Groundwater recharge estimation for perched aquifers in the Ohangwena Region based on Soil water balance modeling and chloride mass balance

By

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Abstract

Ground water recharge estimation into perched aquifers was determined using the chloride mass balance and the soil water balance model (MODBIL) in this thesis. A complete literature studies was done using the published and unpublished literature from various sources. The recharge estimation obtained was then compared to previous studies done in areas with similar amount of rainfall averages as the Ohangwena region.

Villages in the Ohangwena region were sampled randomly for soil and water. The aquifers evaluated for recharge were the perched aquifers which are discontinuous aquifers located at shallow depths. Water samples were taken to the laboratory for hydrochemistry and the soil samples were collected for the eluates and grain size analysis.

Recharge rates vary with intra annual and inter annual variation, the recharge into the perched aquifers range from 46.8 mm/a- 53.6 mm/a from the chloride mass balance method using simple average calculations and 39.4 mm/a- 59.8 mm/a when considering spatial variations. From the soil water balance model recharge rates obtained are relatively lower at 29.1 mm/a, from simple average calculations and 19 mm/a when spatial variations are considered.

Recharge estimations into perched aquifers of the Ohangwena was done to give clearance on the amount of water available for the inhabitants of the area and know how much water is usable.

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To my mother, Ms. V. Naluwe, my aunt Ms. N. Naluwe, my grandmother Ms. P. Kaavela, my late father Mr. S. David and the rest of the family together with my friends, not to forget Mr. J. Thomas. Thank you all for the laughter, joy, and happiness, understanding my shortcomings and giving me emotional support during my studies.

I would also like to thank Josephina Hamutoko for the help and the sieving of the soil samples.

Finally, I would like to thank the almighty God for being my pillar of strength, for the protection and guidance throughout my years at the University of Namibia.

Declaration

I, Anna Kaupuko David declare here by that this study is a true reflection of my own research, and that this work, or part thereof has not been submitted for a degree in any other institution of higher education.

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Anna K David **Date**

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List of Abbreviations

BGR………..Bundesanstalt für Geowissenschaften und Rohstoffe - Federal Institute for Geosciences and Natural Resources

SWBM………. Soil water balance model

CEB…………Cuvelai Etosha Basin

IWRM………Integrated Water Resource Management

Ma……………. million years

mm/a………… millimeters per year

Mio m^3……….million cubes

MODBIL……. Soil water balance model

SW…………….Soil water

GW……………Groundwater

CMB…………….Chloride mass balance

mm……………..millimeter

mV……………millivolts

mS/m…………micro siemens per meter

1 Introduction

1.1 General Introduction

Water is essential for the survival of mankind and the natural environment. In a country like Namibia, the driest country in Southern Africa with arid to semi-arid climate, water resources become extremely limited and highly valued. Surface water availability is closely linked to the rainfall pattern that is extremely inconsistent in both space and time. Too much water can cause floods that are difficult to master and during draughts surface water evaporates quickly (Christelis and Struckmeier, 2001).Thus groundwater becomes the most important source of water in the country as it is widespread and naturally protected from evaporation. The recharge pattern is mainly influenced by the distribution of soil and vegetation units. Groundwater recharge shows a high inter- and intra-annual variability, but not only the sum of annual precipitation is important for the development of groundwater recharge; a large amount of precipitation in a relatively short period is more important. Wanke, Dunkeloh, Udluft, (2007) explain that major decision criterion for choosing the appropriate method is the expected relationship between direct and indirect recharge. If direct recharge is the most important process, numerical or experimental analysis of vertical moisture flux, the chloride mass balance method, or water balance model can be used (Wanke et al. 2007).

1.2 Statement the problem

Due to the fact that the country has arid to semi-arid climate, availability of water becomes a major concern to many inhabitants. . The current and future availability of the groundwater resource needs to assess as changes in climate might affect nearly every aspect of human well-being (Wanke et al. 2007). Pipeline water is not available in all areas of the region and most still depends on water from the hand dug wells. In order to make reasonable prediction on the amount of water available for the inhabitants, the amount of water into the perched aquifer needs to be obtained. This is achieved by determining the groundwater recharge into these perched aquifers

1.3. Purpose and objective of the study

The main purpose of the thesis is to give the estimates of the groundwater recharge into the perched aquifers of the Ohangwena region which forms part of the Cuvelai Etosha basin. The thesis is mainly based on the following objectives.

- Obtain spatial and temporal data for the groundwater recharge estimations.
- Obtain the groundwater recharge rate into the perched aquifers using the chloride mass balance and the soil water balance model.

1.4. Study area

The area of study is situated in the Ohangwena region, located in the Northern part of the Cuvelai Etosha Basin (CEB) (See figure 1 below). The basin extends at an area of about 97600 km^2 and has four sub-basins within it, namely the Olushandja Sub-Basin in the west, the Iishana Sub- Basin in the center, the Niipele Sub-Basin in the North- East and the Tsumeb Sub-Basin in the south- east (Bittner, 2006). The study of interest is mainly in the northern part of the Niipele Sub- Basin
(See figure 1).

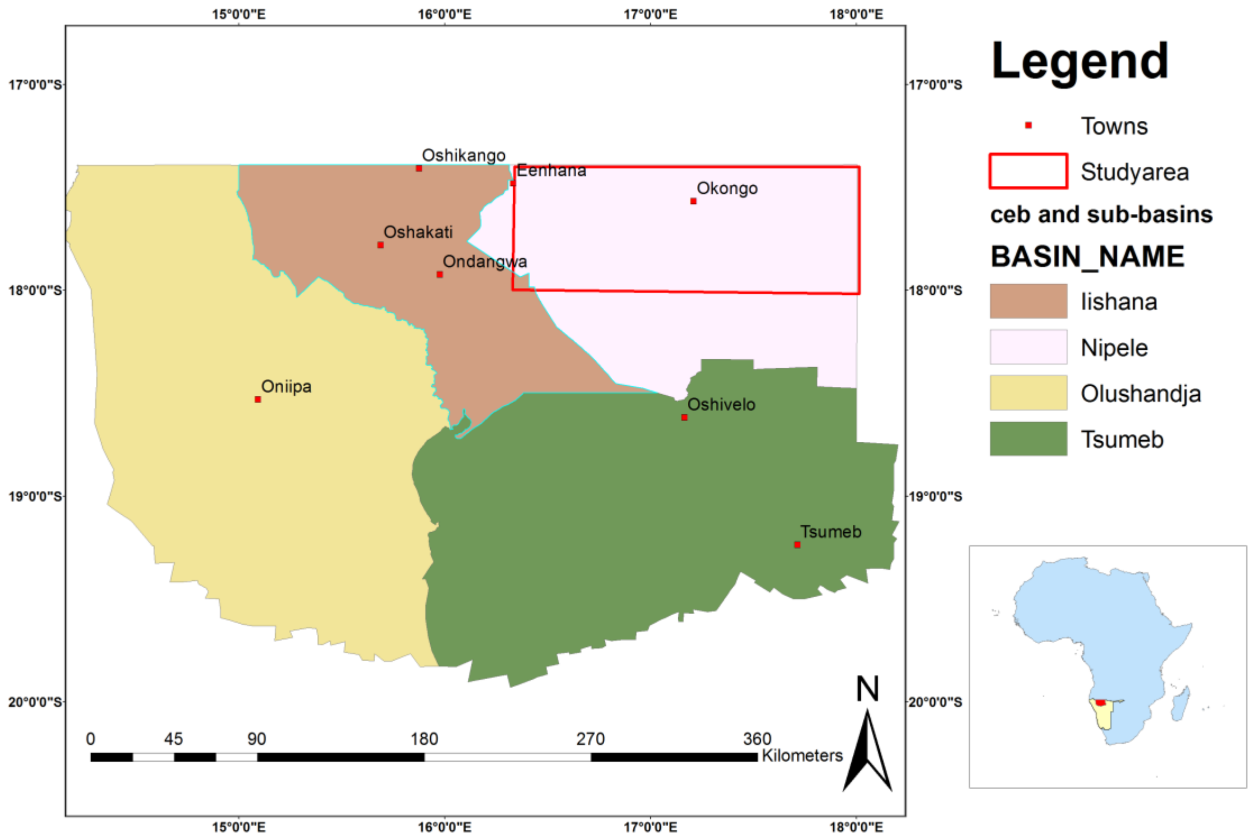

Figure 1: Location of Study Area (Data source Mendelson, 2000).

2 Background

2.1 Climate

The climate of the CEB is considered to be semi-arid region with high annual temperatures resulting in high evaporation and low annual rainfall. Rainfall decreases from 600 mm/a in the north-east to 300 mm/a in the west. In the same direction, potential evaporation increases from 2700 to 3000 mm/a (Bittner, 2006). In particular, the mean annual rainfall ranges from only 250 mm in the south-western area and west of Ruacana to up to 600 mm in the area around Tsumeb and towards the Kavango Region in the north-east (see figure 2). 90% of the annual precipitations have been observed to occur during the period of October to March (max in February) with rainfall variability ranging between 25-40% (Bittner, 2006).

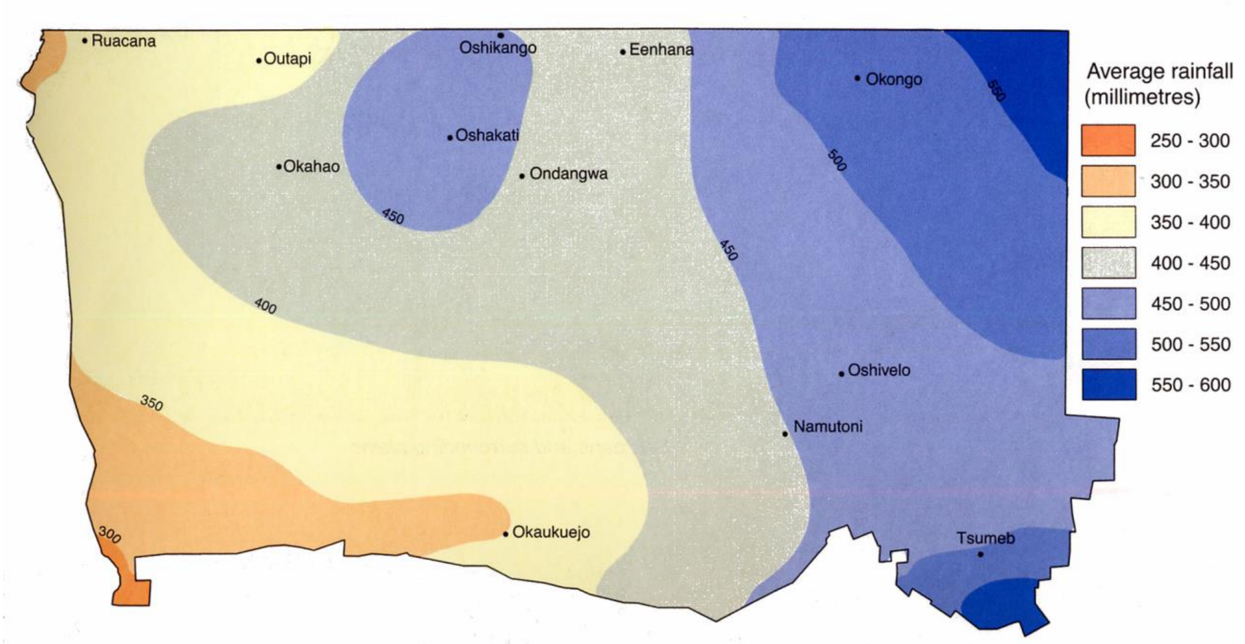

Figure 2: Average annual rainfall across north central Namibia (Data Source, Bittner, 2006).

Within the CEB area the mean monthly temperatures differ from 17° C in June and July to 25 °C from October until December. Generally, in the summer time the maximum daily temperature averages 30 to 35 °C (Bittner, 2006). During winter season the minimum temperatures decrease on average to about 7 °C (after MENDELSOHN et al., 2000 in Bittner, 2006). The mean monthly humidity recorded during midday ranges from 50 % in March to 17 % in September. The groundwater temperature is high as well and is recorded to be 25 °C on average.

The high annual temperatures, the low humidity, the frequently blowing wind and the limited vegetation cover have much influence on the mean annual potential evapotranspiration which reach values of about 2,500 mm from September to January, before the main rainy season, and exceeds the mean annual rainfall by a factor of about six (Bittner, 2006). This means that most rainwater is lost from the system and reduces the effective rainfall to some 80 mm/annum (available to plant growth and groundwater recharge). High evaporation rates cause the drying up of pans and oshana (ephemeral rivers) resulting in the precipitation of salts and increased salinity of the shallow aquifers, in particular in waterlogged areas and areas comprising a low permeable lithology (Bittner, 2006).

2.2 Topography and landscape

The topography in the CEB declines from all directions towards the lowest point of North-central Namibia, the Etosha Pan with the minimum elevation of about 1020 m a.m.s.l (Bittner, 2006).The topography has a major influence on the entire drainage system with the numerous interconnected channels of the oshana system, which are cut into the underlying plane Kalahari sands forming raised, vegetated areas in between (Bittner, 2006). Bittner, (2006) the CEB having a landscape of gently undulating, broad sandfield of low relief (0.2 %) averaging 1110 m a.m.s.l, the oshana (river channels) with elevation averaging about 1120 m a.m.s.l., the interdune valleys and scattered pans filled with clayey sands, the elongated east-west trending paleo-dunes.

2.3 Soil and Vegetation

The soils in the CEB are divided into nine types, comprising mainly sands and clays of Aeolian and fluviatile origin showing poor water-holding capacity and a low nutrient but also a high salt content (Bittner, 2006). The vegetation dominating the area is woodlands and forest savannas, due to a more humid condition in the northern-eastern part of the CEB. The soils and the vegetation in the Ohangwena region are the main contributing factors to the ground water recharge; they can enhance or limit the ground water recharge. The Ohangwena region is extremely flat and poorly drained physiographic region comprising, in the greater part, strongly saline alluvia which have been deposited in the Kunene River (Moller, 1997). The Omuramba Owambo located east of the Cuvelai 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 (Bittner, 2006).

