</b>	<b>Elements</b>	<b>Analytical Laboratory</b>
<b>Services</b>		
Anions	HCO <sub>3</sub> <sup>-</sup> Alkalinity	Titration
	F <sup>-</sup> , Cl <sup>-</sup> , NO <sub>3</sub> <sup>-</sup> , SO <sub>4</sub> <sup>-</sup>	F – Ion Selective Electrode  Cl – Argentometric  NO <sub>3</sub> – Photometric  SO <sub>4</sub> – Turbidimetric
Cations	Na <sup>+</sup> , Mg <sup>2+</sup> , Ca <sup>2+</sup> , K <sup>+</sup>	Plasma Emission Spectroscopy

#### 4.5.4 Stable isotopes analyses

Stable isotopes samples were analysed at the University of Namibia's (UNAM) Geology Departmental laboratory, using an off-axis integrated cavity output spectroscope (OA-ICOS, Las Gatos DLT-100) and a cavity ring down spectrometer (CRDS, model L2120-I, Picarro Inc.) respectively (Fig. 14 and 15). The determination of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  (Deuterium) was performed following the equilibrium method (Knoller and Trettin, 2003). This method brings water samples in separate closed systems into isotopic equilibrium with a CO<sub>2</sub> gas for oxygen isotope measurement and a H<sub>2</sub> gas for hydrogen gas measurement. After reaching the equilibrium, the CO<sub>2</sub> and H<sub>2</sub> was abstracted from each system and was transferred to a mass spectrometer, were

it is measured by the Dual Inlet principle (Knoller and Trettin, 2003). All isotopic ratio values were reported in delta notation values in per mil (‰) normalized to the Vienna Standard Mean Ocean Water (V-SMOW) Standard.



Figure 14: PAL auto sampler

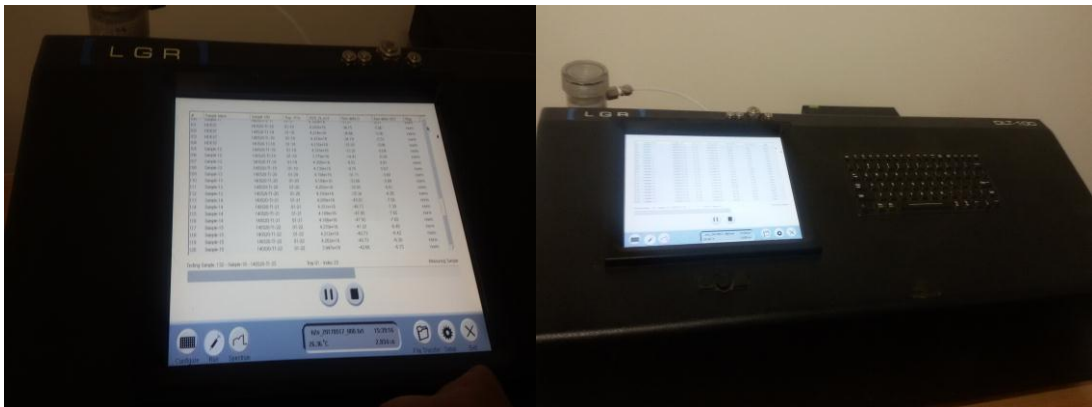


Figure 15: Spectro Analyzer (LGR DLT100)

In contrast to the analysis of the chemical contents, the analysis of deuterium and oxygen, 18 targets are not the absolute isotope contents. Stable isotopes are measured

in isotopic abundance ratios of  $^{18}\text{O}/^{16}\text{O}$  or  $^2\text{H}/^1\text{H}$  respectively, which are compared to an international standard. For practical reasons, instead of using the *isotopic ratio*  $R$ , the isotopic compositions are generally given as  $\delta$  values, and the relative deviation with respect to a standard value is defined by:

$$\delta = \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1$$

(7)

The divergence of the isotopic abundance ratio of a sample in relation to the standard is specified with a delta ( $\delta$ )-value and given in per mille (‰).  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values refer to the international standard **V-SMOW** (**V**ienna **S**tandard **M**ean **O**cean **W**ater), which is close to the original standard of SMOW as defined by Craig (1961b).

## CHAPTER 5: RESULTS

### 5.1 Physio-chemical field parameters

During the field sampling, electrical conductivities, pH and temperature were measured (see Table 4). The EC on each site varied with the lowest shown at Ohameva (407  $\mu\text{S}/\text{cm}$ ) and the highest at Oshanashiwa (1247  $\mu\text{S}/\text{cm}$ ). The pH on each site also varied, indicating the lowest at Omboloka 2 (6.34) and the highest at Oshanashiwa (8.02). The temperature of the sites also varied, indicating the lowest at Omboloka 2 (29.2°C) and the highest at Omboloka 1 (37.2°C) (see Table 4).

### 5.2 Isotope Hydrology

#### 5.2.1 Sulfur Hexafluoride

Table 5 gives the results of the  $\text{SF}_6$  laboratory analysis. The measured dissolved concentrations range from 1.0 to 2.0 fmol/l with an error range from 0.2 to 0.3 fmol/l. All values are excessive. Fig. 15 of the  $\text{SF}_6$  input curve was used to determine the recharge year. The calculated atmospheric concentration of  $\text{SF}_6$  ranges from 4.42 to 8.84 pptv (see Table 5). The recharge year was determined to be in the year 2000 for Omboloka 2 with the age / residence time of 17 years, Ohameva in the 2010 with the age / residence time of 7 years, Okamanya in 2012 with the age / residence time of 5 years, and Omboloka 1 and Oshanashiwa in 2016 with the age / residence time of 1 year respectively. All the recharge years determined with  $\text{SF}_6$  indicate distinctively younger groundwater ages or short residence time.

Table 4: Physio-chemical field parameters

ID	Village	Lat.	Long.	Elevation (m.a.s.l)	Date	Depth of borehole [m]	Rest Water Level [m]	EC $\mu\text{S/cm}$	pH	Temp ( $^{\circ}\text{C}$ )
NLM-1	Omboloka 1	-17.40854	17.13759	1152	19/10/2016	23	10.10	640	6.85	37.2
NLM-2	Omboloka 2	-17.40664	17.13116	1156	19/10/2016	20	9.54	828	6.34	29.2
NLM-3	Ohameva	-17.58091	17.09472	1147	20/10/2016	26	19.81	407	7.37	32.9
NLM-4	Okamanya	-17.53217	17.19983	1150	18/10/2016	31	20.52	748	6.48	31.2
NLM-5	Epumbalondjaba	-17.64386	16.81535	1129	21/10/2016	10	1.93	414	6.58	33.0
NLM-6	Oshanashiwa	-17.51538	17.24938	1157	17/10/2016	30	21.56	1247	8.02	33.4

Table 5: Measured dissolved concentrations of SF<sub>6</sub> and recharge years

Location	Village Names	Measured Dissolved Concentrations fmol/L	Error	Calculated Atmospheric Concentrations pptv	Recharge Year from Input Curve	Groundwater Age
NML-1/T53	Omboloka 1	2.0	0.3	8.84	2016	1
NML-2/T78	Omboloka 2	1.0	0.2	4.42	2000	17
NML-3/T69	Ohameva	1.6	0.2	7.07	2010	7
NML-4/T61	Okamanya	1.7	0.2	7.52	2012	5
NML-6/T73	Oshanashiwa	2.0	0.2	8.84	2016	1



Furthermore, the results indicate that all water samples consist of high proportions of younger water, i.e., Ohameva at 100%, Okamanya at 94%, 75% at both Omboloka 1 and Oshanashiwa, and Omboloka 2 at 64% (Table 6).

Table 6: Results of groundwater age determination using different environmental tracers

Sample Site	T Base Recharge (year)	Assessed Recharge Time Frame According to Motzer (2015) Approach	Recharge Year Based on SF <sub>6</sub> Input Curve	Alternative Interpretation*:
Omboloka 1	Older than 1960 or younger than 1990	Submodern groundwater (Prior to 1950s)	2016	75
Ohameva			2010	100
Oshanashiwa			2016	75
Okamanya			2012	94
Omboloka 2	1974-2016	mix of submodern to modern groundwater	2000	64
Epumbalondjaba	1962-1978		No data**	No data**

Note: \*Alternate interpretation: implies percentage of young ground water (2010 atmospheric concentration used for the young component and SF<sub>6</sub> free water to represent a paleowater) contributing to the water resource. \*\*No data: implies that Epumbalondjaba was not sampled for SF<sub>6</sub> during April 2017 sampling campaign due to the site being flooded

### 5.2.2 Tritium

Tritium activities in the samples from six shallow boreholes range from 0.08 to 2.35 TU (Table 7 and Fig.16). The highest tritium activities were observed in Epumbalondjaba with a value of 2.35 TU, followed by Omboloka 2 at 1.28 TU, Oshanashiwa and Ohameva at 0.18 TU, and the lowest value was at Omboloka 1 with a value of 0.08 TU. It is observed that the electrical conductivity and the pH from the

water samples at Oshanashiwa is very high compared to the other sites (Table 4), that's where the error-TU and the value TU was almost the same.

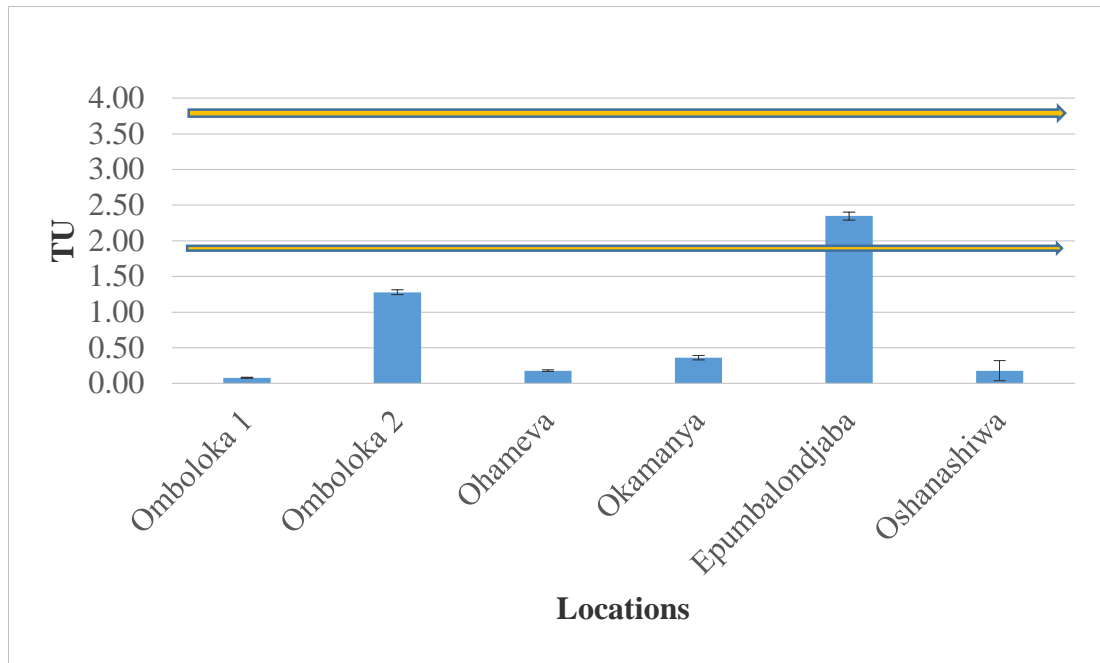


Figure 16: Measured concentration of tritium in the sampled water.

The two boundaries indicated by yellow lines indicate the range for the mix of sub modern to modern groundwater according to Motzer (2015), with 0.8 to 4 TU. Two samples (Omboloka 2 and Epumbalondjaba) plot in this field. All other samples (Omboloka 1, Ohameva, Okamanya and Oshanashiwa) plot in the field <0.8 TU, indicating sub modern groundwater (prior to 1950s) according to Motzer (2015).

### 5.2.3 Hydro-chemistry (Major Ions)

Table 8 shows that groundwater samples of the shallow boreholes in Okongo area have higher cation concentrations for the alkali ions  $\text{Na}^+$  and  $\text{K}^+$ , with concentrations ranging from 3.4 to 125 mg/l and 12.8 to 50.2 mg/l respectively, compared to the alkaline earth  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , which have concentrations ranging from 18.2 to 71.7 mg/l and 11.9 to 41.1 mg/l respectively.  $\text{HCO}_3^-$  has the highest concentration of all anions in all samples. Concentrations of all anions range from 317 to 393 mg/l for  $\text{HCO}_3^-$ , 1.63 to 14 mg/l for  $\text{Cl}^-$ , 1.65 to 4.41 mg/l for  $\text{SO}_4^{2-}$  and 35 to 122 mg/l for  $\text{NO}_3^-$  respectively.

Table 7: Field data and tritium results for 6 shallow boreholes in Okongo (Ohangwena Region)

Borehole Sampled	Oshanashiwa	Okamanya	Omboloka 1	Omboloka 2	Ohameva	Epumbalondjaba
Date of sampling	17.10.2016	18.10.2016	19.10.2016	19.10.2016	20.10.2016	21.10.2016
Latitude	-17.51538	-17.53217	-17.40854	-17.40664	-17.58091	-17.64386
Longitude	17.24938	17.19983	17.13759	17.13116	17.09472	16.81535
RWL [m]	21.56	20.52	10.10	9.54	19.81	1.93
Depth[m]	30	31	23	20	26	10
pH	8.02	6.48	6.85	6.34	7.37	6.48
<b>Tritium activities [TU]</b>	<b>0.18</b>	<b>0.36</b>	<b>0.08</b>	<b>1.28</b>	<b>0.18</b>	<b>2.35</b>
err-TU	0.14	0.03	0.01	0.04	0.01	0.06

Table 8: Selected Geochemistry data for the perched aquifer samples

Village	No	Sampling date	HCO <sub>3</sub> <sup>-</sup> [mg/l]	Cl <sup>-</sup> [mg/l]	F <sup>-</sup> [mg/l]	SO <sub>4</sub> <sup>2-</sup> [mg/l]	NO <sub>3</sub> <sup>-</sup> [mg/l]	Na <sup>+</sup> [mg/l]	K <sup>+</sup> [mg/l]	Mg <sup>2+</sup> [mg/l]	Ca <sup>2+</sup> [mg/l]	Balance [%]	δ <sup>18</sup> O [‰]	δ <sup>2</sup> H [‰]
Omboloka 1	NLM-1	19.10.2016	393	11.6	1.85	4.41	46.7	15.8	24.9	41.1	56.9	0.452	-7.41	-57.0
Omboloka 2	NLM-2	19.10.2016	352	3.28	1.78	1.97	51.7	3.4	12.8	37.8	62.4	0.280	-6.10	-47.8
Ohameva	NLM-3	20.10.2016	347	1.63	1.66	3	35	21.4	27.5	29.4	45.3	0.373	-7.20	-55.4
Okamanya	NLM-4	18.10.2016	317	14	1.16	1.97	112	19.9	50.2	19.2	71.7	0.890	-7.75	-57.7
Oshanashiwa	NLM-5	17.10.2016	358	7.67	2.66	1.65	122	125	27.6	11.9	18.2	0.364	-7.65	-58.2
Epumbalondjaba	JT08-24	Oct 2016	47.7	12.6	0.399	18.6	96.3	26.4	31.9	7.95	12.5	2.29	-5.65	-45.2

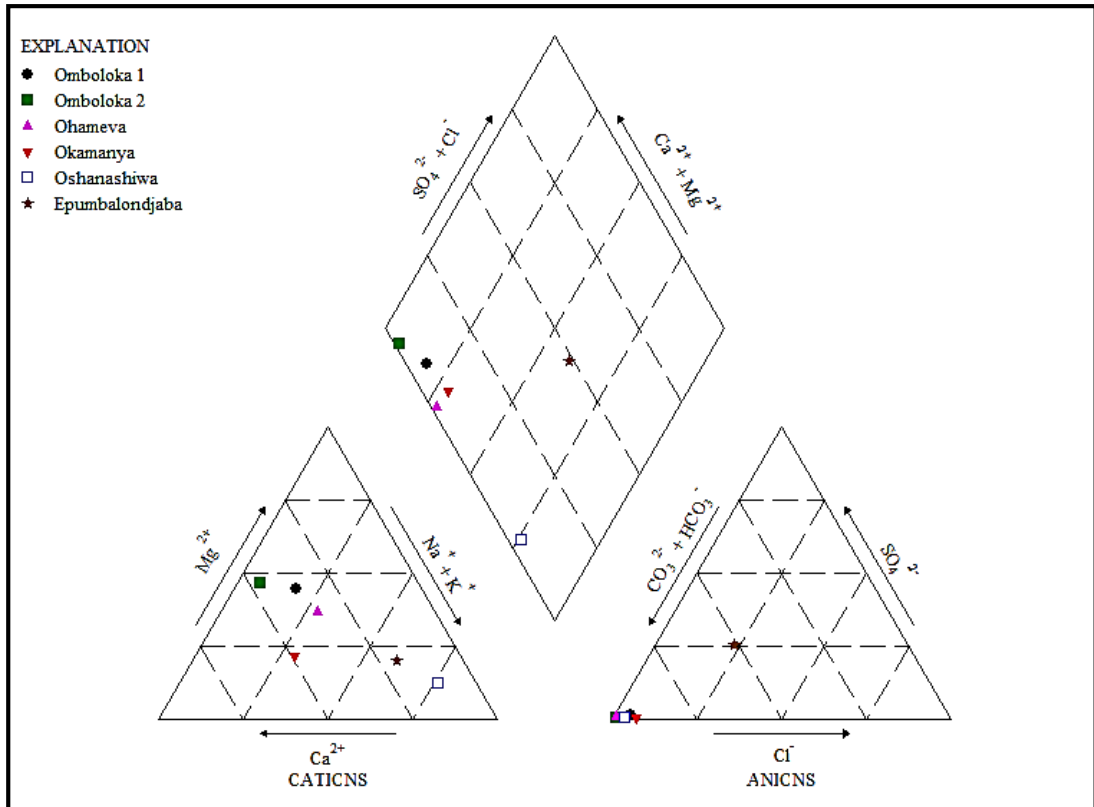


Figure 17: Piper plot for groundwater samples from perched aquifers in Oshanashiwa, Omboloka (1 and 2), Ohameva, Okamanya and Epumbalondjaba.

The result of hydro-chemistry when plotted on a Piper diagram in a diamond plot shows three different groups of water types. The first group of samples (Omboloka 1 and 2; Ohameva and Okamanya) indicates mixed zone water type, the second group indicates  $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3\text{-}$ water type and the third group of samples (Oshanashiwa and Epumbalondjaba) indicates  $\text{Na}^+\text{-K}^+\text{-HCO}_3\text{-}$ water type. In a triangle, the Piper plot for cation shows that samples from Omboloka 1 and 2, Ohameva and Okamanya plot on a mixed zone, indicating a mixed water type, and Oshanashiwa and Epumbalondjaba samples show  $\text{Na}^+\text{-K}^+\text{-}$ water type. While in the anion triangle, all samples plot as  $\text{HCO}_3\text{-}$ water type (Fig. 17 and 20).

## 5.2.4 Stable Isotope

Table 9: Stable Isotopes Data

Locations	Years	$\delta^{18}O$	s.d.	$\delta^2H$	s.d.
Ohameva bh	2016	-7.20	0.12	-55.4	0.8
Oshanashiwa	2016	-7.65		-58.2	
Okamanya bh	2016	-7.75	0.15	-57.7	1.1
Epumbalondjaba bh	2016	-5.98	0.10	-45.7	0.8
Omboloka 1 bh	2016	-7.41	0.04	-57.0	0.4
Omboloka 2 bh	2016	-6.10	0.04	-47.8	0.7
Omboloka 1 (NML-1)	2017	-7.86	0.23	-55.2	0.6
Omboloka 2 (NML-2)	2017	-6.60	0.22	-48.1	1.2
Ohameva (NML-3)	2017	-7.64	0.27	-55.0	1.5
Okamanya (NML-4)	2017	-8.15	0.14	-57.9	0.7
Oshanashiwa (NML-6)	2017	-8.33	0.29	-58.0	1.7

The isotopic composition of Oxygen ( $\delta^{18}O$ ) and Hydrogen ( $\delta^2H$ ) of the shallow boreholes water ranges between -7.75 to -5.98‰, with an average value of -6.89‰ for  $\delta^{18}O$  and -57.7 to -45.7‰ with an average value of -52.72‰ for  $\delta^2H$ , as from the October samples. While samples for April 2017 range from -8.33 to -6.60‰ for  $\delta^{18}O$  and -58.0 to -48.1‰ for  $\delta^2H$  respectively, and they plot below the Global Meteoric Water Line ( $GMWL: \delta^2H = 8 * \delta^{18}O + 10; R^2 = 1$ ) and Local Meteoric Water Line ( $LMWL: \delta^2H = 7.2 * \delta^{18}O + 4.49; R^2 = 1$ ) (Wanke et al., 2018). Two samples (Epumbalondjaba & Omboloka 2) plot further away from the rest of the samples (Ohameva, Omboloka 1, Okamanya and Oshanashiwa). In general, all samples plot below the LMWL and GMWL for both sampling campaigns (October 2016 and April 2017).

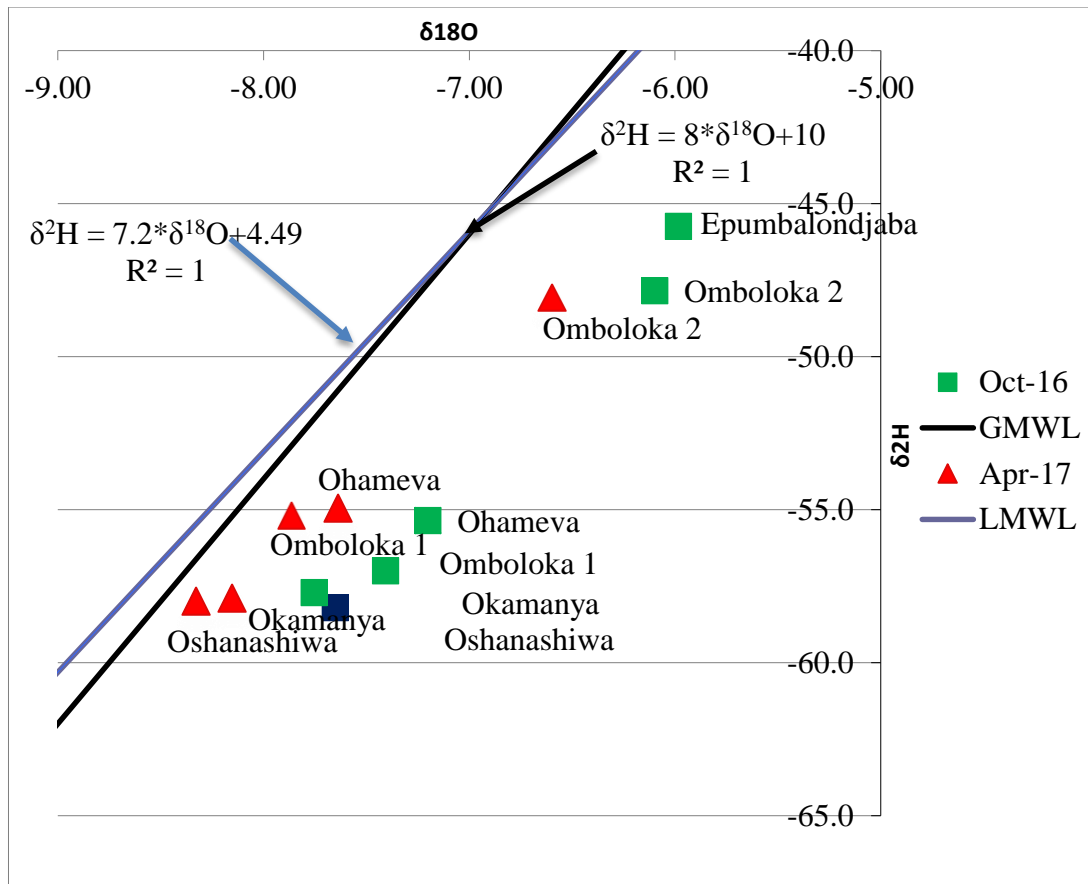


Figure 18: Dual isotope plot of  $\delta^2\text{H}$  versus  $\delta^{18}\text{O}$

**Note:** The Oshanashiwa samples which is indicated with a blue colour was taken from the hand dug well (HDW) next to the borehole provided by Hamutoko (2018).

The plot of  $\delta^2\text{H}$  versus  $\delta^{18}\text{O}$  for groundwater in the Okongo area show a sample of water plotting below the global meteoric water line and the local meteoric water line. In April 2017, Epumbalondjaba borehole was not sampled due to the river which was flooded after the rainy season that is why there are only 5 samples instead of 6 samples as planned.  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values for Omboloka 2 plot between  $-6.10$ ,  $-47.8$  during the October 2016 sample while in April 2017 the sample plot between  $-6.60$ ,  $-48.1$ . The October samples all plot further away from the LMWL than the April samples and indicate more evaporation (Fig. 18).

Samples in Ohameva, Oshanashiwa, Okamanya and Omboloka 1 are more depleted than samples from Epumbalondjaba and Omboloka 2. The Oshanashiwa sample for October 2016 was unfortunately lost. Thus, a sample taken from the hand dug well next to it was used instead.



## CHAPTER 6: STUDY SYNTHESIS

### 6.1 Discussion

#### Sulfur Hexafluoride

The investigation of SF<sub>6</sub> in the shallow groundwater aquifer system of Okongo area shows a detectable signal of measured dissolved concentration of SF<sub>6</sub> ranges from 1.0 to 2.0 fmol/l, with an error of 0.2 to 0.3 fmol/l respectively. The lowest value of measured dissolved concentration of SF<sub>6</sub> is assumed that it comes from the naturally occurring SF<sub>6</sub> because there are no industries in Okongo to contaminate groundwater with SF<sub>6</sub>. When these values were calculated to atmospheric concentration, it shows that it ranges from 4.42 to 8.84 pptv. The SF<sub>6</sub> input curve (Fig. 13) also shows that groundwater recharge for Omboloka 2 happened during the year 2000 with the age of 17 years, Ohameva in the 2010 with the age of 7 years, Okamanya in 2012 with the age of 5 years and Omboloka 1 and Oshanashiwa in 2016 with the age of 1 year. This shows that there are different recharge patterns distributed in the study area. All the recharge years determined with SF<sub>6</sub> indicate distinctively younger groundwater age ranging from 1 to 17 years with a short residence time. This is in agreement with Goddy et al. (2006) that, the concentration in groundwater of anthropogenic atmospheric gas such as SF<sub>6</sub> can provide information on groundwater residence times and mixing processes for waters up to 50 years in age. But when these same samples were calculated using conservative mixing ratio, they were observed to have a higher proportion of young-to-old water concentration, i.e. Ohameva with 100%, Okamanya with 94%, and 75% at both Omboloka 1 and Oshanashiwa. Meanwhile, Marx (2009) determined the recharge year of only five samples that were measured in 2008. For

these five samples, the calculated atmospheric concentration in 2008 is lower than the maximum global concentration of SF<sub>6</sub> in the southern hemisphere, which is 6.19 pptv.