2.4 Geology

The Cuvelai-Etosha Basin is part of the intra-continental Owambo Basin which is an extensive sedimentary basin which is part of much larger Kalahari Basin covering parts of Angola, Namibia, Zambia, Botswana and South Africa (Miller, 1997). The intra-continental Owambo basin formed during the post-cretaceous tectonic development of Southern Africa (Bittner, 2006). Three geological events namely the Damara sequence, Karoo sequence and the Kalahari sequence covers the CEB with a mid- Proterozoic crystalline (Congo craton) as the basement. The sedimentation of the Damara started 900 Ma ago with the terrestrial-fluvial sandstones of the Nosib Group followed subsequently at 730-700 Ma by the Otavi Group carbonates. Finally at 650-600 Ma the Deposition of erosion product of uplift produced the Mulden Group rocks (Miller, 1997). During and after the Damara Sequence deposition a period of tectonic activities occurred resulting in faulting and folding, followed by a period of erosion.

During the Lower Permian to Jurassic the sediments of the Nosib, Otavi and Mulden Groups of the Damara Sequence were covered by up to 360 m thick sedimentary deposits and volcanics of the Karoo Sequence (Bittner, 2006). These rocks of the Karoo sequence do not crop out at surface. The Karoo sequence started its formation during the glacial event which affected the entire continent around 300Ma. The Dwyka Formation of the sequence was deposited during these glacial events which gave rise to glacial valley, tillites, sandstone and shales. Fluviatile reworking of the Dwyka Formation and post-glacial environment led to the deposition of the shales, sandstones and carbonates of the Prince Albert Formation (Bittner, 2006). The Karoo ended with the deposition of the Etjo Formation which was deposited around 250-200 Ma. The Etjo Formation is characterized mainly by the red sandstones which were deposited in arid conditions by Aeolian winds.

A succession of up to 600 m thick, semi-consolidated to unconsolidated sediments of the Kalahari Sequence overlay the intrusive and extrusive rocks of Karoo Age (Bittner, 2006). The Kalahari sequence ranges from late Cretaceous to Quaternary and its entirely continental, ranging from Aeolian to fluvial. The following figure shows the geology of the CEB.

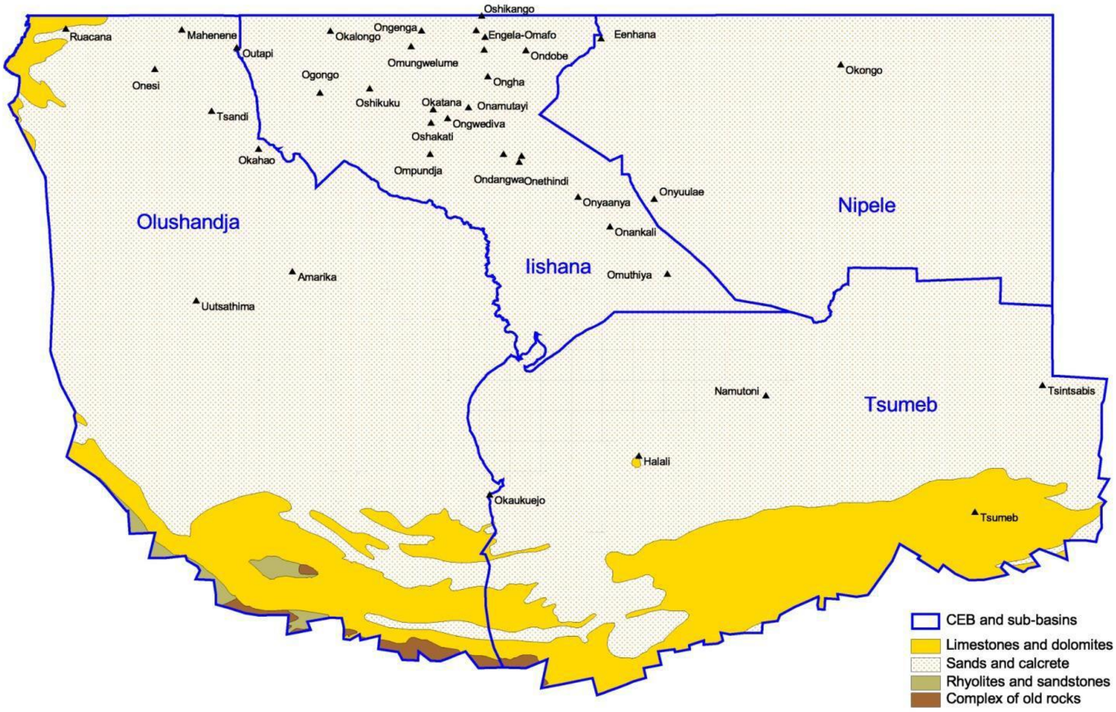

Figure 3: The geology of the CEB (After Nakwafila 2011 in Hamutoko 2013).

The Geology of the study area, the Ohangwena part of the Cuvelai-Etosha basin has been extensively mapped and described by Miller (2008) and Miller (2010). According to Miller, the depositional environment CEB was dominated by calcrete development in the southern and also western margin. The sediments in the Ohangwena region resulted from the erosion of mountains in the Central Angola; it is also believed that some sediment from the Kalahari must have been reworked. The basin is believed to have been filling up with sand, silt and clay for the past 70 Ma. This sand, silt and clay are believed to have been eroded for higher grounds surrounding the Owambo basin. Ananias (2012) after Mendelssohn (2000) stated that cycles of climate with wet and dry periods followed each other with rivers in the area drained into the basin and deposited sediments that formed the Ombalantu, Beiseb, Olukonda and Andoni Formations (Ananias, 2012 after Walzer, 2010 and Miller, 2008). These four Formations are of the Kalahari sequence and represent the youngest unit of the basin with Ombalantu representing the base and Andoni the top of the Owambo Basin. The table below summarises these formations.

Table 1: Stratigraphy of the Kalahari Sequence (Data Source: Bittner, 2006 in Hamutoko Master Thesis 2013).

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

2.5 Hydrogeology

The Hydrogeological Cuvelai Etosha Basin comprises of the Omusati, Oshana, Ohangwena, Oshikoto and parts of the Kunene region. All groundwater within this basin flows to the Etosha pan which is the area of lowest elevation in the CEB.

Bittner (2006) delineated three main groundwater systems which have been distinguished in the CEB

- Groundwater that is recharged in the fractured dolomites of the Otavi mountain Land at the Southern and Western rims of the basin.

- This groundwater flows northwards, feeding the aquifers of the Karoo and Kalahari sequences. The deep seated multi layered aquifer system which flows from Angola in the southern margin towards Etosha and the Okavango region.

- The shallow Kalahari aquifer in the central part of the CEB which consists of saline water and originates from regular floods.

There are six main aquifers which are distinguishable within the CEB (Figure 4) namely the Otavi Dolomite Aquifer (**DO**) located on the western and southern rim, followed in the north by the Etosha Limestone Aquifer (**KEL**), the Oshivelo Multi-layered Aquifer (**KOV**) in the eastern area, the Ohangwena Multi-layered Aquifer (**KOH**) in the north-eastern parts, the Oshana Multi-layered Aquifer (**KOS**) covering the area of the Cuvelai drainage system and the Omusati Multi-zoned Aquifer (**KOM**) situated in the west adjacent to the **KOS** (Bittner,2006).

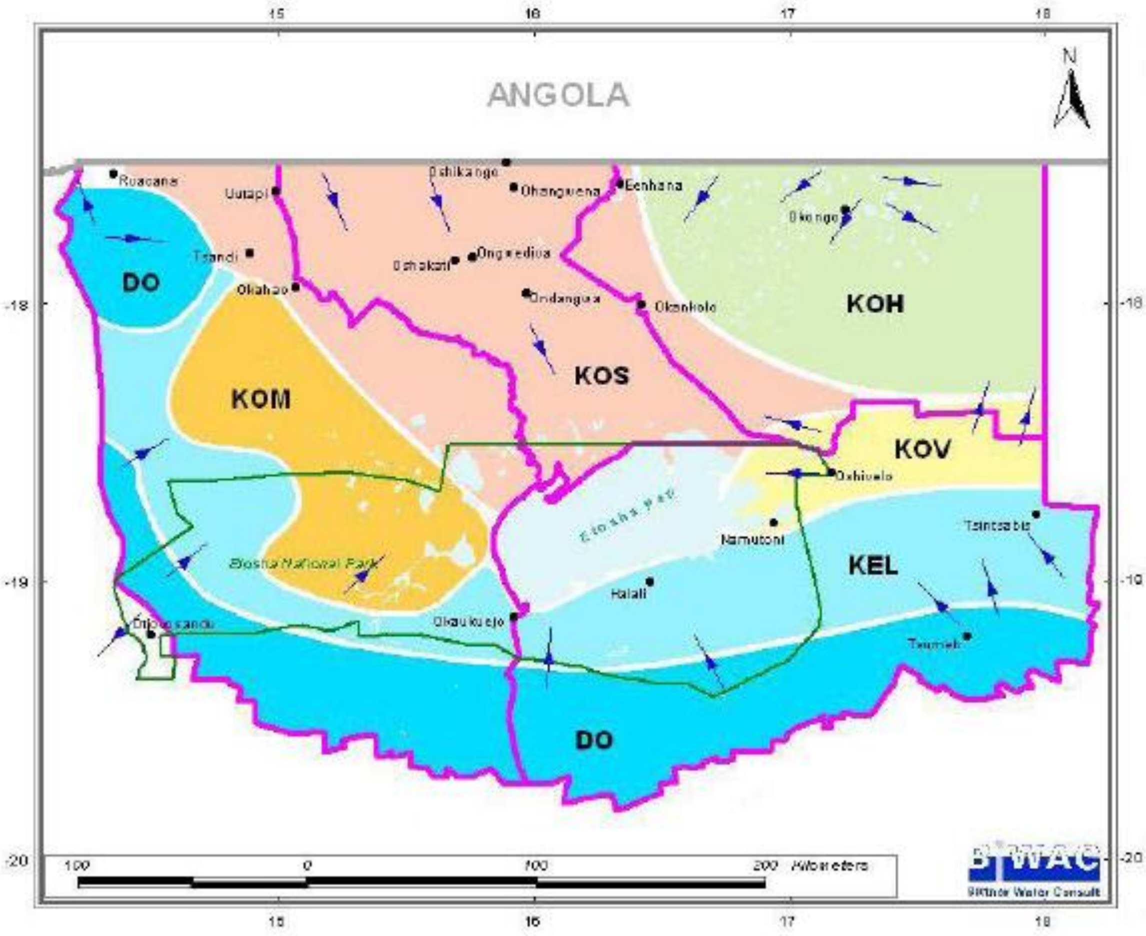

Figure 4: Aquifer system of the CEB, arrows indicating Groundwater flow direction (Data source, Bittner, 2006).

The area of interest is the perched aquifers which are also distinguishable within the CEB (Figure 5). These perched aquifers are discontinuous and occur at relatively shallow depths. The perched aquifer is not a single aquifer but rather, it's a series of small perched aquifers which primarily occur in the dune-sand covered areas (after Christelis & Struckmeier, 2001 In Hamutoko, 2013). The recharge into these aquifers can be from infiltrating precipitation or from groundwater flowing into the aquifer. In area with sufficient precipitation, water infiltrates through pore spaces in the soil, passing through the unsaturated zones. At increasing depths water fills in more pore spaces in the soils until the zone of saturation is reached. In permeable or porous materials, such as sands and well fractured bedrock, the water table forms a relatively horizontal plane.

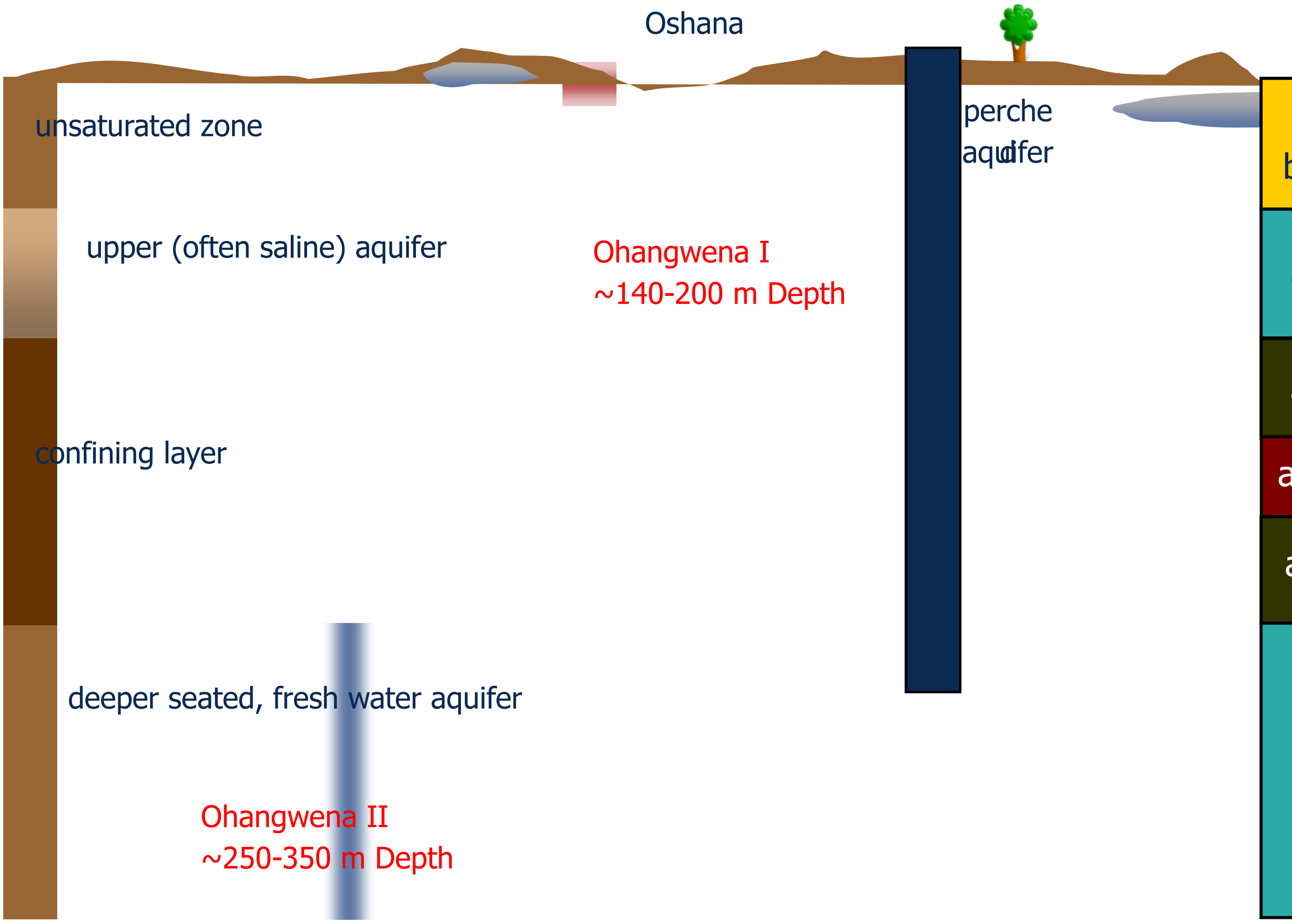

Figure 5: Cross sectional view of the Ohangwena 1 & 2 aquifer and the perched aquifers. (Data Source BGR, in Ananias 2012).