Comparing the SF<sub>6</sub> results to the <sup>3</sup>H results in table 6, the recharge years slightly differs, but the concentration of both SF<sub>6</sub> and <sup>3</sup>H correlates with the age range i.e. that recharge occurred before 1960 (older than 1960 or younger than 1990) with T base recharge, Motzer (2005) approach, and recharge year based on SF<sub>6</sub>.

### **Tritium**

The observed tritium activities in the groundwater for 2016 at the sampling sites were traced back to theoretic / hypothetical tritium activities in source water using the law of radioactive decay equation. These lines are given as "exponential" in the plot (Fig. 19). The resultant calculated tritium activities of source water (the lines "exponential") were then compared to the observed tritium activities in the precipitation for Windhoek, since it is the closet station with long term records. These data are shown as scattering dark red points (Fig. 19). A match of the observe tritium activities in precipitation with the calculated theoretic / hypothetical tritium activities in source water indicates the potential recharge years.

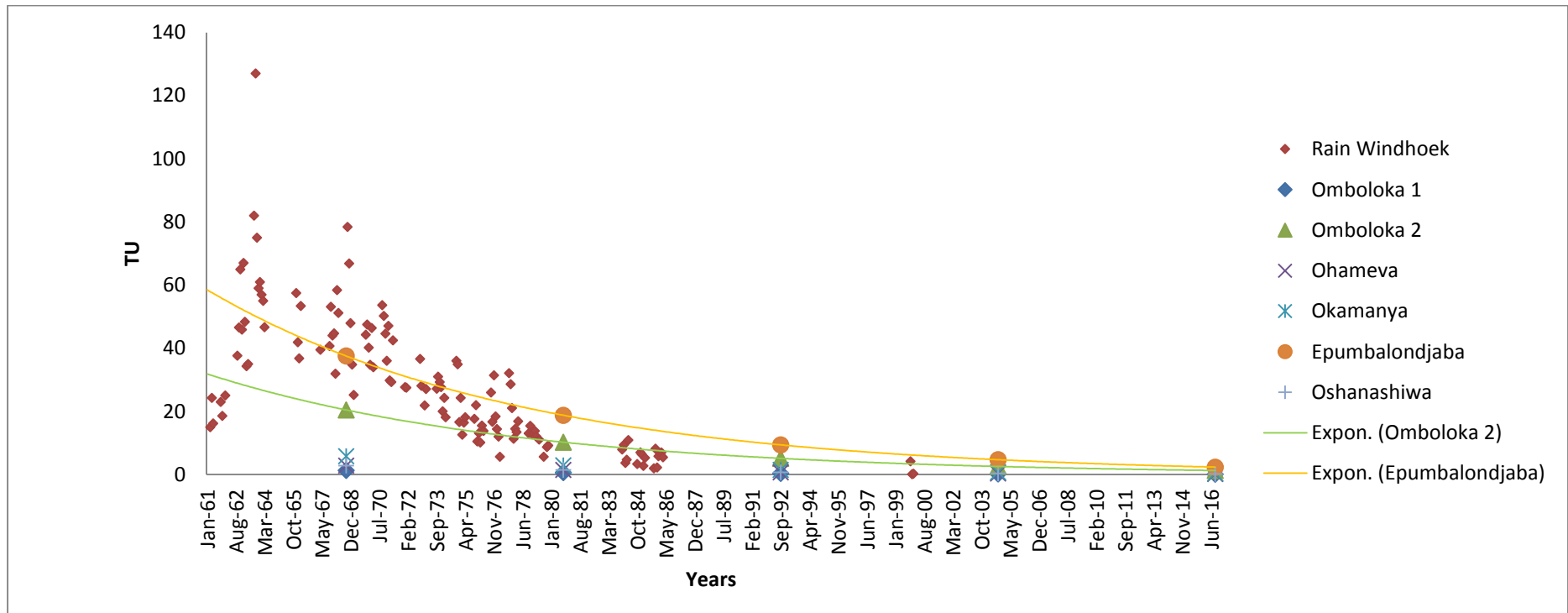


Figure 19: Tritium concentration in groundwater versus tritium concentration in rainwater in Windhoek according to GNIP database (IAEA/WMO)

The results for the stations at Ohameva, Okamanya, Omboloka 1 and Oshanashiwa calculated theoretic / hypothetical tritium activities in source water match with tritium activities in precipitation at Windhoek for the time before 1960 or 1990. This is the same time frame where the highest tritium concentration was observed in the precipitation at Windhoek. According to Aggarwal et al. (2005), this was caused by the time of nuclear weapon testing in 1962. The tritium activities in the water sources of these sites are 0.18, 0.36, 0.08 and 0.18 TU respectively, showing the lowest tritium activities from the samples in the study area. Thus, the drop of groundwater tritium concentration at these four sites during the recharge event could be interpreted as a direct recharge contributed by the Kalahari sand formation with a high infiltration rate. When these tritium activities were compared to Motzer's (2015) theory in table 4, this indicates sub-modern groundwater (prior to 1950s), indicating old groundwater with the potential recharge year. These sites are in the calcrete formation covering the perched aquifer system found in the saturated sand formation at the depth of 10 – 28 m below the topographic surface.

For the station Epumbalondjaba, calculated theoretic / hypothetical tritium activities in source water match with tritium activities in precipitation at Windhoek for the time 1962 - 1978 or after 2000. This is the same time frame where the highest tritium concentration was observed in the precipitation at Windhoek and in the groundwater source. Tritium activities in the water source of Epumbalondjaba is 2.35 TU showing the highest tritium activities from the samples in the study area. When this tritium activity was compared to Motzer (2015) theory in table 2, this indicates a mix of sub-modern and modern water. This site is located in a riverbed that gets frequently flooded every year during the rainy season. The age of the water at this site is young

with a short residence time, indicating the potential recharge year. The rising of groundwater in April 2017 is caused by direct / local recharge most especially for the Epumbalondjaba borehole which is situated in the river channel system.

For the stations Omboloka 2, calculated theoretic / hypothetic tritium activities in source water match with tritium activities in precipitation at Windhoek for the years 1974 - 2016. Tritium activities in the water source of Omboloka 2 is 1.28 TU showing a second highest tritium activities from the samples in the study area. When this tritium activity was compared to Motzer (2015) theory (Table 4), it indicated a mix of sub-modern and modern water. This site is located in the valley / side of a large pan which collects water during the rainy season. Therefore, the age of the water at this site is also young with a short residence time, indicating the potential recharge year.

Overall, the tritium concentration varies across all sampling sites with higher concentration variation observed at Omboloka 2 (20.45) and Epumbalondjaba (37.55) in the initial sampling dates. These two sites had a higher concentration than all the other sampling sites which had a tritium concentration range of between 1.25 and 5.76. However, the variation / gap across all sites reduced as the groundwater ages towards the year 2016. These findings are further supported by a statistical test for correlation (P-value of 0.01, 2-tailed mean) and linear regression (R-square with a P-value of 0.03) (see table 10 and 11).

Table 10: Correlation of P-Value

		age	tritium cons
Age	Pearson Correlation	1	-.474**
	Sig. (2-tailed)		.008
	N	30	30
tritium cons	Pearson Correlation	-.474**	1
	Sig. (2-tailed)	.008	
	N	30	30

\*\* . Correlation is significant at the 0.01 level (2-tailed).

Table 11: Linear Regression

**Model Summary**

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.168 <sup>a</sup>	.028	-.044	1.775

a. Predictors: (Constant), tritium cons, age

When comparing the tritium data of KOH-0 (Table 12) to other aquifers of the CEB with similar lithology and environmental settings, the mean value for KOH is higher, meaning that there is potentially some "more modern" influence in the Ohangwena region. This is because either it is further up gradient than the other groundwater sources and thus younger or because we have a little bit of influence from the perched aquifers.

Also, if one compares the TU of Omboloka for KOH-1 (1.2 TU) and the KOH-0 from Geyh (1997), it is interesting to note that they are the same for the site at Omboloka 2 which is in the *mahangu* field closer to the large pan, but the site in the calcrete near

the *Kuka* shops, Omboloka 1, KOH-0 has a much lower tritium activity (see appendix G).

Table 12: Descriptive statistics of tritium activities in groundwater based on database compiled by Turewicz (2013)

Tritium activity [TU]		
Mean	0.63	all aquifers CEB
Min	0	all aquifers CEB
Max	1.3	all aquifers CEB
Mean	0.93	Ohangwena regional aquifer
Min	0	Ohangwena regional aquifer
Max	1.3	Ohangwena regional aquifer
Observation: Omboloka	1.2	Ohangwena regional aquifer

In overall, a match of the observed tritium activities in precipitation with the calculated theoretic / hypothetical tritium activities in source water indicates the potential recharge years. It was also indicated by several members of the communities that the groundwater levels in these boreholes recover every year, indicating that recharge takes place every rainy season. However, if the percentage of young water is higher than old water, the tritium concentration will increase and indicate the young groundwater. Vice-versa is true, if the percentage of young water is less than the percentage of older water, and the tritium concentration will reduce and indicate the age of the groundwater.

### Major Ions

The Piper diagram (Fig. 17 and 20) suggests three groups of water types in the shallow boreholes characterised by the mixed zone water type with neither a dominant cation nor anion, the  $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3$  water type, and the  $\text{Na}^+\text{-K}^+\text{-HCO}_3$  water type. The mixed water, where no particular water type could be identified, indicates cation exchange as the main process responsible for the groundwater chemistry. Hamutoko

(2018) also alluded that mixing water type normally indicates the mixing of two water sources and this implies that the shallow wells have at least two sources and or experience at least two different hydrochemical processes.  $\text{Na}^+\text{-K}^+\text{-HCO}_3$  water type demonstrates groundwater formed in formations where alkali carbonates are present. Whereas the  $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3$  water type indicates that the groundwater was formed in carbonate-rich rocks or derived from a recent / local recharge with short residence times. It can also be argued that the  $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3$  water type is a result of the dissolution of calcrete which is outcropping in some sites such as Oshanashiwa, Okamanya, Omboloka 1 and 2 and Ohameva. Hamutoko (2018) in her study also attest that water in the pans / depression similar to this study evolved from  $\text{CaMgHCO}_3$  to  $\text{NaKHCO}_3$  water type as result of heterovalent cation exchange processes of calcium and sodium, where by calcium is sourced from calcrete and sandstone matrix dissolution while sodium is from plagioclase weathering. Most of these boreholes were located in the depressions and pans characterised by layers of calcrete embedded into unconsolidated sands. Obiefuna and Orazulike (2011) as cited in Hamutoko et al. (2017) state that evaporation increases the concentration of ions in the remaining water and leads to precipitation and deposition of evaporates. Thus, the results suggest that evaporation processes may be responsible for the geochemical composition of shallow boreholes in the Okongo area. The  $\text{Na}^+\text{-K}^+\text{-HCO}_3$  water type indicates groundwater formed in the formations where alkali carbonates are present. While the mixed zone water demonstrates that no particular water type could be identified and therefore indicates cation exchange as the main process responsible for groundwater chemistry (Hamutoko et al., 2017).



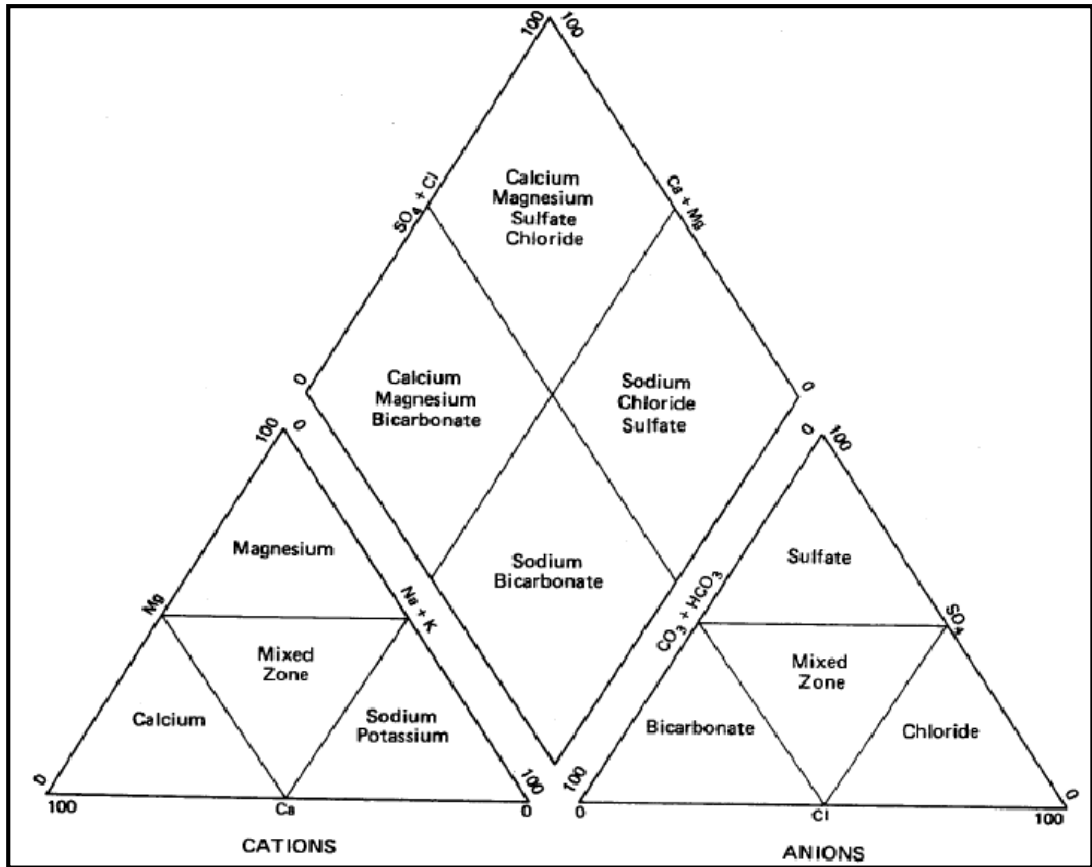


Figure 20: Piper diagram showing water type categories (Tatawat and Chandel, 2007).

### Stable Isotopes

The analysis of the stable isotope ( $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) shows that the groundwater samples taken in the perched aquifer system in Okongo area is saturated and subjected to evaporation. In this case, samples plotting below the GMWL and LMWL indicate evaporation that is possibly contributed by the unsaturated zone and the presence of the open hand dug wells next to the boreholes. Evaporation is also caused by the low relative humidity of the air (Mendelsohn et al., 2000) and high temperature in the study area which ranges from 29.2°C to 37.2°C; this was also observed in the samples taken in October 2016 (see Table 4). A comparison of the two samples shows that the samples in October 2016 plots further away from the GWML and LMWL than samples from April 2017 (Fig.18), indicating that, recharge in the perched aquifer

occurred during less-intense / small rainfall events as confirmed by Hamutoko et al. (2017). The samples can be categorised in two groups, Group 1: consists of Epumbalondjaba which is in the river, and Omboloka 2 is in the valley / side of a large pan. These samples were from different locations in the landscape, indicating a less depleted water source, revealing that recharge could take place through river bank exfiltration consisting of sand formation with 96-100% (Uutoni, 2017) (see appendix F). Furthermore, the samples indicate that water still flows through the subsurface of the Ephemeral River or paleo-channels. Group 2 samples consist of Oshanashiwa, Okamanya, Ohameva and Omboloka 1. These sites were all in the calcrete areas surrounded by the hand dug wells, showing more depleted isotope values revealing that, recharge is associated with a very intense rainfall event, either of high intensity or long duration infiltrating through preferential paths. This indicates that small amount events can recharge KOH-0 (perched aquifer) as the mean parent water source is slightly enriched. In overall, stable isotope method indicates the origin of the water, define the recharge location and determine the mean residence time and mixing conditions (Barbecot et al., 2000).

## CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

### 7.1 Conclusions

In conclusion, the study aimed to determine the residence time, investigate the distribution of recharge areas and examine the origins of recharge to the perched aquifer using the sulfur hexafluoride, tritium, major ion chemistry and stable isotopes  $^{18}\text{O}$  and  $^2\text{H}$ . The concentration of  $\text{SF}_6$  in the groundwater samples proves that recharge to the perched aquifer happened in 2000 for Omboloka 2, Ohameva in the year 2010, Okamanya in 2012 and Omboloka 1 and Oshanashiwa in the year 2016 with the ages from 17, 7, 5 and 1 years respectively. All the recharge years determined with  $\text{SF}_6$  indicate distinctively younger groundwater ages. The same samples were observed to have higher proportion of young-to-old water concentration when calculated using conservative mixing ratio. This proves that the groundwater in the perched aquifer is young with a short residence time.

Tritium method using calculated theoretic / hypothetical revealed that, groundwater at Ohameva, Okamanya, Omboloka 1 and Oshanashiwa indicates sub-modern groundwater, while the Epumbalondjaba and Omboloka 2 indicates a mix of sub-modern and modern water. In addition, the tritium method has shown that local precipitation which has infiltrated the unsaturated sand zone has contributed to the direct recharge in the perched aquifer. Thus, it can be concluded that the distribution of the recharge areas in the perched aquifer can be observed using the tritium method.

When comparing the SF<sub>6</sub> results to the <sup>3</sup>H results, the recharge years slightly differs, but the concentration of both SF<sub>6</sub> and <sup>3</sup>H correlates with the age range, that recharge occurred before 1960 (older than 1960 or younger than 1990).

On the other hand, the major ion chemistry shows that the water samples from the shallow boreholes have three major groups; the mixed zone water type with neither a dominant cation nor anion, the Na<sup>+</sup>-K<sup>+</sup>-HCO<sub>3</sub> water type, and the Ca<sup>2+</sup>-Mg<sup>2+</sup>-HCO<sub>3</sub> water type. The dominated water type in the perched aquifer is Ca<sup>2+</sup>-Mg<sup>2+</sup>-HCO<sub>3</sub>, caused by the dissolution of calcrete and the formation of carbonate-rich rocks derived from a recent recharge with short residence times. Therefore, the combination of stable isotopes, hydrochemistry analyses, tritium and sulfur hexafluoride can be successfully used to estimate the groundwater age and residence time of the perched aquifer system.

Isotopic composition of groundwater in the perched aquifer indicates depleted samples which are subjected to evaporation and shows the origin of recharge to the perched aquifer. This reveals that recharge is associated with a significantly intense rainfall event from local precipitation, either of a high intensity or for a long duration, infiltrating through preferential paths.

## **7.2 Recommendations**

- Since the study used only data from 6 boreholes to determine the age of the groundwater in the perched aquifer, it is recommending that these trace gases (tritium and sulfur hexafluoride) should be applied to a wide range of groundwater in the entire perched aquifers of the Okongo.

- It is necessary to further investigate the distribution of recharge areas of both groundwater chemistry and isotopic composition of perched groundwater aquifer.
- It is recommended to establish long term monitoring stations for water levels, water quality and stable isotopes.
- A further study at PhD level should be conducted in the same study area using tritium and sulfur hexafluoride in order to close the gaps identified.

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## 9. APPENDIXES

### Appendix A: Request letter to drill and take water samples in Study area

**UNIVERSITY OF NAMIBIA**

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Private Bag 13301, 340 Mandume Ndemufayo Avenue, Pioneerspark, Windhoek, Namibia. 

Faculty of Science, Geology Department      Tel: 061 - 206 3212      Email: [jhamutoko@gmail.com](mailto:jhamutoko@gmail.com)

Windhoek, 06/10/2016

Dear Chief Regional Officer, Honorable Councilors,

As usual, we are planning to carry out our quarterly sampling between from 10<sup>th</sup> October to 25<sup>th</sup> October 2016. The field trip will again take place in our study sites as from the previous years.

Water samples will be taken from hand-dug wells, surface water and boreholes from surrounding areas in some villages in Ohangwena region in Okongo, Oshikunde and Epembe constituencies. The names of the villages to be visited are as follow (exceptions are only when villagers ask us to check their water or we discover something interesting when we are in the field already but it should still be in the vicinity):

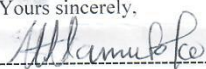
- Oshana-shiwa, Ongalangobe, Okamanya, Omboloka, Oluwaya, Ohameva, Epumbalondjaba, Walye-inda, Onambaladhi, Oshikunde, Oshuuli, Omulonga


Additionally, in this period we would drill shallow boreholes (maximum 40m) which will be strictly used for research for the time being in the following villages: Oshana-shiwa, Okamanya, Oluwaya, Ohameva, Epumbalondjaba and Omboloka. We would also do more ground geophysical surveying in these villages.

It would be highly appreciated if you could render us with the necessary support.

Should you need any further information, please contact me at [jhamutoko@gmail.com](mailto:jhamutoko@gmail.com) or telephonically at ++264-81-3129833 or contact my supervisor Dr Heike Wanke at [hwanke@unam.na](mailto:hwanke@unam.na) or telephonically at ++264-81-4111118

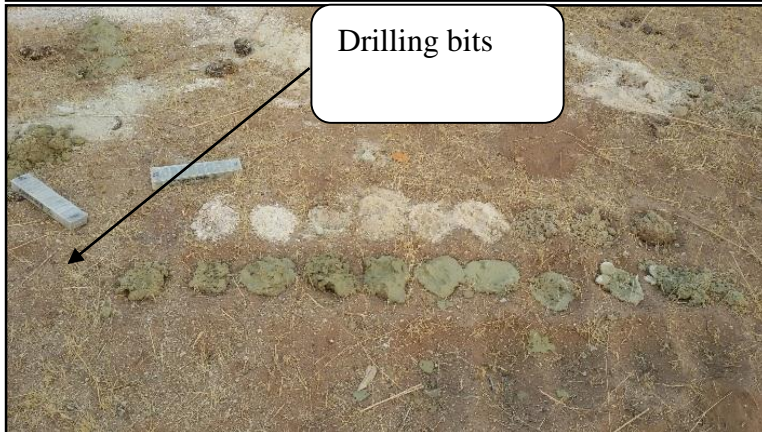
Thank you.

Yours sincerely,  
  
-----  
Josefina T. Hamutoko  
PhD Candidate at UNAM

  
-----  
06 OCT 2016  
Dr Mengist Teklay  
HoD: Geology Department

**GEOLOGY DEPARTMENT**  
OFFICE  
Private Bag 13301 WINDHOEK

**Appendix B: Air Percussion drilling rig, drilling bits and borehole log samples and chip tray at Ohameva.**





### **Appendix C: Detailed Lithology**

The simplified lithology log for 6 boreholes can be observed in Figs. 22-28 showing the sand layer from the ground surface at 1 m, followed by calcrete layer at the depth 2-6 m. At the depth of 7-25 m sand formation was again observed followed by a clay layer at the depth of 26-31 m. In general, the formation of all borehole logs shows sand layer being the common soil observed on the ground surface.

The hydrogeology of the perched Ohangwena Aquifer in Okongo area consists of Kalahari sand cover with calcrete and clay layer formations. The groundwater is contained in the primary porosity of the Kalahari cover. The depth of the aquifer is between 10-28 m and the rest of the water level (RWL) in the shallow boreholes is between 1.93-21.56 m. The lithology shows that the perched aquifer in the study area is found in saturated sand above the aquitard formation of the clay layer as summarized in Fig. 21.