3 Literature Review

3.1Groundwater recharge

Wikipedia defines groundwater recharge as a hydraulic process where water moves downward from surface water to groundwater. This process usually occurs in the vadose zone below plan roots and is often expressed as a discharge to the water table surface. Wikipedia, further stated that recharge occur both naturally (through the water cycle) and through anthropogenic processes (i.e., “artificial groundwater recharge”), where rainwater and or reclaimed water is routed to the subsurface. de Vries and Simmers (2002) defined recharge as the downward flow of water reaching the water table, which forms addition to the groundwater reservoir. Explosion of groundwater recharge studies have been reported in the literature since the mid-1980s. Recharge can either be direct, indirect or localized, this are the recharge mechanisms of groundwater (de Vries and Simmers, 2002). Lerner, Issar and Simmers (1990) defined direct recharge as water that is added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration by direct vertical percolation through the vadose zones. Lerner et al. (1990) also defined indirect recharge as percolation to the water table through the beds of surface-water courses. Localized recharge is the intermediate form of groundwater recharge resulting from the horizontal near surface concentration of water in the absence of well-defined channels (Lerner et al., (1990). These recharge mechanisms are clearly simplified in the figure below.

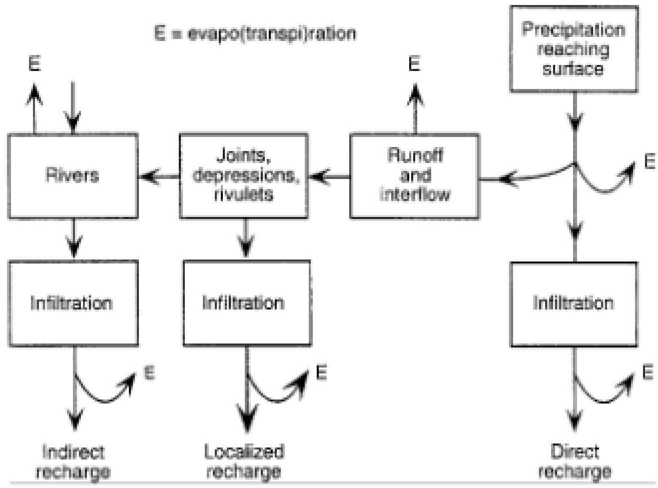

Figure 6: Various mechanisms of recharge in arid- semi arid areas, Lerner, 1997 in (de Vries and Simmers, 2002).

Groundwater recharge over a certain area is usually considered to be equal to infiltration excess over the same area, even though not all the water reaches necessary the water table (de Vries and Simmers, 2002). This water might be hampered by low-conductivity horizons and disappear as interflow to nearby local depressions, the water then runs off or evaporates instead of joining the regional groundwater systems. Recharge process is determined by the interaction of climate, geology, morphology, soil condition and vegetation. Thus, in general groundwater recharge in semi-arid and arid regions is more susceptible to near-surface conditions than in humid regions. Recharge in humid areas is mainly controlled by the potential precipitation surplus, the infiltration capacity of the soil and the storage and transport of the sub-surface while recharge in semi-arid and arid areas have potential evapotranspiration that normally exceed rainfall on average. de Vries and Simmers (2002) further stated that recharge in semi-arid and arid areas depends particularly on high rainfall events, accumulation of rainwater in depression and streams and the ability of rain water to escape evapotranspiration, where water percolates rapidly through cracks, fissures or solution channels. Groundwater recharge is normally hindered by thick alluvial soils; these soils allow high retention storage during the wet season and vegetation that as a result extract soil water in the next dry season. Favorable conditions for recharge can be created in areas with poor vegetation cover on a permeable soil or fractured bedrock near the surface together with high intensity rainfall (de Vries and Simmers, 2002).

3.2 Groundwater recharge estimation

Due to the fact that groundwater recharge sources and processes are different, the applicable value of available estimation varies (de Vries and Simmers, 2002). Recharge estimates in arid and semi-arid regions are particularly difficult by the immense variability of hydrologic events in time and space (Kinzelbach, Aeschbach, Alberich, Goni, Beyerler, Brenner, Chiang, Rueedi, Zoellman, 2002). The most common recharge methods for (semi-) arid areas are categorized into four main categories (Kinzelbach et al., 2002).

- Direct measurements

- Water balance methods (including hydrograph methods)
- Darcyan methods
- Tracer methods

Direct measurements consist of the lysimetry, which is the only method that facilitates direct measurement of precipitation recharge flux. Water balance methods include the soil moisture budgets, River channel water balance, water table rise methods, river baseflow method, spring or river flow recession curves, Rainfall-recharge relationships and the cumulative rainfall departure method (Kinzelbach et al. 2002). The Darcyan methods include methods that estimate the flux from a head gradient and a hydraulic conductivity, this method are the unsaturated zone Darcy law based on measurements of matrix potential, the Saturated Zone Darcy law based on pumping tests and head measurements, Unsaturated Zone: Solving Richards' equation and the numerical flow model (Kinzelbach et al. 2002). Tracers used in the studies of groundwater flow comprise both chemical and isotopes. These tracers provide valuable information on the flow processes in the vadose zone when combined with water balance models. There are three types of tracers, artificial, historical and natural. Chloride is the most commonly used environmental tracer using the chloride mass balance, this method is the simplest, least expensive and more universal (Allison, Gee and Tyler, 1994).

The common methods are explained in detail in Kinzelbach et al. (2002) and Allison et al. (1994).

The methods used in the thesis for the determination of groundwater recharge are explained in detail below, their theoretical background and previous applications in Namibia have been mention below as well.

Chloride mass balance method

The chloride mass balance method is a simple method application which does not depend on sophisticated instrumentals; the method is based on the knowledge of annual precipitation and the concentration of Cl^- in the rainfall and groundwater storage (Sabyani and Şen, 2006). The method is also based on the comparison of the Cl^- deposition rate at the soil surface with the concentration in the soil water or groundwater. Interception, soil evaporation, and or root water uptake by the vegetation causes an increase of Cl^- concentration relative to the rainwater. As stated in Sabyani and Şen (2006), the total precipitation depth and the total wet and dry deposition of Cl^- determine the rainwater's Cl^- concentration at the surface. Thus groundwater recharge can be estimated from the increase in precipitation provided that no other source of Cl^- exists, this assumption is valid for the estimation of evaporation. The concentration of Cl^- is homogeneously distributed within the aquifers (Sabyani and Şen, 2006).

Cl^- has a conservative nature, it is neither leached from nor absorbed by sediments particle and is thus use in chemical recharge studies (Sabyani and Şen, 2006). It is assumed that the Cl^- concentration in the rainfall and recharge areas is in a steady-state balance as the input of

$Cl^{‾}$ is equal to the output without $Cl^{‾}$ storage change during a specific time period which is often taken as a month or a year. As stated in Bazuhair (1996), the chloride mass balance method yields groundwater recharge rates that are integrated spatially over the watershed over tens of thousands of years.

The chloride mass balance method is universal and common method (Allison et al., 1994). In Namibia several studies have been conducted to determine groundwater recharge using the method, Wrebel (1999) obtained recharge rates of 7 mm/a in the Hochfeld area. Külls (2000) used the CMBM for the Grootfontein area and obtained recharge rates ranging from 8.5-14 mm/a. Klock (2002) also used the CMBM through a regionalization approach in the Kalahari catchment, North-eastern Namibia and obtained recharge rates ranging from 1.5-5 mm/a. Brunner, Bauer, Eugster and Kinzelbach (2004) also used the method for the Ngamiland area and obtained recharge rates ranging from 30 to 90 mm/a. for the upper Khaudum-Nhoma catchment, Wanke, Beyer, Dünkeloh and Udluft (2007) obtained recharge rates of 11.5 mm/a.

Soil water balance model (MODBIL)

MODBIL is a physical water balance model which is based on the simulation of the water fluxes and water storages in and between the different physical atmosphere, interception, snow, soil and bedrock (Dünkeloh, 2005). The water balance modelling program (MODBIL) has been developed since 1988 by (Udluft 1988-2005) at the department of Hydrogeology and Environment at the University of Würzburg, Germany (Mederer, 2005). Dünkeloh (2011) developed a more enhanced and redesigned MODBIL, which was done in the framework of various projects which were mostly in semiarid areas. The model gives out spatial patterns for the main water components, which are precipitation, real evapotranspiration, runoff, and groundwater recharge (Dünkeloh, 2005). The spatially differentiated water balance is calculated by simulating water fluxes and storages at temporal and spatial resolutions, this is based on meteorological, topographic, soil physical, land cover and geological input parameters (Wanke et al. 2007). As stated in Dünkeloh (2005), precipitation, temperature, relative humidity, wind speed and radiation are the meteorological data needed and elevation, slope, aspect are the topographic parameters while the vegetation parameters are land use and interception. The soil parameters are permeability and field capacity while the bedrock permeability is the bedrock parameter needed. This are the input parameters required for the model (Dünkeloh, 2005).

The model has been calibrated and used in several countries, mainly in semi-arid areas of Jordan, Israel, Greece, Namibia, Cyprus, Brazil, Central African republic and Lower Franconia/ Germany (Dünkeloh, 2005). In Namibia, the model was used on several studies, Külls (2000) used the model on the upper Omatako catchment and obtained annual recharge rates of 6.9 mm/a. Wanke et al. (2007) used the model to assess the groundwater recharge for the Kalahari catchment of North-eastern Namibia and North-western Botswana and obtained mean annual recharge of 8 mm/a.

3.3 Previous work

Most of the studies done in the project area were done under the framework of a technical cooperation between Namibia and Germany through the BGR on groundwater projects for the north of Namibia. The project started running in 2007 and is expected to end by May 2014. Phase 1 commenced in January 2007 and was completed in the first half of 2010. Hamutoko (2013) parallel worked on the study area using similar hydrogeological parameters focusing on the vulnerability of the perched aquifers and the Ohangwena 1 aquifer. Several students under the same project from the University of Namibia (UNAM) also did their thesis baseline on different hydrogeological parameters in the area. The aim of the BGR is to improve access to safe drinking water with objectives of providing well founded information concerning the groundwater resources in the Cuvelai-Etosha Basin (CEB) as a basis for Integrated Water Resource Management (IWRM) (BGR, 2013).

4 Methodology

Determination of groundwater recharge rates involve quite a number of procedures ranging from field work to laboratory analysis, literature review to interpretation of results. In this thesis ArcGIS 10 (ESRI 2010) and Microsoft Excel 2010 were the main software used for the production of maps and data interpretations.

4.1 Regionalization

Sampling procedure was done according to the regionalization of the area using the hydrotop approach. This approach disaggregates land surfaces according to their natural mosaic structure into hydrotopes and each hydrotope is treated as one modeling unit. In other terms, it categorizes different parts of hydro geological system having similar hydro geological properties. Such properties usually result from specific processes for example recharge or surface runoff and soil forming processes. For that reason, identification of hydrotopes requires (After Külls, 2000 in Hamutoko 2013):

- a hydro geological disaggregation
- an understanding of processes causing the typical physical and chemical properties, and

- a concept of its external links and its function within the system.”

In this study five hydrotopes were recognized from field observations. This hydrotopes were identified in past studies and are classified as Dune, river, sand field, Oshana and depression. In short a dune is an area next to the pans which is result of deflation and is characterized by reddish soils with larger particles than those in the pans. A river can be defined as regularly flooded depressions composed of areno soils while depressions are areas with low elevation comparing to its surrounding and they characterized by fine sands with considerable amount of clay and thin calcrete layer which on or near land surfaces. A pan can be defined as local depressions as result of deflation which have dune next to them often contain remarkable thickness of calcrete. Sandfields are reddish to brownish soils covers the large part of the study area with all other hydrotopes appearing as lenses in it. Figure 6 show the spatial variations of the hydrotopes in the study area and figure 7 indicate the types of hydrotopes found in the study area.