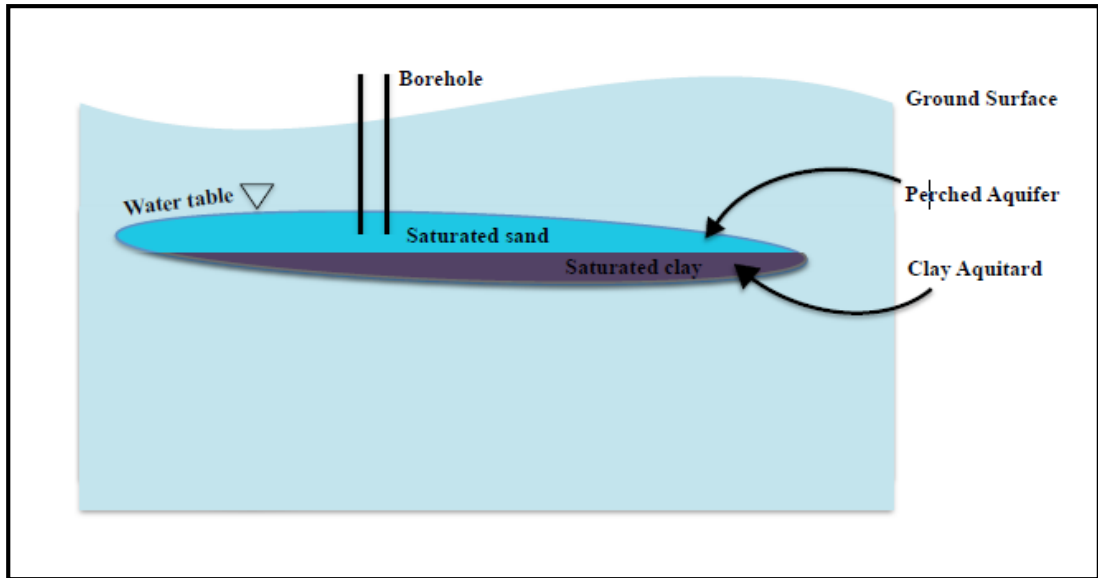


Figure 21: Schematic cross-section of a perched aquifer in Okongo area

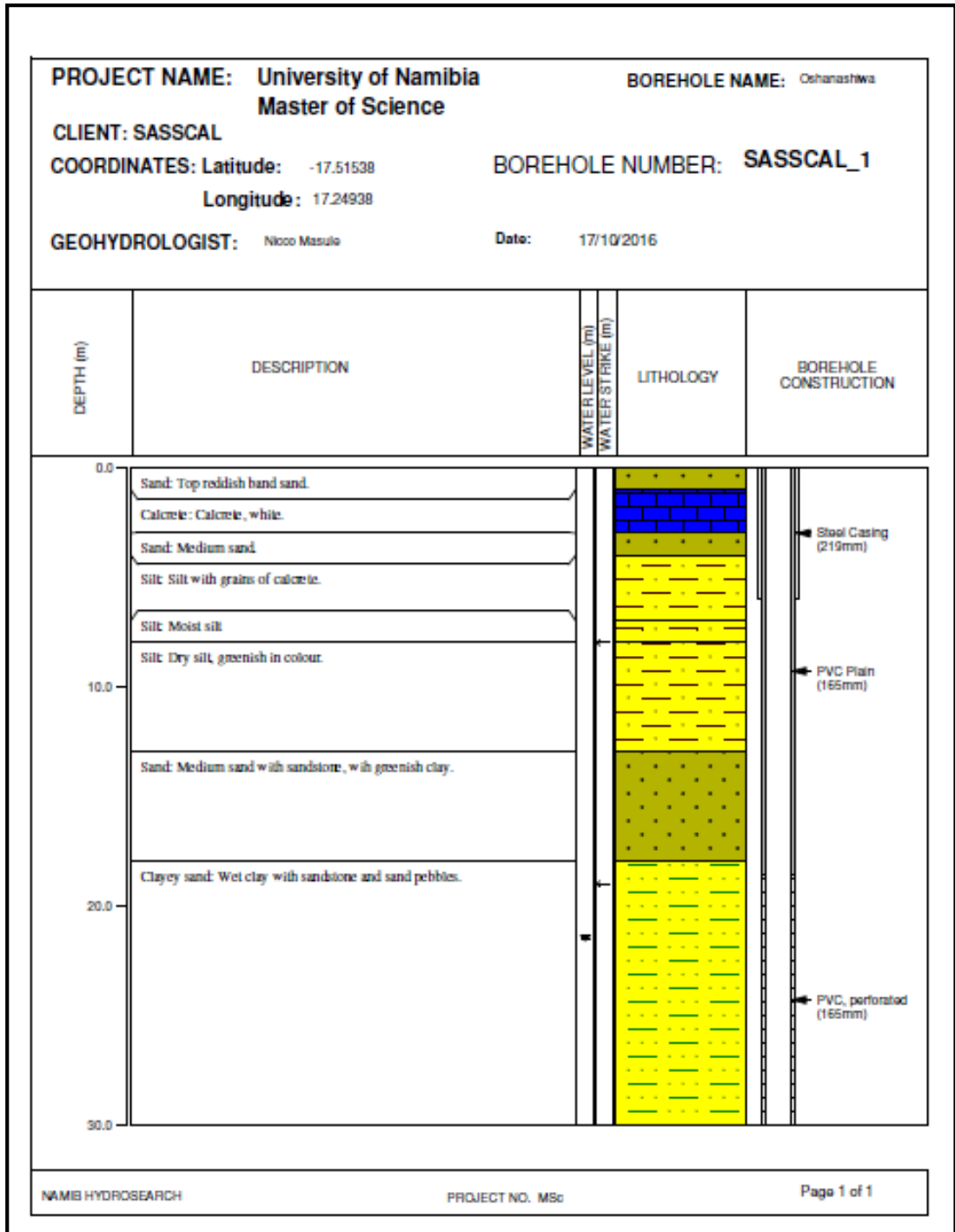


Figure 22: Borehole log in Oshanashiwa

Oshanashiwa borehole log has a total depth of 30 m, with the rest water level at 21.56 m below topographic surface. The water strike is at 19 m below topographic surface.

The upper meters of the layer consist of reddish-brown sandy soil; followed by the calcrete at the depth of 2 – 3 m. Medium sand is found at 4 m while the silt with a greenish colour occurs at the depth of 5 – 13 m deep. The sand formation is observed at the depth of 14 – 18 m. The clayey sand formation is found at the depth of 19 – 30 m. The borehole construction was cased with steel casing (219 mm) from 0 – 6 m from the top. The PVC Plain (165 mm) casing was installed from 0 – 19 m, then connected to the PVC perforated (165 mm) casing at 20 – 30 m.

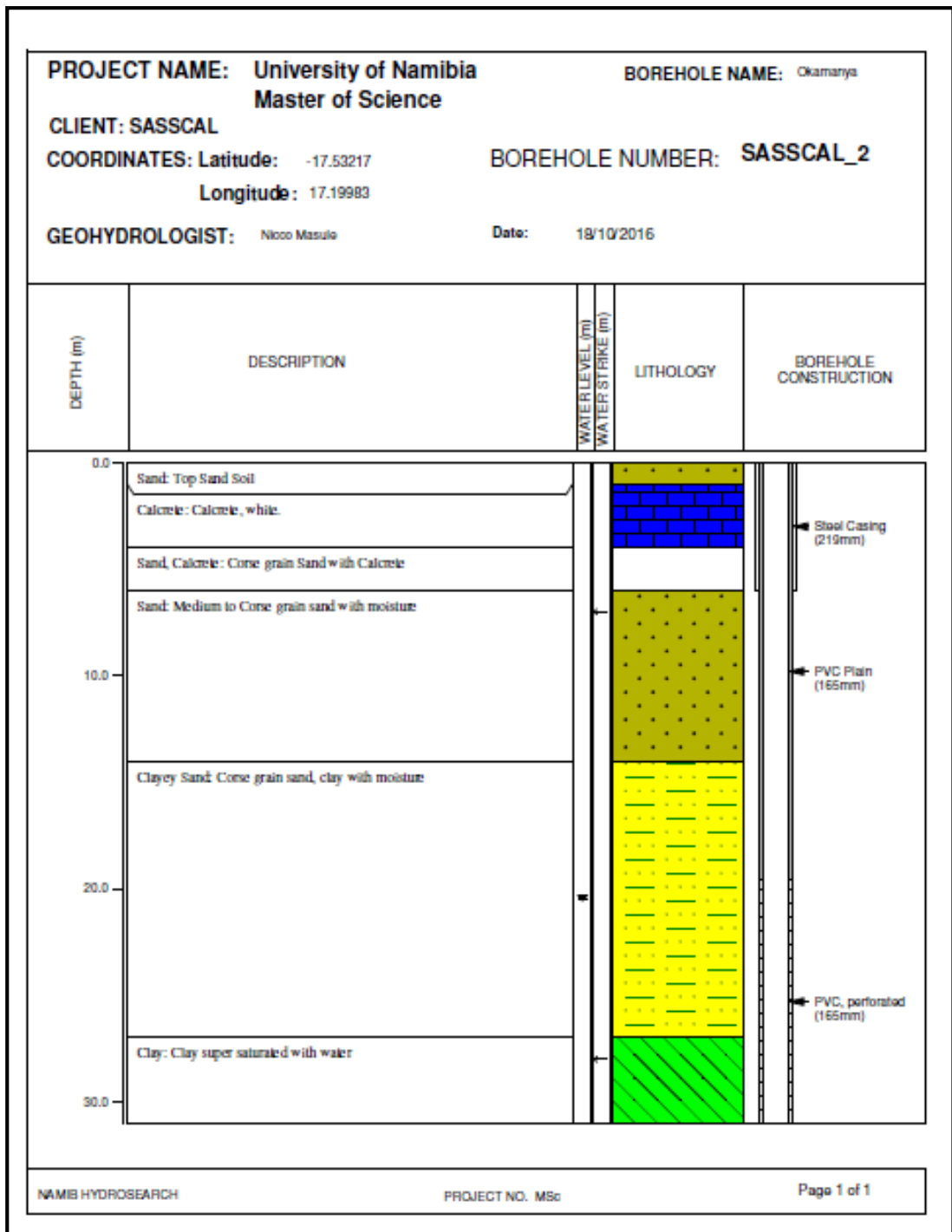


Figure 23: Borehole lithology at Okamanya

Okamanya borehole has a total depth of 31 m, with the rest water level at 20.52 m below topographic surface. The water strike is at 27 m below topographic surface. The upper meters of layer consist of sand soil, followed by the calcrete formation at the

depth of 2 – 4 m. Sand and calcrete is found at the depth of 5 – 14 m while clayey sand with moisture occurs at the depth of 15 – 27 m. Clay saturated with water is observed at the depth of 28 – 31 m. The borehole construction was cased with steel casing (219 mm) from 0 – 6 m from the top. The PVC Plain (165 mm) casing was installed from 0 – 19 m, then connected to the PVC perforated (165 mm) casing at 20 – 31 m.

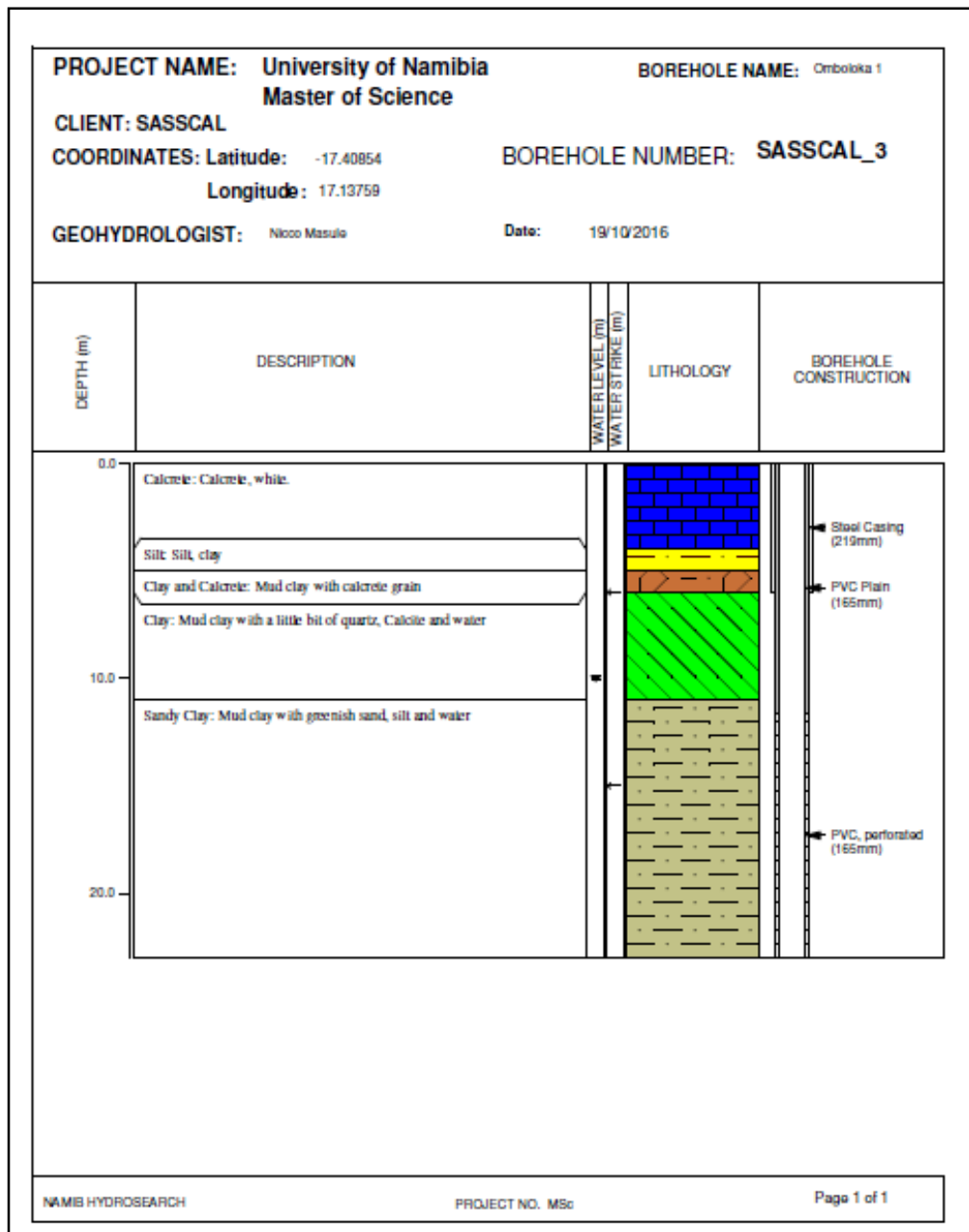


Figure 24: Borehole lithology at Omboloka 1



Omboloka 1 borehole has a total depth of 23 m, with the rest water level at 10.10 m below topographic surface. The first water strike is at 7 m below topographic surface and the second water strike is at 14 m below topographic surface. The calcrete is found at the depth of 1 – 4 m, followed by silt with clay at the depth of 5 m. The clay and calcrete with mud is observed at the depth of 6 – 11 m, while sandy clay is observed at the depth of 5 – 13 m. The sand is observed at the depth of 14 – 18 m. The clayey sand is observed at the depth of 12 – 23 m. The borehole construction was cased with steel casing (219 mm) from 0 – 6 m from the top. The PVC Plain (165 mm) casing was installed from 0 – 11 m, then connected to the PVC perforated (165 mm) casing at 12 – 23 m.