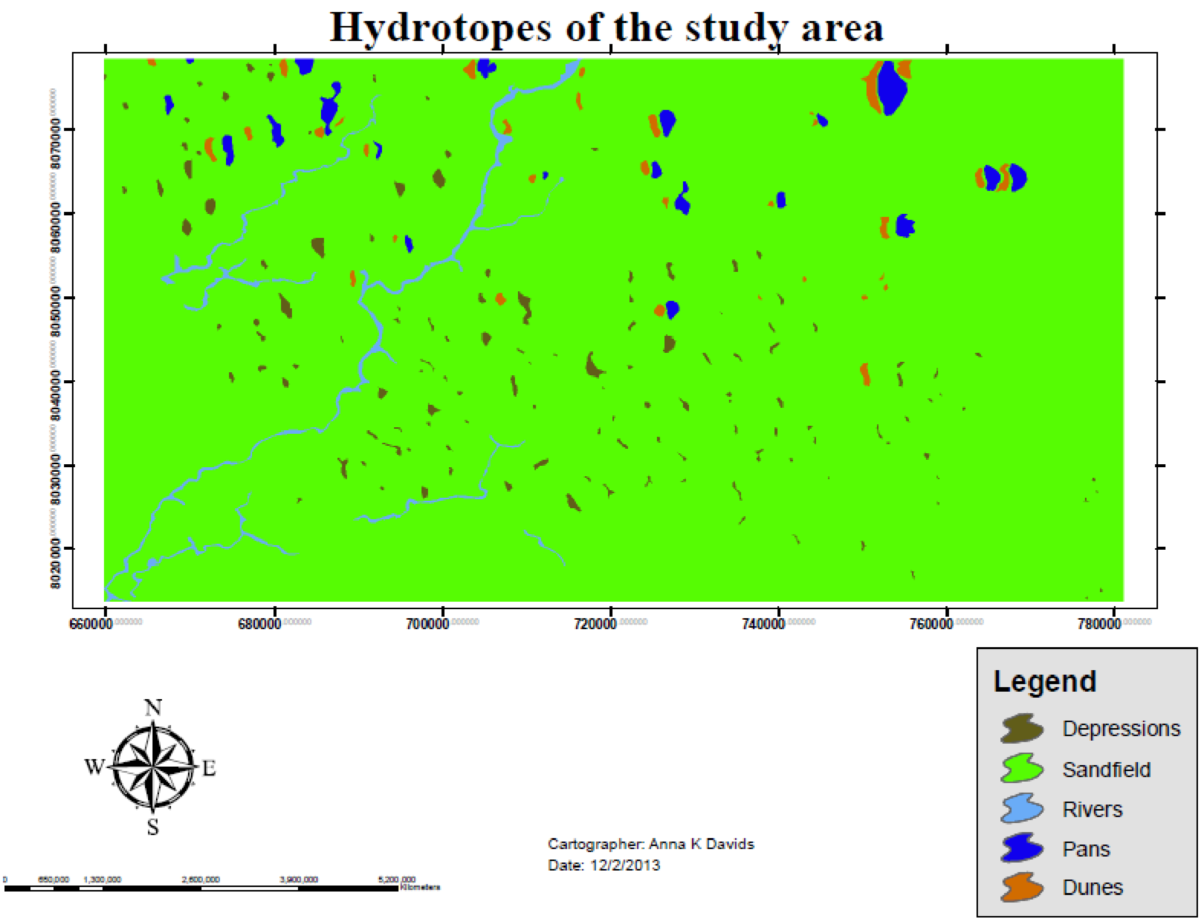

Figure 7: Spatial variations of the hydrotopes in the study area.

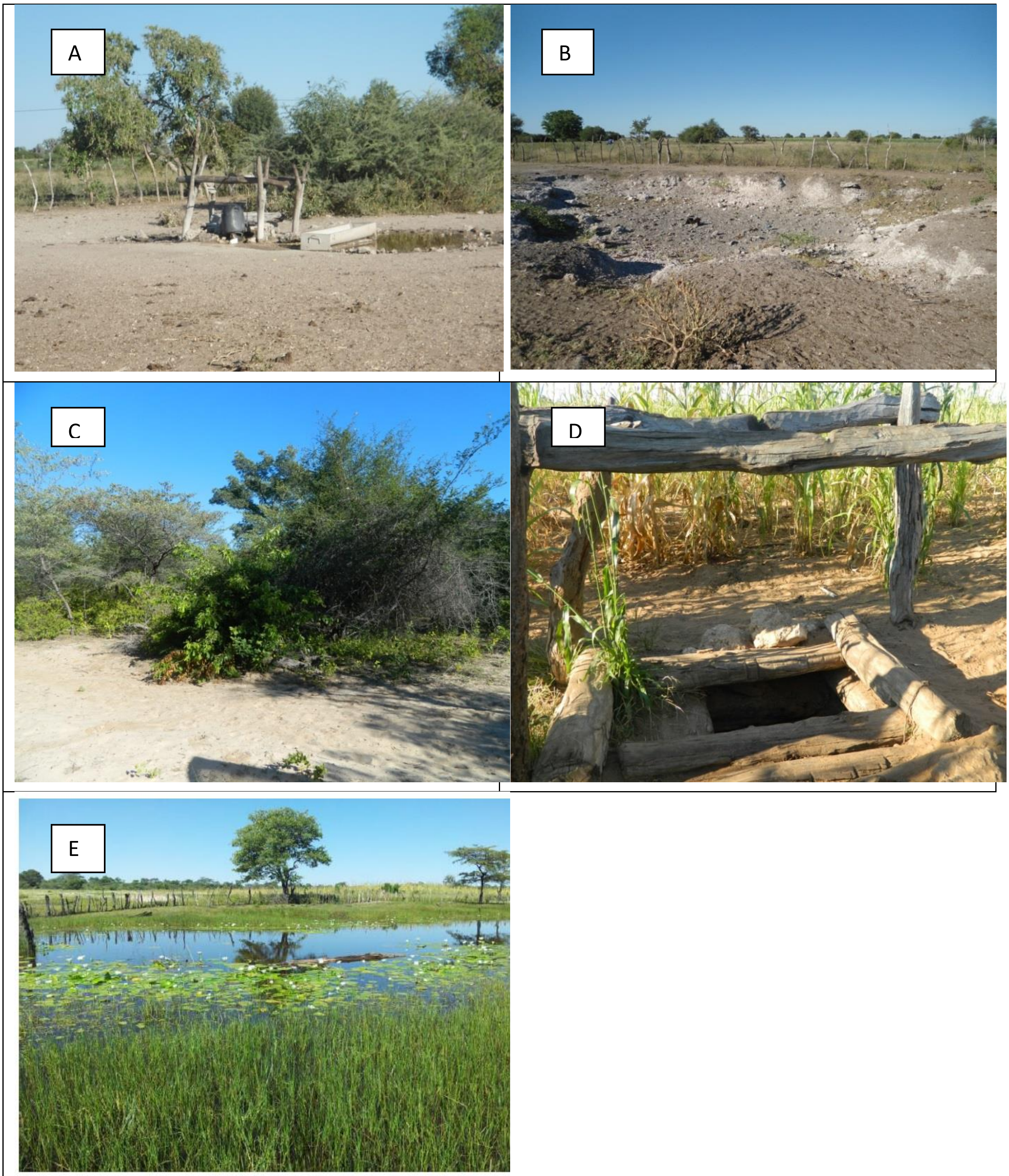

Figure 8: The hydrotopes in the area: (A) Depression, (B) Pan, (C) Sandfield, (D) Dune, (E) River.

4.2 Chloride mass balance

The methodology was applied with reference to work done by Klock (2001) in the Kalahari. The surface water which recharges groundwater always passes through the unsaturated zone. As a result, the chemistry of recharge water is combination of rain water chemistry, input from dry deposition and reactions with soil matrix (Klock, 2001). The following mass balance formula derive by (Edmunds, Darling and Kinniburgh, 1988) was used for to calculate the chloride content. Formula:

$$FN + FD = FS + FM$$

Where FN, FD, FS and FM are mean mass input by wet deposition (precipitation), mean mass input by dry deposition, mean mass output by seepage water, and mean mass output by adsorption and transformation into the mineral phase. But FM term is considered negligible because Gieske et al. (1995) illustrated that chloride is a conservative tracer (Klock, 2001). As a result areas which have no geogenic chloride sources is obtained by balancing the flux of chloride into a soil column with the outflow at the bottom of the root zone and assuming both surface runoff is not significant that the chloride up-take by plants is negligible into the equation:

$$R = \frac{P * Cl_p}{Cl_{sw}}$$

Where R is groundwater recharge, P is mean annual precipitation; Cl_p is the chloride concentration in precipitation and Cl_{sw} the chloride concentration in the soil water of the unsaturated zone (Klock, 2001).

The chloride concentration in the soil samples and the water samples collected in the field were determined by lab analysis. The average chloride concentration in soil water was determined from the eluates prepared in the laboratory at the University of Namibia while the concentration of chloride in groundwater was determined at the analytical lab in Windhoek. The chloride concentration in precipitation and the mean annual precipitation average of the study area were obtained from literature. The chloride content in precipitation was obtained from Klock (2001) and the precipitation average of the study area was obtained from Bittner (2006).

In the study area rainfall ranges from 400 mm in the west up to 600 mm with an average of 450 mm/a . The chloride content in precipitation is approximately 1 mg/l.

4.3 Soil water balance model

As stated in chapter 3, Modbil is a physically based water balance model which is based on the simulation of the water fluxes and water storages in and between the different physical system atmosphere, interception, snow and the soil bedrock (Dünkeloh, 2005). The important water balance components (Fig.9) are simulated for each grid box of the study area on a daily time scale. The major water balance components are precipitation, groundwater recharge, surface runoff/ interflow, and evapotranspiration (Dünkeloh, 2005).

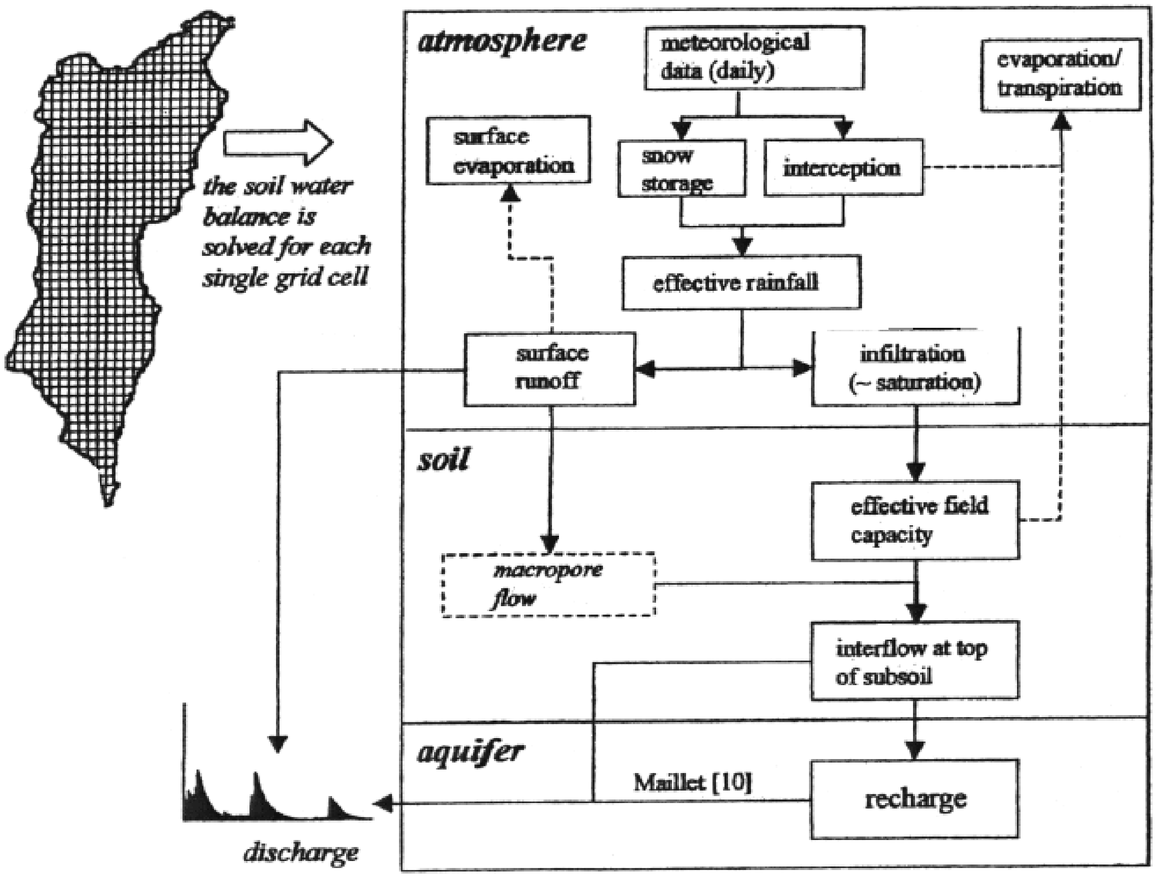

Figure 9: Concept of the model showing important processes simulated for each grid box of the study area (Udluft and Külls, 2000, in Dünkeloh, 2005).

As explained in Dünkeloh (2005), MODBIL has two modelling steps. In the first step, the model calculates meteorological parameters for each grid cell depending on topographic parameters. Furthermore effective precipitation is calculated with respect to the canopy of the storage capacity. Evapotranspiration, surface runoff, interflow, and groundwater recharge are stimulated in the second model step; the simulation is based on meteorological, soil, subsoil and land cover parameters. For each time step, the soil layer module is implemented as a one-layey approach into and out of the soil system. Dünkeloh (2005) also stated that the calculations of all relevant fluxes are based on factors of soil permeability, effective field capacity and the actual soil moisture.

In detail; effective precipitation, soil permeability, soil water content, and soil surface permeability are prerequisite for infiltration to the soil. The infiltrating part is added to the soil water storage. Surface runoff/interflow is modelled when soil permeability and or surface permeability is too low, or when soil moisture storage exceeds field capacity (Dünkeloh, 2005).

Dünkeloh (2005) also mentioned that the real evapotranspiration is modelled according to a modified method after Renger et al. (1974) and Sponagel (1980) using potential evaporation, soil water content and vegetation type. Water loss in every time step is due to the real evapotranspiration. The potential evaporation used in the modelling of the real evapotranspiration is derived from the Penman-Monteith equation (Montheith, 1965).

Groundwater recharge/ Deep percolation, which is the main focus in this thesis begins when the soil water content exceeds effective field capacity (Dünkeloh, 2005). The amount of recharge into the ground is driven by the percolation amount into the soil .The recharge amount is also driven by the permeability of the soil and the subsoil. The Macropore flow also result in additional groundwater recharge which is assessed with transfer functions depending on precipitation and soil conditions (Dünkeloh, 2005).

Secondary evapotranspiration in the model originates from surface water, groundwater or piped water for irrigation, thus the effects of irrigation and wetland areas can be considered in the MODBIL (Dünkeloh, 2005).

The meteorological (precipitation, maximum temperature, relative humidity), topographical (elevation, slope, aspect), vegetation (obtained from fieldwork) and soil (permeability, field capacity) parameters have been collected and prepared as input parameters for the model.

The temporal input data which is the meteorological data were retrieved from the Ondangwa meteorological station which is proximal to the study area. The retrieved data was for a total time period of 6 years (4/01/2003 -3/31/2008).

The spatial input data used in the MODBIL are topographic elevation, slope and aspects, hydraulic conductivity at field capacity of the soil, plant available water content, interception storage and saturated hydraulic conductivity of the sub soil. This data has been derived from published data on vegetation and soil in combination with detailed field work (Moller, 1997). Elevation was retrieve from the DEM of the study area. Vegetation and soils were determined per hydrotop; five hydrotopes were recognized in the study area from field observations.

Table 2: Soil and vegetation parameters for the 5 land cover classes used in the water balance model.

Hydrotopes	Land Unit	Area	Soil type	Eff. Root depth (cm)	Available water content (cm)	Eff. kf at field capacity m/s	Interception (mm)	K_c	Land use Class
Depressions	Mixed Savanna	0.8	Arenosol calcisol	80	134	3.6*10-8	4/0	0.96	1
Sandveld	*Burkea Africana* Savanna	96.5	Arenosol	80	82	2.6.10-8	4/2	0.98	2
Pan	Acacia shrubland	1	Regosol. Calcisol	80	87	2*10-8	4/4	0.99	6
Oshana	Grassland	0.9	Fluvisol	40	41	3.1*10-8	1/0	1	3
Dune	*Baikiaea plurijuga* Woodland	0.5	arenosol	100	107	2.1*10-8	5/0	0.98	10

4.4 Field work

Field work was carried out from the 6th to the 9th of April 2013. A total of 37 Soil and 19 water samples were collected, Water and soil was sampled with regards to the hydrotopes which were previously identified from past studies. Each hydrotopes represented a hydrogeological setting and thus at least an average of two soil and/ or water sample was taken from each hydrotopes. The field was done together with one student from the Brandenburg University of Technology who is parallel researching for a master thesis on vulnerability to pollution in the same study area, and thus same data is but for different purposes.

4.5 Soil sampling

Soil was sampled at various depths depending on the material below surface, whether it was sand, calcrete or clay. Sand field had soil samples up to 275cm depth while depressions with Calcrete had shallower sampling depths up to 25cm. soils were sampled at random within various hydrogeological settings. The amount of samples collected depended on the nature of the area as different soil types allowed only collections up to a certain depth. The Puerckhauer figure 10(A) was used for soil sampling and was hammered into the soil for greater depth samples with a hammer. The soil colour was determined with the munsell soil colour chart. The soil was sampled from the five hydrotopes in the area, riverbed, sand field, depression, dunes and pans. The soil was then put into the sampling bags, clear plastic bags which were used, clearly labeled and taped to prevent mixing of samples from a different areas.

4.6 Water sampling

The water samples were collected from various hand dug wells and put in various sampling bottles. A total of two sampling bottles were clearly labeled and used per hand dug well: One liter bottle for cations and anions and 250 milliliters for trace elements. The 250 ml bottles were acidified with 5 ml of 65 % NHO_3. The samples were labeled with the village name and sample identification number which consists of OH representing Ohangwena region. The hand dug well varied from relatively shallow to deeper wells. A bucket as shown in figure 10 (B) was used to collect the water from the hand dug wells and onsite parameters were measured from the collected water in the bucket. PH/ Redox meter, Conductivity meter were placed into the bucket of water (Figure 10(B)), to measure the onsite parameters, which were pH, redox potential, temperature and conductivity. The water level and depth of the wells were measured by deep meter. Fluoride, phosphate, nitrate and alkalinity were also measured in the field using a calorimeter, whereas turbidity was measured with turbidity meter. Results from field parameter are in appendix 1.

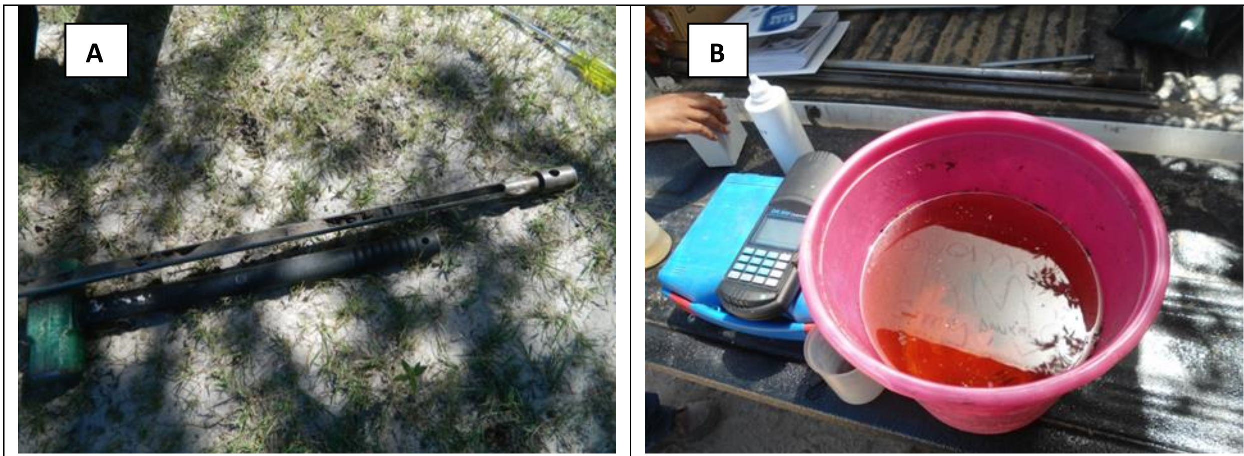

Figure 10: Soil and water sampling parameters. (A) Puerckhauer used for soil sampling. (B) Water used for onsite parameters measurements and water sample collection.

4.7 Analytical methods

4.7.1 Sieving method

Firstly the moisture content of the soil was determined weighing the sample before and after drying (11 B).The soils were dried in an oven (figure 11 C) at a temperature of 105 $^{\circ}C$ for 24 hours. After drying the soil sample was analyzed for grain size distribution, sieving was used to separate soils into different fractions according to their grain size.

This was achieved by shaking the samples through a set of sieves that only grains which were smaller than then sieve openings could pass through. Five sieves were used, 2 mm, 1 mm, 500 µm, 250 µm, 63 µm and 45 µm. The sieves were fitted on a pan (sample tray) with mesh size decreasing from top to bottom. The sample was passed through the 2 mm sieve into the tray without pushing it through the opening and the sieve was covered. The 38 electrical stirrers were then switched on for 3 minutes at amplitude of 0.25 mm/g (figure 11 A). The mass of soil retained on each sieve was determined including that retained in the pan, the amount retained into this sieves is then weighed and the grain size distribution curves were drawn with respect to the calculation and findings (Appendix B), this distribution curve were used for the determination of the hydraulic conductivity.

4.7.2 Sedimentation method

Soil particles are allowed to settle from suspension. The size of the soil particles and their density determines their settling velocity and times. A 500 ml cylinder was filled with tap water and the temperature of the water was measured. The temperature determined how long it took for the clay sample to be taken. A 20 g soil sample was added to the cylinder and well shook (figure 11 D). Then first sample which determined the amount of clay and silt is taken after 50 seconds with only 10 cm of the pipette going in the solution. Then clay content sample was at taken after 6 hours 33 minutes. The samples were then heated in the oven until all water had evaporated and were weighed.

4.7.3 Eluates

A 100 ml of water is mixed with 100 g of soil and left to settle for 24 hours. After 24 hours 25 ml of sample is titrated into a 50 ml beaker. A solution of silver nitrate is prepared from the 2 ml of the 0.1 M silver nitrate and 8 ml of deionized water. 20 ml of the sample was titrated into a conical flask and 0.25 ml of potassium chromate was added. 2 ml of silver nitrate was put in a pipette and titrated into the sample until the sample turned brown. The chromate indicator gives a faint lemon-yellow colour from the potassium chromate that was added. After the brown solution pipette readings were taken and the amount of silver nitrate titrated was used for the chloride content calculations (Figure 12).

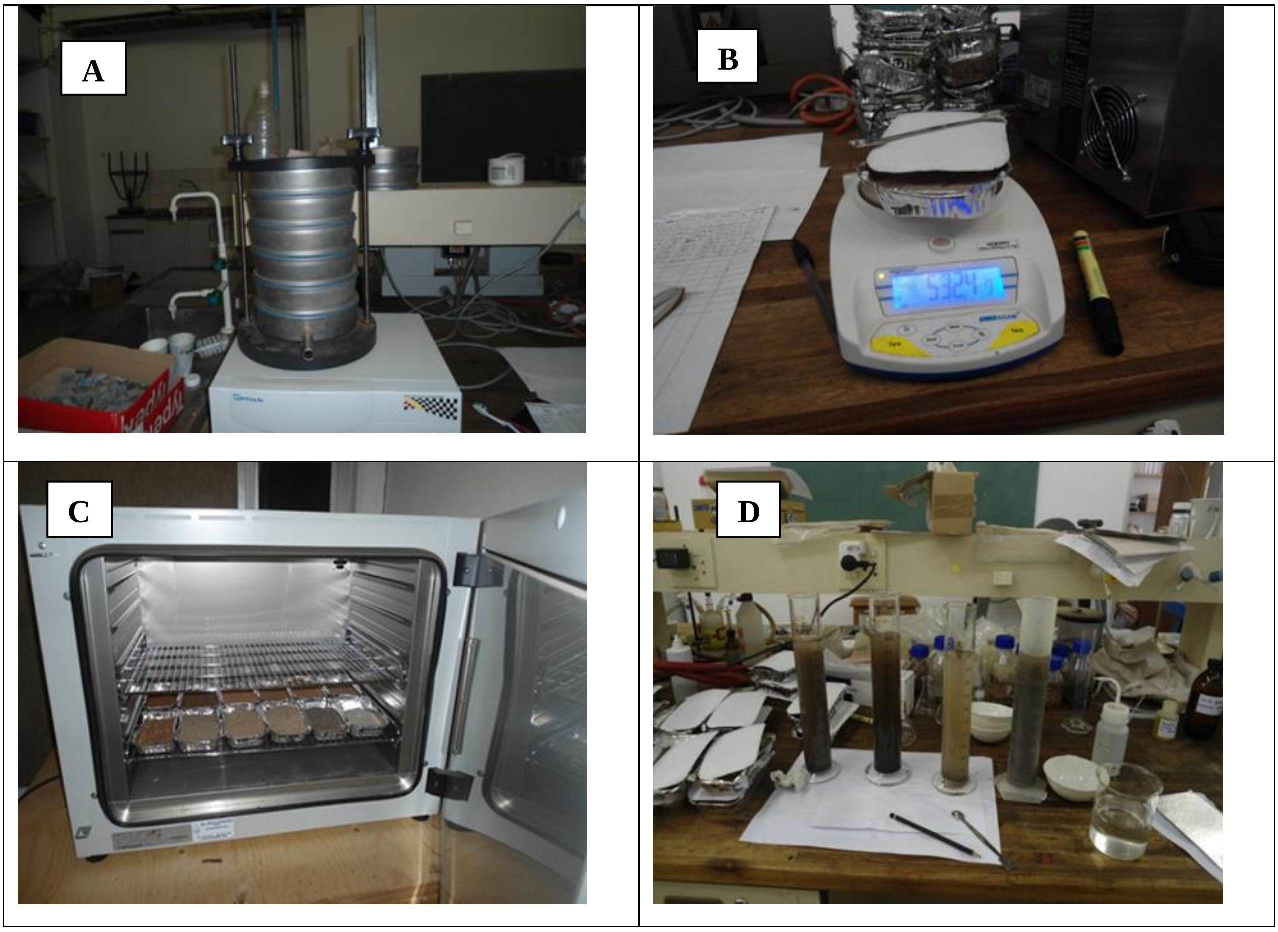

Figure 11: Analytical instruments used for soil analysis, (A) Sieve, (B) electrical scale, (C) oven, (D) cylinders used for the sedimentation method.