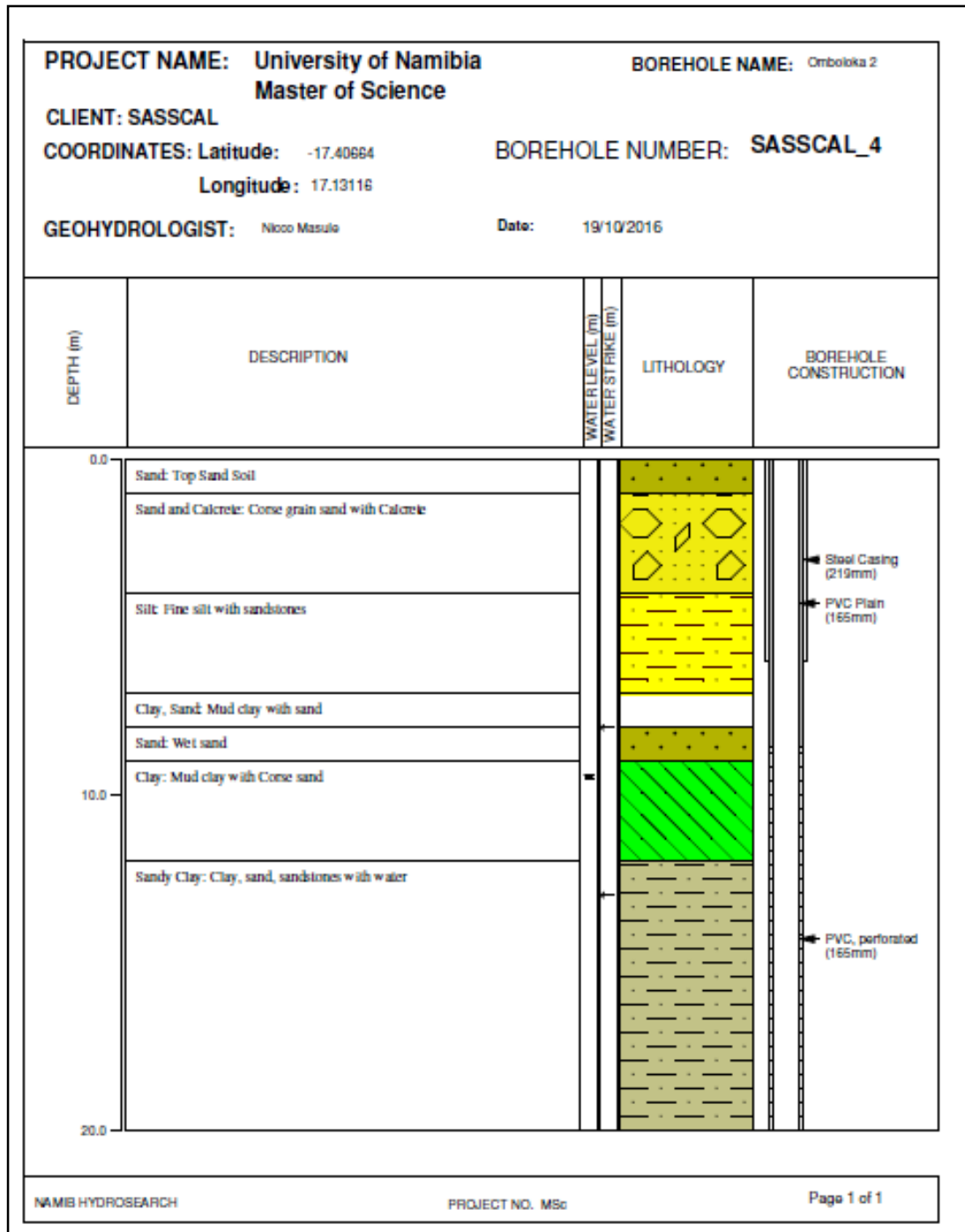


Figure 25: Borehole lithology at Omboloka 2

Omboloka 2 borehole has a total depth of 20 m, with the rest water level at 9.54 m below topographic surface. The first water strike is at 9 m below topographic surface and the second water strike is at 13 m below topographic surface. The upper meters of

layer consist of sand soil, followed by sand and calcrete found at the depth of 2 – 4 m. The silt with sandstone occurs at the depth of 5 – 7 m. The clay with sand is observed at the depth of 8 m with wet sand observed at the depth of 9 m. The clay is found at the depth of 10 – 12 m, whilst sandy clay occurs at the depth of 13 – 20 m. The borehole construction was cased with steel casing (219 mm) from 0 – 6 m from the top. The PVC Plain (165 mm) casing was installed from 0 – 8 m, then connected to the PVC perforated (165 mm) casing at 9 – 20 m.

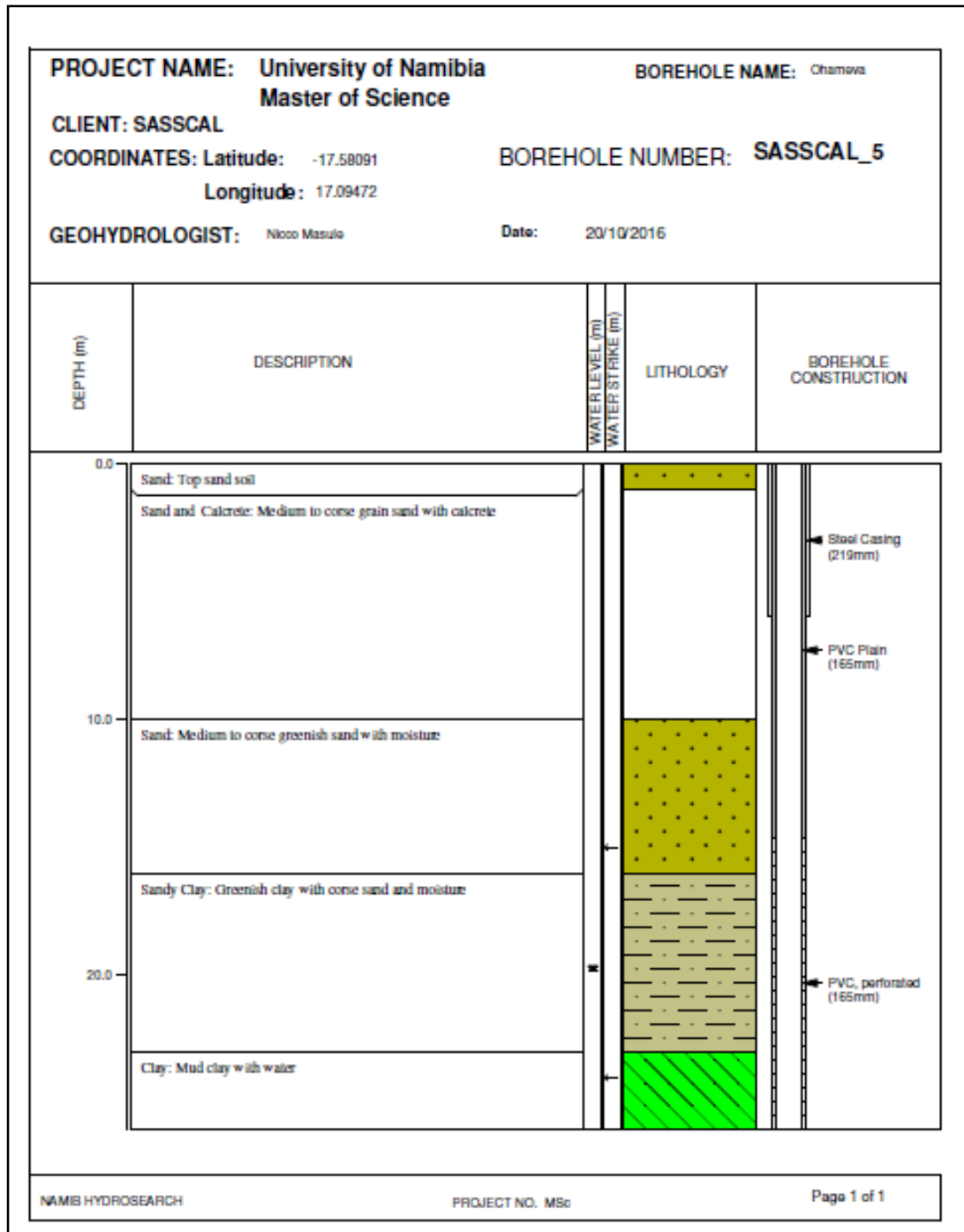


Figure 26: Borehole lithology at Ohameva

Ohameva borehole has a total depth of 26 m, with the rest water level at 19.81 m below topographic surface. The first water strike is at 17 m below topographic surface and the second water strike is at 24 m below topographic surface. The upper meters consist of sand soil, followed by sand and calcrete found at the depth of 2 – 10 m. The sand is

found at the depth of 11 – 16 m. The sand and clay in greenish colour occurs at the depth of 17 – 23 m. The clay is observed at the depth of 24 – 26 m. The borehole construction was cased with steel casing (219 mm) from 0-6 m from the top. The PVC Plain (165 mm) casing was installed from 0 – 14 m, then connected to the PVC perforated (165 mm) casing at 15 – 26 m.

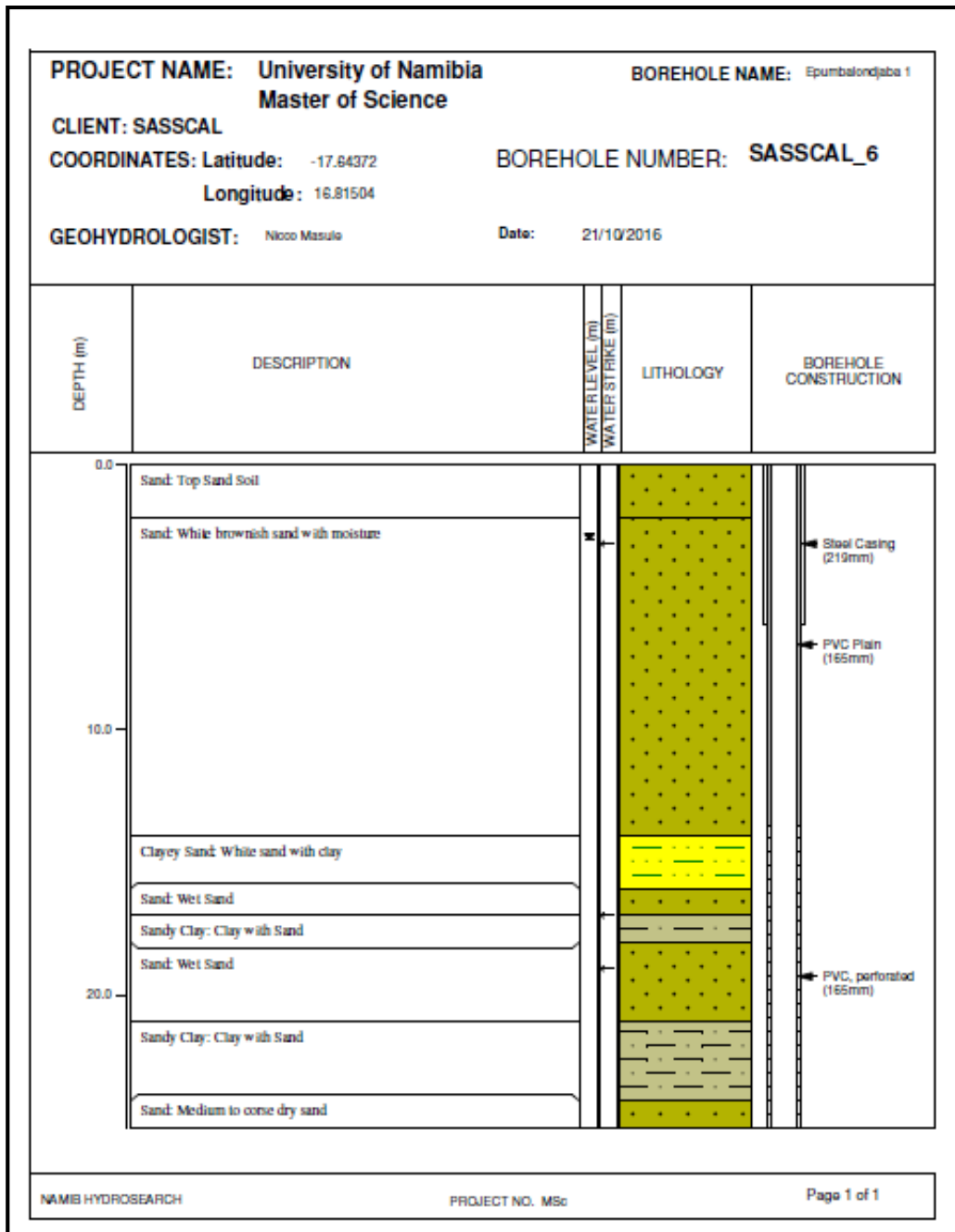


Figure 27: Borehole lithology at Epumbalondjaba 1

Epumbalondjaba 1 borehole has a total depth of 25 m, with the rest water level at 2.80 m below topographic surface. The water strike is at 3 m below topographic surface. The upper meters of layers from 1 – 2 m consists of sand soil, followed by a sand layer at the depth of 3 – 14 m. Clayey sand is again found at the depth of 15 – 16 m and a mixture of wet sand and clay occurs at 17 – 25 m. The borehole construction was cased with steel casing (219 mm) from 0 – 6 m from the top. The PVC Plain (165 mm) casing was installed from 0 – 13 m, then connected to the PVC perforated (165 mm) casing at 14 – 25 m.

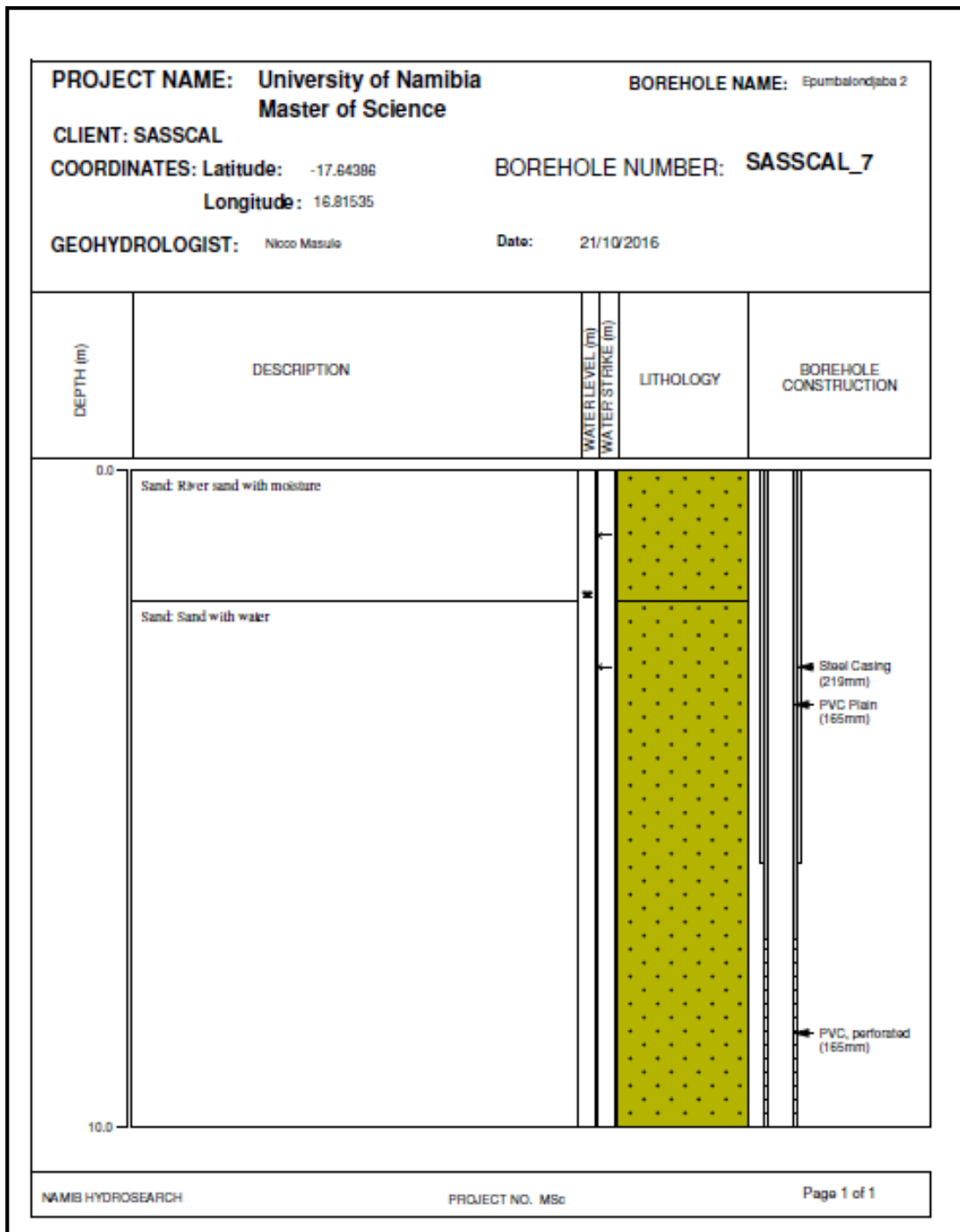


Figure 28: Borehole lithology at Epumbalondjaba 2

Epumbalondjaba 2 borehole has a total depth of 10 m, with the rest water level at 1.93 m below topographic surface. The first water strike is at 2 m and the second water strike is at 4m below topographic surface. The upper and lower meters from 1 – 10 m


consist of sand soil. The borehole construction was cased with steel casing (219 mm) from 0 – 6 m from the top. The PVC Plain (165 mm) casing was installed from 0 – 8 m, then connected to the PVC perforated (165 mm) casing at 9 – 10 m.

**Appendix D: Plastic-coated glass bottle with a polyseal cone lined cap for SF<sub>6</sub> and Tritium bottles**





## Appendix E: Sampling procedures for SF<sub>6</sub>



Dr. Harold Oster  
Bornweg 10  
67157 Wachenheim  
Telefon 0 63 22/94 38 0  
Fax 0 63 22/98 02 26  
eMail: harold.oster@t-online.de

### CFC/SF<sub>6</sub> sampling instructions

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**Material:**

1. A tube with draining water
2. A glas bottle (500 ml) with a stop cock and a metal clip
3. A metal container with a top, a sealing ring and a clamp ring
4. **A 10 l bucket**

**Sampling:**

- Open the metal container and the bottle, insert the tube with draining water into the bottle.
- Insert the container+**bottle** into the bucket.
- Wait until the bucket is overflowing.
- Take the tube out of the bottle.
- The following steps have to done below the water table in the bucket:
  - (1) Close the bottle with the stop cock and
  - (2) fix it with the metal clamp.
  - (3) Check the correct position of the sealing ring of the top.
  - (4) Close the metal container with the top and the clip ring.
- Take the metal container out of the bucket.
- Please check the metal container for leaks (turn for a short time upside down).
- For packing/shock-protection of the samples please use newspapers (no foam chips)

Omboloka 1				
				sand [%]
depth (m)	mass (g)	mass passing through sieve (g)	mass retained from sieve (g)	Percentage retained (%)
1	27.9	0	27.9	100
2	22.9	0	22.9	100
3	21.8	0	21.8	100
4	24.5	0.3	24.2	98.7755102
5	21.3	0.5	20.8	97.65258216
6	16.9	0.2	16.7	98.81656805
7	23	0.7	22.3	96.95652174
8	21.2	1.3	19.9	93.86792453
9	19.4	0.9	18.5	95.36082474
10	20.9	1	19.9	95.215311
11	19.6	0	19.6	100
12	21.9	0.3	21.6	98.63013699
13	32.2	0.8	31.4	97.51552795
14	31	0.6	30.4	98.06451613
15	39.3	0.7	38.6	98.21882952
16	35.5	0.8	34.7	97.74647887
17	34.8	0.7	34.1	97.98850575
18	39.8	0.8	39	97.98994975
19	36.5	0.6	35.9	98.35616438
20	32	0.5	31.5	98.4375
21	34.3	0.6	33.7	98.25072886
22	31.8	0.4	31.4	98.74213836
23	33.1	0.5	32.6	98.48942598

## Appendix F: Percentage of grain size analysis of sand

Percentage grain size analysis				
Omboloka 2				
				sand [%]
depth (m)	mass (g)	mass passing through the sieve (g)	mass retained from the sieve (g)	Percentage retained (%)
1	31.2	0.5	30.7	98.3974359
2	28	0.3	27.7	98.92857143
3	28.4	0.8	27.6	97.18309859
4	27.1	0.9	26.2	96.67896679
5	24.7	0.5	24.2	97.9757085
6	25.5	0.3	25.2	98.82352941
7	25.9	1.2	24.7	95.36679537
8	25.1	0.5	24.6	98.00796813
9	34.1	0.7	33.4	97.94721408
10	29.4	1	28.4	96.59863946
11	40.6	1.5	39.1	96.30541872
12	37.3	1.1	36.2	97.05093834
13	39.6	1.6	38	95.95959596
14	36	1.1	34.9	96.94444444
15	39.3	1.3	38	96.69211196
16	35.4	1.7	33.7	95.19774011
17	24.6	1.2	23.4	95.12195122
18	40.2	0.8	39.4	98.00995025
19	44.3	0.7	43.6	98.41986456
20	34.5	0.3	34.2	99.13043478

Percentage grain size analysis				
Ohameva				
				sand [%]
depth (m)	mass (g)	mass passing through the sieve (g)	mass retained from sieve (g)	Percentage retained (%)
1	34	0.3	33.7	99.11764706
2	29.4	0.3	29.1	98.97959184
3	19.1	0.6	18.5	96.85863874
4	23.8	0.9	22.9	96.21848739
5	23.2	0.8	22.4	96.55172414
6	26.9	0.3	26.6	98.88475836
7	30.3	0.7	29.6	97.68976898
8	28.5	0.6	27.9	97.89473684

9	28.7	0.6	28.1	97.90940767
10	15.1	0.4	14.7	97.35099338
11	29.1	0.3	28.8	98.96907216
12	28.1	0.2	27.9	99.28825623
13	30.2	0.6	29.6	98.01324503
14	30.1	0.4	29.7	98.67109635
15	26.7	0	26.7	100
16	27.3	0.3	27	98.9010989
17	24.8	0.3	24.5	98.79032258
18	26.7	0.2	26.5	99.25093633
19	28.4	0.3	28.1	98.94366197
20	26.5	0.3	26.2	98.86792453
21	21.1	0.3	20.8	98.57819905
22	25.7	0.2	25.5	99.22178988
23	23.8	0.3	23.5	98.7394958
24	38.4	0.5	37.9	98.69791667
25	30.6	0.3	30.3	99.01960784
26	40.2	0.4	39.8	99.00497512

Percentage grain size analysis				
Okamanya				
				sand [%]
Depth (m)	mass (g)	mass passing through the sieve (g)	mass retained from sieve (g)	Percentage retained (%)
1	6.9	0	6.9	100
2	28.6	0	28.6	100
3	35.4	0	35.4	100
4	34.3	0.3	34	99.12536443
5	34.6	0.4	34.2	98.84393064
6	34.7	0.9	33.8	97.40634006
7	32.9	1.6	31.3	95.13677812
8	37.9	1.9	36	94.98680739
9	25.7	1.6	24.1	93.77431907
10	8	0.6	7.4	92.5
11	24.1	0.3	23.8	98.75518672
12	30.5	0.4	30.1	98.68852459
13	32.5	0.4	32.1	98.76923077
14	44.1	0.5	43.6	98.86621315
15	20.2	0.2	20	99.00990099
16	28.6	0	28.6	100
17	29.7	0	29.7	100
18	27.4	0	27.4	100
19	28.2	0	28.2	100

20	28.4	0	28.4	100
21	33.3	0	33.3	100
22	35.3	0	35.3	100
23	34.1	0	34.1	100
24	33.3	0	33.3	100
25	30.4	0	30.4	100
26	26.6	0	26.6	100
27	24.9	0	24.9	100
28	23.2	0	23.2	100
29	26.6	0.4	26.2	98.4962406
30	28.9	0.6	28.3	97.92387543
31	32.5	1	31.5	96.92307692

Percentage grain size analysis				
Oshanashiwa				
				sand [%]
depth (m)	mass (g)	mass passing through the sieve (g)	mass retained from sieve (g)	percentage (g)
1	16.3	0	16.3	100
2	36.3	0.2	36.1	99.44903581
3	36.4	0.2	36.2	99.45054945
4	24.1	0.3	23.8	98.75518672
5	26.9	1.1	25.8	95.91078067
6	30	1.9	28.1	93.66666667
7	30	1.4	28.6	95.33333333
8	21	1.5	19.5	92.85714286
9	16.8	0.6	16.2	96.42857143
10	12.8	0.4	12.4	96.875
11	21.1	0	21.1	100
12	29.9	0.5	29.4	98.3277592
13	32.3	0.3	32	99.07120743
14	32.3	0.2	32.1	99.38080495
15	32.3	0	32.3	100
16	31.9	0	31.9	100
17	32.6	0	32.6	100
18	29.1	0.4	28.7	98.62542955
19	34.7	0	34.7	100
20	23.5	0	23.5	100
21	26.1	0.2	25.9	99.23371648
22	19.5	0.2	19.3	98.97435897
23	21.6	0	21.6	100
24	24	0	24	100
25	20.4	0	20.4	100
26	24.8	0.3	24.5	98.79032258

27	23	0.2	22.8	99.13043478
28	23.8	0.2	23.6	99.15966387
29	24.9	0.2	24.7	99.19678715
30	22.2	0.2	22	99.0990991

Percentage grain size analysis				
Epumbalondjaba 1				
				sand [%]
Depth (m)	mass (g)	mass passing through (g)	mass retained (g)	Percentage retained (%)
1	30.4	0	30.4	100
2	28.2	0	28.2	100
3	23.7	0	23.7	100
4	26.3	0	26.3	100
5	22.2	0	22.2	100
6	29.8	0	29.8	100
7	29.9	0	29.9	100
8	30.9	0	30.9	100
9	26.1	0	26.1	100
10	30.6	0	30.6	100
11	32.5	0	32.5	100
12	33.3	0	33.3	100
13	31.9	0	31.9	100
14	35.5	0	35.5	100
15	30.8	0	30.8	100
16	25.1	0	25.1	100
17	32.4	0	32.4	100
18	25.4	0	25.4	100
19	28.7	0	28.7	100
20	28.7	0	28.7	100
21	30.7	0	30.7	100
22	27	0	27	100
23	24.3	0	24.3	100
24	26.6	0	26.6	100
25	21.3	0	21.3	100