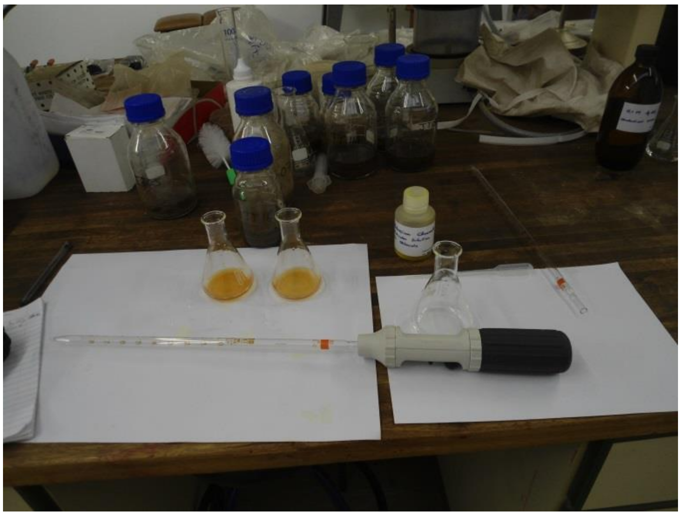

Figure 12: Eluates prepared for the determination of chloride content in the soil.

5 Results

In the following section recharge rates determined are from the chloride mass balance and the soil water balance method (MODBIL). The chloride mass balance method use both the chloride from the soil water, obtained from eluates and the chloride from groundwater obtained from the analytical lab to calculate the recharge rate into the perched aquifers. The MODBIL input data are summarized in table 2.

5.1 Chloride mass balance

Average rainfall in the area is 450 mm/a. Mean annual recharge values produced from the hydrotopes range from 35 mm/a to 79 mm/a, from this method recharge is highest in depressions and the lowest in rivers. Table 3 shows the calculated recharge from different hydrotopes in villages of the Ohangwena region.

Table 3: Chloride data for 2013 sampled together with Hamutoko (see full hydrochemistry analysis in Hamutoko, 2013). Chloride data from 2012 are based on Neumbo (2012). Chloride data from 2010 are based on Nakwafila (2011). Calculated recharge rates per hydrotop.

Hydrotop	Sample Number	Villages	Time	Cl in groundwater [mg/l]	recharge [mm/a]
Depression	OH12	Ongalangombe	April 2013(H)	5	90
	OH13	Ongalangombe 2	April 2013 (H)	4	113
		Ongalangombe	Feb 2012 (Ne)	2	225
		Ongalangombe	Oct-2010 (Na)	3	150
	OH5	Ohameva	April-2013 (H)	8	56
	OH6	Ohameva 2	April-2013 (H)	12	38
		Ohameva	Feb-2012 (Ne)	3	150
		Ohameva	Oct-2010 (Na)	17	26

	OH8	Oluwaya 2	April-2013 (H)	30	15
	OH7	Oluwaya	April-2013 (H)	9	50
		Oluwaya	Feb-2012(Ne)	28	16
		Okongo	Feb-2012 (Ne)	14	32
		Okongo	Oct-2010 (Na)	7	64
Dune	OH1	Oshuuli	April-2013 (H)	40	11
	OH11	Omboloka 3	April-2013 (H)	14	32
		Omboloka	Feb-2012 (Ne)	6	75
Sand field	OH14	Oshanashiwa	April-2013 (H)	7	64
	OH15	Oshanashiwa 2	April-2013 (H)	17	26
		Oshanashiwa	Feb-2012 (Ne)	2	225
		Oshanashiwa	Oct-2010 (Na)	11	41
	OH16	Okamanya	April-2013 (H)	26	17
	OH17	Okamanya 2	April-2013 (H)	23	20
		Okamanya	Oct-2010 (Na)	19	24
Pan	OH9	Omboloka	April-2013 (H)	11	41
	OH10	Omboloka 2	April-2013 (H)	16	28
River	OH18	Epumbalondjaba	April-2013 (H)	8	56
	OH4	Omulonga 3	April-2013 (H)	7	64
	OH3	Omulonga 2	April-2013 (H)	9	50
	OH2	Omulonga	April-2013 (H)	9	50
	OH19	Epumbalondjaba	April-2013 (H)	8	56

Figure 13 shows the recharge rate over the three years and how they are varying with each other. The data was obtained from sampling done in February in 2012; October 2010 and April 2013. The February 2012 sampled data, done during the rainy season gave relatively higher recharge rates compared to the sampling of the year 2010 and 2013. Recharge rates are also observed to be high in 2013 compared to that of 2010.

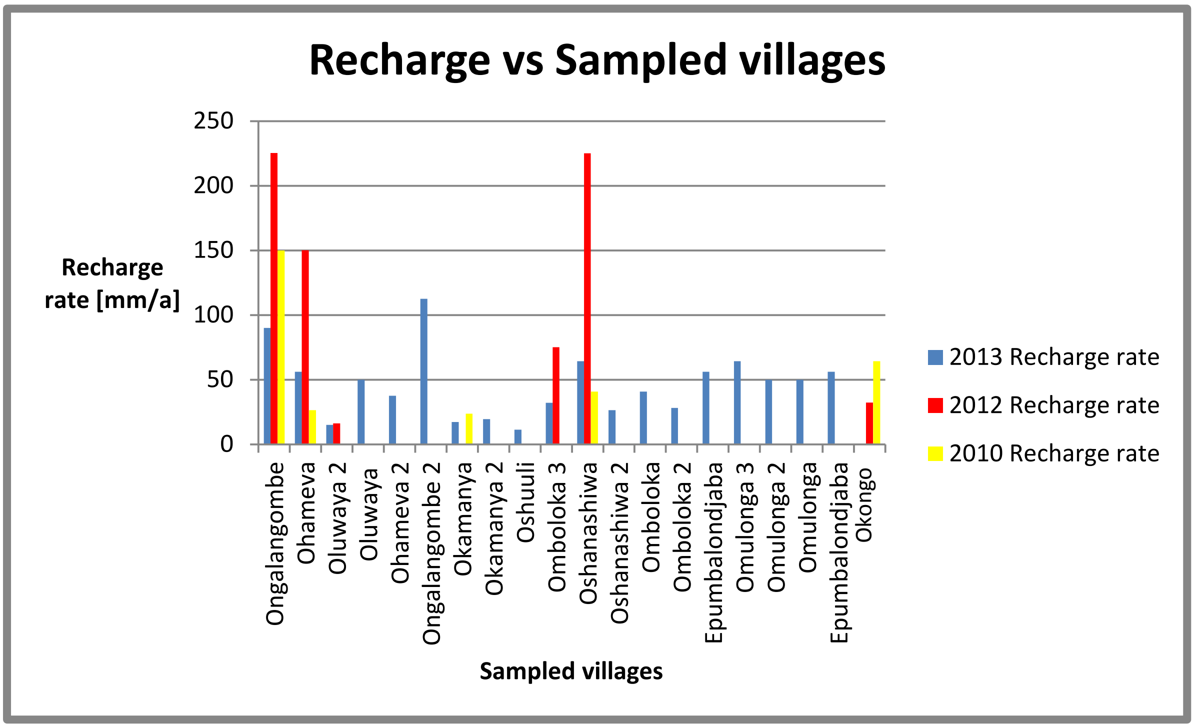

Figure 13: Bar graph summarizing recharge rates for years 2010, 2012, 2013.

The chloride content in the soil water is relatively different from the chloride content in the groundwater and thus different results of recharge rates are obtained. Table 4 below summarises recharge estimates from the chloride mass balance method in the soil water.

Table 4: Calculated Recharge Estimations from soil water.

Hydrotopes	Villages	Time	Cl in soil water [mg/l]	Recharge [mm/a]
Depression	Epembe	April-2013	18	25
	Ohameva	April-2013	13	33
	Oluwaya	April-2013	12	37
	Ongalangombe	April-2013	7	63
River	Omulonga	April-2013	9	49
	Epumbalondjaba	April-2013	9	49
Dune	Oshuuli	April-2013	10	45
	Omboloka Dunes	April-2013	11	40
Sandfield	Epembe	April-2013	9	49
	Ongalangombe	April-2013	12	37
	Oshanashiwa	April-2013	13	35
	Okamanya	April-2013	13	35
Pan	Omboloka	April-2013	7	63

Figure 14 shows recharge estimates from the sampled villages in the Ohangwena region, the pan and depressions have relatively high recharge rates compared to other hydrotopes in the area.

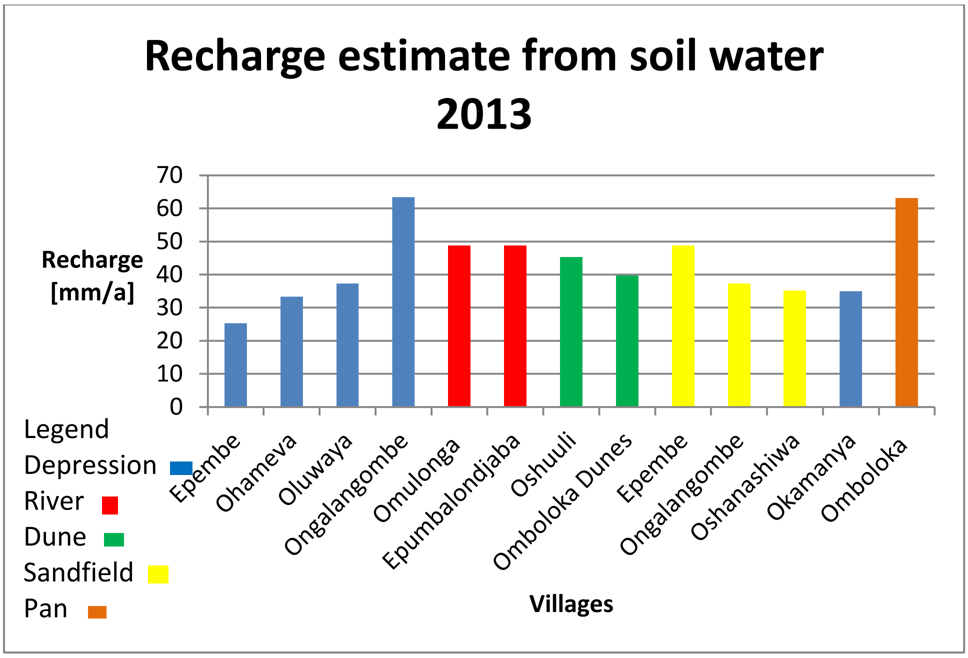

Figure 14: Bar graph indicating amount of recharge per hydrotop from soil water.

The highest recharge obtained is from the depressions with a mean of 79 mm/a, and the lowest is from a pan with an average of 35 mm/a. The depression has relatively high ranges with the minimum recharge rate of 15 mm/a ; maximum recharge rate of 222 mm/a. Table 5 summarises mean recharge and the maximum and minimum recharge in the study area from the ground water.

Table 5: Mean recharge calculated using chloride mass balance method from groundwater.

Hydrotop	min recharge [mm/a]	max recharge [mm/a]	Mean Recharge [mm/a]	N
Depression	15	225	79	13
Dune	11	75	39	3
Sandfield	17	225	60	7
Pan	28	41	35	2
River	50	64	55	5

Mean recharge rates from soil water is relatively different from that in groundwater. The recharge rates from the soil water are relatively lower than that from the groundwater. Table 6 summarises the mean, minimum and maximum recharge obtained by the chloride mass balance method from soil water.

Table 6: Mean recharge obtained using the chloride mass balance method from soil water.

Hydrotop	min recharge [mm/a]	max recharge [mm/a]	Mean Recharge [mm/a]	N
Depression	25	63	40	4
Dune	40	45	43	2
Sandfield	35	47	39	4
Pan	63	63	63	1
River	49	49	49	2

5.2 MODBIL

Mean annual precipitation of the study area is 493 mm/a. Mean actual evapotranspiration is 477 mm/a. The mean annual groundwater recharge for the Ohangwena region in this study is 19 mm/a (4 % of the mean annual precipitation) from the spatial variations and 23.9 mm/a, from simple average calculations. Higher recharge rates were observed locally ranging from 0-82.3 mm/a (see table below). The highest recharge rates occur in the river which is still constantly flowing while the lowest occur in the depressions.

Table 7: Mean values of major components of the water balance modelling for the Ohangwena region. Period February 2003- March 2008).

		Minimum [mm/a]	Maximum [mm/a]	Mean [mm/a]
Precipitation	Study area	484.7	503.4	493
ET actual	Study area	418.5	493.1	477
	Depression	478.6	490.3	484.5
	Sandfield	473.7	481.2	477.5
	River	418.5	422.7	420.6
	Dune	484.7	493.1	488.9
	Pan	452.7	459.3	456
Interflow	Study area	0	0	0
	Depression	0	0	0
	Sandfield	0	0	0
	River	0	0	0
	Dune	0	0	0
	Pan	0	0	0
Groundwater Recharge	Study area	0	83	19
	Depression	0	2	1
	Sandfield	11	22	16.5
	River	40	83	61.5
	Dune	2	11	6.5
	Pan	22	40	31

Different recharge rates are obtained from different hydrogeological settings; the following figure below gives recharge ranges in different hydrotopes. From the figure below the river has the highest recharge values ranging from 74-82.8 mm/a, with the depressions having the lowest values ranging from 0-2 mm/a.