Percentage grain size analysis				
Epumbalondjaba 2				
				sand [%]
Depth (m)	mass (g)	mass passing through (g)	mass retained (g)	Percentages retained (%)
1	28.3	0	28.3	100
2	29	0	29	100
3	35	0	35	100
4	33.7	0	33.7	100
5	37.5	0	37.5	100
6	39.6	0.3	39.3	99.24242424
7	37.3	0.2	37.1	99.46380697
8	38.4	0.2	38.2	99.47916667
9	37.9	0.2	37.7	99.47229551
10	37.7	0	37.7	100

## Appendix G: Tritium activities in the CEB

ID	SANSCAL	Object ID	Borehole No	Region	Location or Farm	Longitude	Latitude	East (UTM Grid)	North (UTM Grid)	Altitude [m]	Type	Aquifer	Sample No/Name	Laboratory No	Sample Date	T [°C]	EC [ns/m]	pH	δ <sup>18</sup> O [‰]	δ <sup>2</sup> H [‰]	D <sub>excess</sub>	H [TU]	δ <sup>13</sup> C [‰]	<sup>14</sup> C [pMC]	<sup>14</sup> C Age [BP]	Source/Owner
1739		92	WW9586	Central Southern Margin of Etosha Pan	22 km E of Hakli	16.50610	-18.95640	658489.93838	7903243.19570	1095	Artesian	DO	E-017	Hv20763	7/15/1995	28.2	345	6.9	-7.97	-59.1	4.7	1.1	-9.6	54.5 ± 0.4	4870 ± 60	Geyh, 1997
1224		2603	WW37346		Pump "L"	17.52420	-18.46790	766480.03226	7956104.44094	1142	Groundwater	K	65884		3/7/2002		107	7.6	-8.5	-62.5		0.9	-9.1	13 ± 0.1	BGR	
1718		2606	WW93419		Poya Andoni	17.24240	-18.42950	736762.72324	7960747.82528	1122	Groundwater	K	1000015		11/22/2001		107	7.4	-7.85	-59.7		0.27	-9.43	40 ± 0.36	BGR	
1707		2599	WW31452		Pump D3	17.46750	-18.42510	760554.33312	7960925.72038	1137	Groundwater	K	9470		11/18/2001		96	7.6	-7.9	-61.5		0.1	-8.9	33.2 ± 0.35	BGR	
2605		2605	WW93416		Okatope	17.53130	-18.40910	767321.19067	7962604.18958	1140	Groundwater	K	1000011		11/19/2001		181	7.9	-8.49	-63		0.28	-8.84	19 ± 0.24	BGR	
1005		2598	WW31445			17.65590	-18.40850	780493.36365	7962482.23029	1146	Groundwater	K	1000007		11/17/2001		1312	7	-8.33	-60.5		0.6	-11.15	49 ± 0.37	BGR	
1713		2604	WW93413		Omaimbi	17.09290	-18.35440	721063.45054	7969249.68482	1127	Groundwater	K	1000005		3/6/2002		161	7.5	-7.68	-59.5		0.38	-8.36	76 ± 0.48	BGR	
1223		2602	WW37345		OTANAHA	17.18450	-18.29300	730826.83343	7975932.49797	1132	Groundwater	K	65879		3/6/2002		599	9.3	-8.1	-61.4		0.24			BGR	
1086		2601	WW34222		OSHANASHOSINO	17.49340	-18.27270	763522.61388	7977761.19996	1136	Groundwater	K	35324		11/22/2001		906	9.4	-8.3	-62.9		0	-6.1	2.7 ± 0.13	BGR	
1590		76	WW6329	Central Southern Margin of Etosha Pan	Dungaries	16.78690	-19.17890	687807.35911	7878340.47643	1140	Groundwater	KEL	E-019	Hv20765	7/15/1995	27.3	204	6.8	-7.6	-57.8	3	1.2	-11	71.5 ± 0.5	2715 ± 55	Geyh, 1997
1046		2610	WW32624		HOHENECK now Farm: Belladonna	17.65190	-18.73340	779537.87324	7926512.87463	1150	Groundwater	KEL	19244		11/14/2001		99	7.3	-7.5	-56.8		0.4	-10.7	49 ± 0.4	BGR	
1225		2611	WW37349		VET FARM	17.49660	-18.55140	763436.11366	7946900.09985	1137.8	Groundwater	KEL	65901		11/17/2001		93	7.6	-7.7	-59.1		0.3	-8.7	38 ± 0.25	BGR	
1719		2623	WW93420		Ongumbwa	17.48880	-18.19320	763155.78419	7986569.56294	1137	Groundwater	KOH	1000016		11/22/2001		188	7.6	-8.76	-62.1		0	-8.36	53 ± 0.29	BGR	
1202		2618	WW36845			17.20860	-18.17720	733529.82041	7987230.36649	1133	Groundwater	KOH	65874		4/5/2002		547	9.2	-8.9	-66.9		0.09	-6.2	1 ± 0.06	BGR	
1714		2622	WW93414		Tatachi	17.05530	-18.16460	717325.59931	7990303.38267	1133	Groundwater	KOH	1000006		3/6/2002		1698	7.6	-8.44	-62.8		0.51	-9.31	62 ± 0.4	BGR	
1201		2617	WW36907		Ohila 1, Eizengdi	17.04140	-18.08780	715985.86436	8002140.90231	1136	Groundwater	KOH	65876		3/6/2002		336	9.4	-9.1	-67.4		0	-5.8	5 ± 0.1	BGR	
1676		5	WW8219	Eastern Owambo	Omala	16.82590	-17.92650	693314.86464	8016910.90527	1126	Groundwater	KOH	OE-001	Bh10891	10/24/1993	27.8	280	9.6	-9.05	-67.6	4.8	1.2				Geyh, 1997
1066		6	WW33427	Eastern Owambo	Ohumbulwa	16.86100	-17.92610	697033.79584	8016918.33535	1130	Groundwater	KOH	OE-002	Hv19560	10/24/1993	27.3	240	9.4	-9.2	-67.6	6	1.3	-7.3	10.8 ± 0.2	17950 ± 170	Geyh, 1997
1082		16	WW34176	Eastern Owambo	Onkolo	17.41610	-17.91110	755871.46954	8017902.87350	1135	Groundwater	KOH	OE-013	Hv20349	10/15/1994	27.5	70	8.9	-9.07	-67	5.6	1.2	-10.4	15.2 ± 0.5	15090 ± 270	Geyh, 1997
1096		14	WW34639	Eastern Owambo	Oongodhi	17.01970	-17.89880	713880.03155	8019764.60916	1133	Groundwater	KOH	OE-011	Hv20347	10/15/1994	27.9	140	9.1	-9.04	-66.4	5.9	1.2	-9.3	15.4 ± 0.3	15010 ± 175	Geyh, 1997
1095		17	WW34637	Eastern Owambo	Onatwe	17.03380	-17.84350	715440.85226	8025869.06433	1138	Groundwater	KOH	OE-014	Hv20350	10/15/1994	27.9	250	8.6	-8.84	-66	4.7	0.9	-8.2	50.4 ± 1	5510 ± 155	Geyh, 1997
1094		15	WW34631	Eastern Owambo	Oshifu	16.96770	-17.69960	708601.45833	8041870.51867	1144	Groundwater	KOH	OE-012	Hv20348	10/15/1994	27.1	210	8.6	-9.03	-67.2	5	1.2	-9.7	29.9 ± 0.5	9695 ± 150	Geyh, 1997
1028		13	WW32252A	Eastern Owambo	Omukonga	16.86220	-17.58110	697539.47564	8055098.71660	1145	Groundwater	KOH	OE-010	Hv20346	8/26/1994	27.2	53	8.5	-8.81	-64.5	6	1.2	-11.1	27.2 ± 0.6	10475 ± 185	Geyh, 1997
1749		11	WW32252A	Eastern Owambo	Okongo Army Camp	17.21890	-17.56350	735427.39808	8056639.32804	1154	Groundwater	KOH	OE-008	Hv20345	8/24/1994	27.3	59	7.1	-9	-66.5	5.5	1.2	-11.4	36.5 ± 0.7	4590 ± 105	Geyh, 1997
1072		9	WW33919	Eastern Owambo	Efunde	16.98030	-17.48280	710188.82845	8065851.09713	1155	Groundwater	KOH	OE-006	Hv20343	8/24/1994	27.9	94	7.3	-8.97	-65.2	6.6	1.2	-12.6	47.5 ± 0.7	5940 ± 115	Geyh, 1997
1080		7	WW34151	Eastern Owambo	Oxlinba	16.50350	-17.48170	659555.35737	8066435.44567	1128	Groundwater	KOH	OE-003	Hv19561	10/26/1993	27.4	230	9.4	-9.17	-66.9	6.5	1.3	-8.3	7.9 ± 0.3	20440 ± 275	Geyh, 1997
1088		10	WW34238	Eastern Owambo	Ondema	17.15280	-17.48140	728512.26148	8065807.43351	1145	Groundwater	KOH	OE-007	Hv20344	8/24/1994	26.8	69	7.3	-8.64	-65.4	3.7	1.2	-8.6	42 ± 0.4	6970 ± 80	Geyh, 1997
1083		8	WW34207	Eastern Owambo	Ormundungilo	16.70370	-17.42800	680867.74183	8072199.12353	1145	Groundwater	KOH	OE-005	Hv20342	8/23/1994	26.8	220	8	-8.22	-60.8	5	1.2	-7.2	72.5 ± 0.7	2585 ± 80	Geyh, 1997
902		2624	WW22538		OMUTHIYA	17.07940	-18.48740	719467.66213	7954544.29829	1115	Groundwater	KOS	2912		2/23/2001							0.2	-7.3			BGR
1101		2625	WW35185		Cham - Cham	16.94500	-18.45730	705309.64869	7958033.99723	1116	Groundwater	KOS	3991		9/8/2001		3660	7.5	-7	-53.2		0.1	-6	44.6 ± 0.3	BGR	
1717		2627	WW93418		Mangenti / KK	17.30600	-18.58200	743266.85391	7943781.06266	1126	Groundwater	KOV	1000014		11/21/2001		223	8	-7.73	-60.6		0.1	-8.89	56 ± 0.28	BGR	
1715		2626	WW93415		Oshanshompedi Pump X4	17.42310	-18.36680	755948.68135	7967443.48307	1134	Groundwater	KOV	1000010		11/19/2001		231	7.6	-8.03	-61.2		0.65	-9.17	31 ± 0.32	BGR	
1086		2628	WW31450		PumpA	17.27500	-18.42290	74021.635630	7961435.50368	1126.7	Groundwater	KOV1	9466		4/6/2002		346	7.3	-7.7	-59.4		0.34	-10.1	77.7 ± 0.5	BGR	
1085		2629	WW34219		Y	17.46920	-18.36560	760823.62657	7967510.73951	1137	Groundwater	KOV1	8388		3/7/2002		488	9.4	-8.1	-61.4		0.1	-6.5	0.4 ± 0.05	BGR	
1707		2649	WW91418		Hakli-Namutoni	16.83460	-18.86640	693184.95412	7912876.87541	1092	Groundwater	KOV2	55200		7/15/1995		510	6.8	-8	-61.4		1.1	-10.1	19.5 ± 0.8	BGR	
1659		2648	WW7959		OSHIVELO	17.16950	-18.61980	728806.90736	7939776.15506	1105	Groundwater	KOV2	2975		2/22/2001				-7	-46		0.2	-10.3			BGR
1210		2638	WW37203		1817CA	17.12510	-18.61880	724122.47607	7939942.94820	1096	Groundwater	KOV2	65887		3/7/2002		132	7.3	-8	-59.5		0.4	-9.7	37.6 ± 0.27	BGR	
1209		2637	WW37202		1817CA	17.08330	-18.61870	719711.23502	7940005.76644	1095	Groundwater	KOV2	65886		3/7/2002		143	7.2	-8.1	-60.5		0.3	-8.4	28.2 ± 0.24	BGR	
1207		2635	WW37200		1817CA	17.21240	-18.61780	733337.18364	7939942.24661	1113.63	Groundwater	KOV2	65885		2/23/2001				-8	-59.1		0.3	-8			BGR
1450		2646	WW40013			17.29930	-18.57260	742572.86687	7944830.74823	1123.77	Groundwater	KOV2	1000021		5/12/2002		131.4	8.2	-7.8	-60.4		0.3	-8.66	38 ± 0.3	BGR	
993		2630	WW30762		ETOSHA	17.11800	-18.53630	723480.78861	7949084.03699	1102	Groundwater	KOV2	2986		9/8/2001		145	7.7	-7.8	-69		0.9				BGR
1386		2645	WW39871			17.10670	-18.51880	723210.32936	7951035.14635	1110.23	Groundwater	KOV2	1000004		3/5/2002		121	6.6	-7.89	-60		0.6	-8.4	4 ± 0.09	BGR	
1073		2632	WW33920		KING KAULUMA KK13A	17.01530	-18.47360	712715.03987	7956148.51956	1109.94	Groundwater	KOV2	8351		3/5/2002		267	7.3	-7.8	-59.2		0.3	-7.8	7.5 ± 0.11	BGR	
1045		2631	WW32617		OSHIVELO	17.18000	-18.45520																			