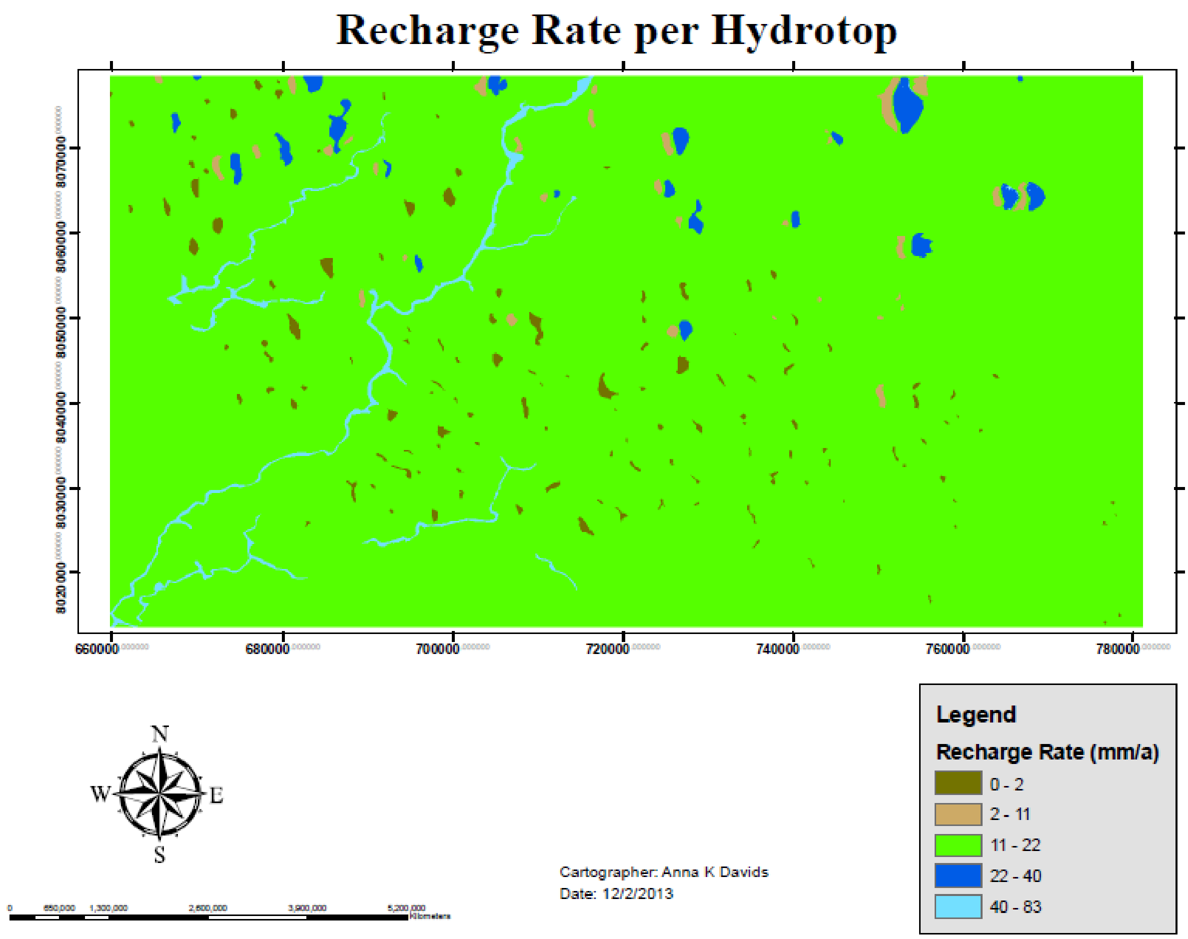

Figure 15: Spatial distribution of recharge in the study area.

Mean recharge rates from the chloride mass balance method are relatively higher than that obtained in the soil water balance model. In the chloride mass balance method recharge rate is higher for the simple average calculations where a recharge rate of 46.8 mm/a, was obtained compared to the recharge obtained when considering spatial fractions which is 39.4 mm/a. From the recharge rate obtained by the chloride mass balance from groundwater, recharge obtained from the simple average calculations is lower at an average of 53.6 mm/a and that obtained when considering spatial variations is higher at a range of 59.8 mm/a. Recharge amount obtained by the MODBIL is lower than that obtained by the chloride mass balance. Within the MODBIL, mean recharge from simple average calculations at a value of 23.3 mm/a is higher than the mean recharge obtained when spatial variations are considered which is 19 mm/a. Table 8 summarises recharge rates from the chloride mass balance method and the soil water balance model used in this thesis.

Table 8: Showing mean recharge rates obtained by the chloride mass balance and the soil water balance model per hydrotop and the summarized mean recharge for the whole study area from the MODBIL and the chloride mass balance method.

Hydrotop	Recharge rates obtained from chloride mass balance method using soil water [mm/a]			Recharge rates obtained from chloride mass balance method using ground water [mm/a]			Recharge rates obtained from MODBIL [mm/a]		
	min	max	mean	min	max	Mean	min	max	mean
Depression	25	63	40	15	225	79	0	2	1
Dune	40	45	43	11	75	39	2	11	6.5
Sandfield	35	47	39	17	225	60	11	22	16.5
Pan	63	63	63	28	41	35	22	40	31
River	49	49	49	50	64	55	40	83	61.5
Mean recharge in the study area [mm/a] based on simple average calculations	46.8			53.6			23.3		
Mean Recharge rate [mm/a] of the study area considering spatial fractions	39.4			59.8			19		

6 Interpretation & Discussions

There is a difference in recharge rate determined by the different methods used in the thesis. The chloride mass balance method obtained higher recharge rates compared to the soil water balance model.

Recharge calculated using the chloride mass balance method takes into account both the recharge through the infiltration matrix of the soil and the recharge through the preferred flow path, e.g. via shrinkage cracks or rootlet channels. Thus the recharge obtained from the chloride mass balance is relatively higher compared to the recharge rate obtained by the soil water balance model (MODBIL). This recharge from the CMB ranges from 46.8-53.6 mm/a, from simple average calculations and 39.4-59.8 mm/a when considering spatial variations in the soil water balance model which is higher than the MODBIL data which is 23.3 mm/a, from simple average calculations and 19 mm/a, from spatial variations. The application of the method with chloride in SW and chloride in GW yield different results, this is due to the fact that SW only consider recharge through the soil matrix while the GW takes into account both the soil matrix and the preferred flow paths.

Certain assumptions are considered for a successful application of the CMB in determination of recharge flux, these assumptions can however give misleading results if an extra source of chloride is present in a study area. The following is assumed, that atmospheric deposition is the only source for Cl in groundwater, assumptions are also made that Cl behaves as a conservative tracer along its path, The Cl uptake by the roots and anions is negligible, there is a complete leaching of Cl deposit at ground surface and in the soil, groundwater movement in both unsaturated zone and saturated zone can be approximated as one-dimensional piston flow, and that the surface run-on and runoff can be neglected. With this assumption a conclusion is drawn that the Cl concentration of groundwater recharge is a result of evapotranspiration (Fouty, 1989). If external sources are present in the area of research, lower than expected or higher than expected recharge rates can be obtained from the CMB method.

There has been a change in chloride content in the groundwater observed, which indicates that there is an inter annual and intra annual variations in recharge rates.

The chloride mass balance method used data from 2010, 2012 and 2013. From the climatic record the rainy season of 2011 and 2012 had the highest average precipitations thus recharge rate was expected to be at its highest during these years. This can be the reason why relatively high recharge rates are obtained.

Comparing with previous studies done using the same method in areas with rainfall averages similar or close to that in study area, lower recharge rates were obtained than that obtained in this from study area. Wanke et al. (2007) found recharge rates extremely low at a mean of 11.5 mm/a in the Upper Khaudum-Nhoma area. Külls (2000) also obtained low recharge rates ranging from 8.5-14 mm/a for the Grootfontein area, the area has mean rainfall of 465 mm/a, with the mean relatively higher than the mean rainfall in the study area which is 450 mm/a. Wrabel (1999) did his studies in the Hochfeld area and obtained a recharge of 7 mm/a, the area had mean rainfall of 397 mm/a which is relatively low than the rainfall mean of the study area. Klock (2002) found lower recharge estimates for the Kalahari Catchment of the North-eastern Namibia using regionalization approach that include satellite imaginary interpretation and the use of the chloride mass balance, Klock obtain a recharge rate ranging from 1.5-5 mm/a. Very close matches are found in the Ngamiland area by Brunner et al. (2004), with the mean annual recharge of 0-150 mm/a, with about 80% of the area at 30-90 mm/a.

Results from the soil water balance model indicate recharge rates ranging from 0-83 mm/a locally, with the mean spatial rate of 19 mm/a, and the simple calculated mean recharge of 29.1 mm/a. The highest recharge is observed in the rivers at a maximum rate of 83 mm/a. The model only captures recharge through the infiltration via matrix of the soil and does not consider recharge through preferred flow path and thus precipitation amount is an important factor for the generation of direct groundwater recharge which is captured by the model. Wanke et al. (2007) specified that spatial patterns of groundwater recharge follow mainly vegetation units, which are largely to two important vegetation-related factors: soil permeability and root depth. The determination of areal rooting depth however, is difficult, although point data can be obtained very easily (see discussion under limitation). Intra annual and inter annual precipitation variations lead to a variation of the amount of recharge obtained. The modelling period in this thesis includes only data from 2003 until 2008 therefore the recharge obtained will relate to the time at which modelling was done.

Using a water balance model, Külls (2000) found lower recharge in the upper Omatako catchment at an average of 4.5 mm/a, his modelling period included only data from 1980 until 1986. Wanke et al. 2007 also used MODBIL and obtained recharge rate of 8 mm/a in the Kalahari Catchment, the area has an average rainfall of 409 mm/a, her modelling period includes data from 1 October 1985-30 September 2004. Thus the discrepancy is likely to be due to the different time periods covered in each case, the differences in mean annual precipitation and also the temporal pattern of precipitation events.

6.1 Limitations

The limitations of this study include several assumptions made to simplify very complex recharge processes in the natural environment. It includes the assumption that precipitation is the only source of chloride in groundwater and that the surface run-off is negligible in the study area. Surface run-off was not observed in the field and thus it could not be determined, but during single rain events of extraordinary magnitude, local run-off might occur but could not be quantified in this study.

Another parameter that is insufficiently well determined is the unsaturated hydraulic conductivity at field capacity that is used in MODBIL. In this study the unsaturated hydraulic conductivity was only determined using the grain size distribution as not methodology is available at the University of Namibia. Further the applicability of the concept of field capacity is not yet proof: it is a concept that was developed for agricultural crops in humid conditions but natural vegetation in dry lands like Namibia might not follow this concept. This is currently an area of active research.

Root depth is the very variable vegetation cover in the study area that ranges from the order of tens of cm for grass to several meters where there are large trees and shrubs respectively, thus rooting depth becomes point data which is difficult to model as spatial data is needed for the modelling.

A further significant drawback of the current study is the lack of calibration data for the model, calibration can be done on the basis of the gauging station data and this was not carried out in this thesis. Thus the soil water balance model can only be verified against the recharge data from the chloride mass balance, but these are data from single points and they are also from a different time and different precipitation years and can thus not be reasonably compared.

Not all data was available, some parts of the research areas have not been sampled, and thus an assumption was made that only five hydrotopes were available in the study area. Time was also limited; the data collected represented only one season, recharge rates vary from season to season due to the seasonal effects.

7 Conclusion

The primary purpose of this project was to estimate recharge rates into the perched aquifers in the Ohangwena region using the chloride mass balance and the soil water balance model. The aim of the study was determine the amount of water usable with the region.

Recharge rates in the study area was obtained using the chloride mass balance and the soil water balance model using simple average calculations and the spatial variations in the study area.

Considering the size of the study area 121552 m by 68320 m (8304.4 km^2) and the range of recharge rates (19 mm/a to 60 mm/a) as summaries in table 9, it reveals that the annual recharge volume is in the range of 160 to 500 Mio m^3/a recharged into the perched aquifers every year. Compared to the estimate of the abstractable groundwater from the newly discovered Ohangwena 2 aquifer with 5000 Mio m^3, the perched aquifer appears to be a viable additional water source. However, the estimates done in this study here have to be seen together with the limitations of the study and open questions in the reliability of the data. If the recharge rates can be confirmed and also, the spatial approach applied in this study is correct, a possibility to use these aquifers could be considered. In addition to the given uncertainty in the quantity of the water source, also the water quality needs to be considered. Studies by Nakwafila (2011) and Neumbo (2012) have shown that at several locations the water quality is unfit for human consumption and these aquifers are extremely vulnerable to groundwater pollution (Hamutoko, 2013).

Table 9: summarizes volume of water recharged into the perched aquifers of the Ohangwena region.

x extension		121552 m		
y extension		68320 m		
Mean recharge based on simple calculations from SW using CMB	46.8 mm/a	0.0468 m/a	388647448 m^3/a	390 Mio m^3/a
Mean recharge based on simple calculations from GW using CMB	53.6 mm/a	0.0536 m/a	445117590 m^3/a	450 Mio m^3/a

Mean recharge based on simple calculations using SWBM	23.3 mm/a	0.0233 m/a	193493281 m^3/a	190 Mio m^3/a
Mean recharge from SW using CMB based on spatial fractions.	39.4 mm/a	0.0394 m/a	327194646 m^3/a	330 Mio m^3/a
Mean recharge from GW using CMB based on spatial fractions.	59.8 mm/a	0.0598 m/a	496605072 m^3/a	500 Mio m^3/a
Mean recharge using SWBM based on, spatial variations.	19 mm/a	0.019 m/a	157784220 m^3/a	160 Mio m^3/a

The overall picture that can be drawn from the result obtained is that recharge rate can be influenced by a number of factors. Depressions have a relatively high recharge rates and river have a higher recharge rate when flowing and during direct recharge. Sandfields and dunes have the lowest recharge rates and this was confirmed by both the chloride mass balance and the soil water balance model. Rainfall patterns also influence the amount of recharge in the area, the highest recharge into these perched aquifers are observed during the rainy seasons and during the years when rainfall was at its highest.

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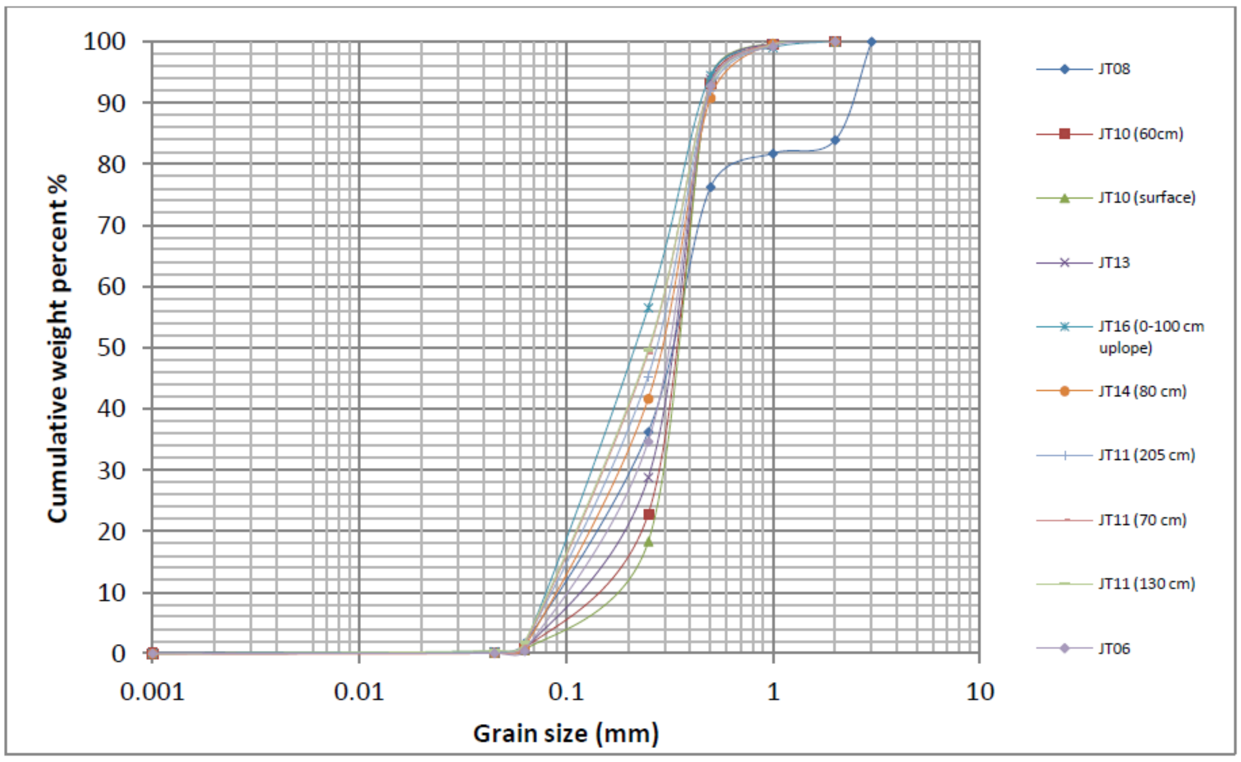
9 Appendix

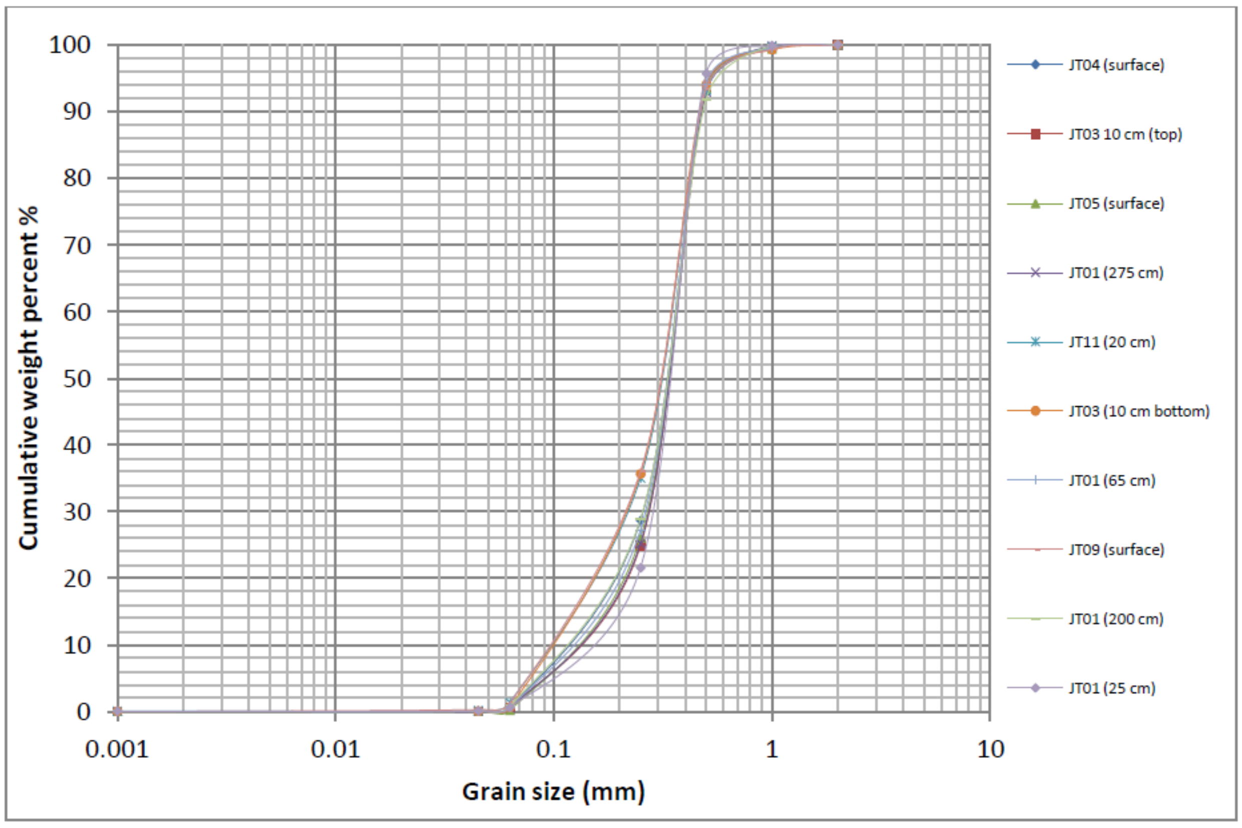
Appendix A: Field Results

Sample name	Site name	date	time	Depth [m]	Water level [m]	Latitude	Longitude	Elevation [m]	pH	Ec [µS/cm]	T [°C]	ORP [mVH]	Alkalinity [mg/l]	Nitrate [mg/l]	Fluoride [mg/l]	Phosphate [mg/l]	Turbidity [NTU]
OH1	Oshuuli	7/4/2013	14:29	unknown	9.7				7.08	878	22.1	322	540	0	0	33	63.4
OH2	Omulonga	7/4/2013	17:05	8.5	0.04	17° 33.876'	016° 53.498'	1132	6.69	89.4	25	375	40	0	-	1.3	very high
OH3	Omuonga 2	8/4/2013	7:50	15	12.8	17° 33.901'	016° 53.385'	1122	6.72	66.6	16.3	400	60	0	-	2.2	146
OH4	Omulonga 3	8/4/2013	8:32	12.4	11.4	17° 33.949'	016° 53.289'	1124	7.07	132.1	17.7	406	60	10	-	2.1	19.9
OH5	ohameva	8/4/2013	10:30		10.62	17° 34.933'	017° 05.611'	1138	7.72	529	26.4	410	180	25	-	11.8	1.37
OH6	Ohameva 2	8/4/2013	11:30	17.4	11	17° 35.033'	017° 05.632'	1143	7.6	639	25.9	371	280	0	-	8.2	4.32
OH7	Oluwaya (Mahangu field)	8/4/2013	12:50	10.62	9.4	17° 32.228'	017° 03.529'	1140	7.78	584	27.6	357	280	50	1.81	17.3	1.25
OH8	oluwaya 2	8/4/2013	13:30	11	9.5	17° 32.196'	017° 03.556'	1140	7.57	1017	25.7	377	220	250	1.2	17.2	1.44
OH9	Omboloka	8/4/2013	14:50	13.1	5.18	17° 24.481'	017° 08.310'	1150	7.26	614	27.4	402	300	0	-	8.5	2.52
OH10	Omboloka 2	8/4/2013	15:14	10.1	6.9	17° 24.354'	017° 08.250'	1149	7.44	734	26.9	392	280	100	-	11.7	4.36
OH11	Omboloka 3	8/4/2013	16:05	9.6	5.7	17° 24.356'	017° 07.893'	1153	7.52	559	25.4	370	220	50	-	9	7.31
OH12	ongalangobe	9/4/2013	8:00	30.2	25.2	17° 29.645'	017° 15.859'	1149	8.4	1304	25.3	311	600	10	-	10	7.72
OH13	ongalangobe 2	9/4/2013	8:30	28.9	24.3	17° 29.620'	017° 15.876'	1148	7.58	645	25.7	348	280	0	-	5.7	11.3
OH14	Oshanashiwa	9/4/2013	9:00	more than 30	19.5	17° 30.864'	017° 14.953'	1149	7.92	701	25.4	409	-	25	-	9.8	1.83
OH15	Oshanashiwa 2	9/4/2013	9:15	more than 30	17	17° 30.863'	017° 15.044'	1146		994	25.4	272	-	250	-	7.4	3.6
OH16	Okamanya	9/4/2013	10:30	more than 30	16.04	17° 31.891'	017° 12.042'	1145	7.42	841	24.9	379	-	100	-	6.5	2.17
OH17	Okamanya 2	9/4/2013	10:31	more than 30	16.2	17° 31.870'	017° 12.044'	1148	7.45	818	25	400	-	100-250	-	6.9	4.6
OH18	Epumbalondjaba	9/4/2013	13:40	3.9	3.5	17° 37.873'	016° 48.592'	1117	6.57	162	32	365	40	10	-	8.5	32.3
OH19	epumbalondjaba 2	9/4/2013	14:04	0.3	0.1	17° 38.566'	016° 43.953'	1120	7.82	309	29.6	374	140	0	-	6.7	23.3

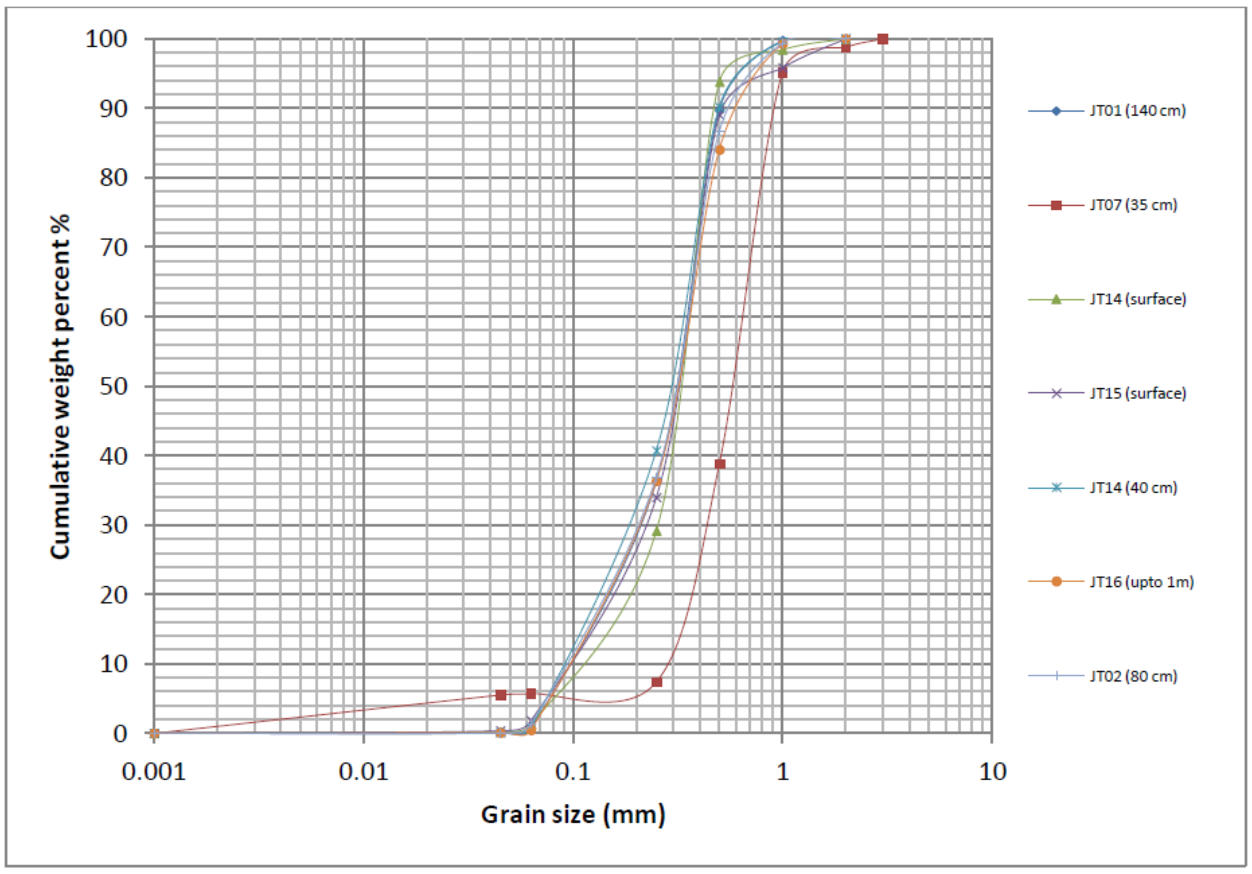
Appendix B: Grain size distribution curves used for the determination of hydraulic conductivity.



Cumulative weight percent %
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
Grain size (mm)
JT08
JT10 (60cm)
JT10 (surface)
JT13
JT16 (0-100 cm uplope)
JT14 (80 cm)
JT11 (205 cm)
JT11 (70 cm)
JT11 (130 cm)
JT06



Cumulative weight percent %
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
Grain size (mm)
JT04 (surface)
JT03 10 cm (top)
JT05 (surface)
JT01 (275 cm)
JT11 (20 cm)
JT03 (10 cm bottom)
JT01 (65 cm)
JT09 (surface)
JT01 (200 cm)
JT01 (25 cm)



Cumulative weight percent %
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
Grain size (mm)
JT01 (140 cm)
JT07 (35 cm)
JT14 (surface)
JT15 (surface)
JT14 (40 cm)
JT16 (upto 1m)
JT02 (80 cm)